Lynn Andrew Bollinger

# Fostering Climate Resilient Electricity Infrastructures

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Knowledge for Climate

NEXT GENERATION INFRASTRUCTURES FOUNDATION

# Fostering Climate Resilient Electricity Infrastructures

# Fostering Climate Resilient Electricity Infrastructures

PROEFSCHRIFT

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Keywords: Electricity, infrastructure, network, climate change, resilience, modeling and simulation, interdependency

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Propositions belonging to the dissertation

# Fostering Climate Resilient Electricity Infrastructures

by Lynn Andrew Bollinger

1. Infrastructures do not “bounce back”.
2. Distributed infrastructures degrade more gracefully than centralized ones.
3. Resilience is a prerequisite to sustainability.
4. Modelers should learn from Cubism.
5. The co-evolution of shared mental models with shared computer models enables us to address ever more “wicked” problems.
6. The more we model social systems, the more difficult it becomes to model social systems.
7. Creativity thrives on incongruity.
8. Provision of standing desks to PhD students would benefit science.
9. Peer review is to science as democracy is to government.
10. The Dutch concept of “gezellig” is a defense mechanism against the emotional effects of high population density.

*These propositions are regarded as opposable and defendable and have been approved as such by the promotors, prof. dr. ir. M.P.C. Weijnen and prof. dr. ir. G.P.J. Dijkema*

Stellingen behorende bij het proefschrift

# Fostering Climate Resilient Electricity Infrastructures

door Lynn Andrew Bollinger

1. Infrastructuren veren niet terug.
2. Gedistribueerde infrastructuren vertonen eleganter faalgedrag dan gecentraliseerde infrastructuren.
3. Veerkracht is een voorwaarde voor duurzaamheid.
4. Modelleurs kunnen een voorbeeld nemen aan het kubisme.
5. Door de co-evolutie van gedeelde mentale modellen en gedeelde computermodellen kunnen we in toenemende mate “ontembare” problemen aanpakken.
6. Hoe meer we sociale systemen modelleren, hoe moeilijker het wordt om sociale systemen te modelleren.
7. Creativiteit gedijt op incongruentie.
8. De wetenschap zou gebaat zijn bij het verstrekken van lessenaars in plaats van bureaus aan promovendi.
9. ‘Peer review’ staat tot de wetenschap als democratie staat tot de overheid.
10. Het Nederlandse begrip “gezelligheid” is een afweermechanisme tegen de emotionele effecten van een hoge bevolkingsdichtheid.

*Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotoren prof. dr. ir. M.P.C. Weijnen en prof. dr. ir. G.P.J. Dijkema*

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# Contents

# Chapter 1

# Introduction

## 1.1 Motivation

This book is about climate change, resilience and electricity infrastructures. My route to this intersection of domains passes through the related fields of sustainability and industrial ecology. The first book I read on the topic of sustainability – about 12 years ago – had the (probably unintended) effect of convincing me that the path to a sustainable world was all about getting the *prices right* – setting the prices of goods to reflect their real ecological and social costs. As I have learned since, this is eminently more difficult than it sounds. The second book I read assured me that the true path to sustainability lay in designing sustainable *products* – generating win-win solutions benefiting both the bottom line and society at large. This, too, is not the silver bullet I had imagined. But, I thought, if we could also design the societal *metabolisms* within which these products circulated, we could generate truly sustainable product systems capable of ensuring the complete recovery of the precious materials in our products. This, it turns out, is thermodynamically impossible.

My studies in sustainability have left me with several insights. First, there is no secret to a sustainable world. The pursuit of sustainability requires all of the above and more: "The truth is that our species at its current scale of population and activity is beyond silver bullets – no technological systems, no matter how mythic, can provide permanent and simple solutions... solutions will be complex, will involve difficult trade-offs and inevitably will be partial and contingent" (Allenby, 2005).

Second, sustainability is not a destination. We will never be able to paint a robust vision of a sustainable world because the world is changing too quickly, too unpredictably and too drastically for any worthy vision to survive intact. The world is a funhouse of nonlinearity, chaotic behavior and unintended consequences. Sustainability is a constantly shifting target, and its pursuit must be viewed as a continuous process of adjusting and readjusting to better align the manner of our existence with our desire to persist and flourish as a species.

*Resilience* is a notion complementary to sustainability. Where sustainability is about meeting our current needs without compromising future generations, resilience is about ensuring that both we and our descendants continue to meet these needs in a turbulent world. It is about ensuring that unanticipated events – whether they be hurricanes, floods, terrorist attacks or alien incursions – do not derail us from our quest to persist and flourish as a species.

Moreover, resilience implies that we are not helpless in the face of such turbulence and uncertainty. While we may not be able to predict the future, we can prepare for it. While we don't know precisely what climate change will bring, we can use the growing diversity of sophisticated tools at our disposal to say something about likely ranges of future meteorological conditions. And we can use these projections as a basis for heightening our seawalls, guiding the development of our building codes and making investments in our infrastructures.

Inevitably, whatever we do, it will be wrong. We will be underprepared in some areas and overprepared in others, and we will be blindsided by events that we did not even imagine. Like my search for the path to sustainability, adaptation to climate change must be a perpetual learning process. There is no magic bullet; there is no final destination; and there are no guarantees. We can only adjust and readjust as our knowledge and capabilities develop. This research is motivated by a desire to contribute to this perpetual process of adjustment.

## 1.2 Electricity infrastructures and climate change

The electricity infrastructure is a globe-spanning network composed of innumerable technical and social components – gas turbines, solar photovoltaics, overhead transmission lines and sub-sea cables, as well as consumers, power production companies, regulators, transmission system operators and others. The technical components of the infrastructure are designed to function optimally within a particular range of environmental conditions. Overhead power lines may fail at windspeeds greater than 130-180 km/hr (Rademaekers et al., 2011). Wind turbine output falls to zero above its rated cut-out speed. Transformer capacity drops by approximately 1% with every degree Celsius increase in temperature (Rademaekers et al., 2011).

And it is not only the technical components of the power system that are sensitive to environmental fluctuations; it is the social components as well. Demand for electricity is a byproduct of humans' desire to fulfill certain needs (e.g. thermal comfort, adequate lighting) and carry out certain activities (e.g. transporting goods, communicating electronically). The quantity of electricity required to fulfill these needs and carry out these activities fluctuates over time, sometimes in a manner correlated with meteorological variables such as temperature, insolation and precipitation. These fluctuations give rise to regular seasonal and daily variations in aggregate electricity demand, as well as occasional spikes and dips induced by extreme weather events.

For the most part, the meteorological sensitivities of the infrastructure's technical and social elements are irrelevant to the overall functioning of the infrastructure. Most power systems have sufficient redundancy in generation, transmission and distribution to accommodate periodically reduced performance, sporadic failures and heightened demand. But what happens when reduced performance and heightened demand become the norm, or when numerous failures occur simultaneously?

Recent years have seen several dramatic failures in electricity infrastructures sparked by short-term departures of environmental conditions from their norms. In the summer of 2012, 630 million people lost power across Northern India, partially as a result of tardy monsoons that increased electricity demand for irrigation and air conditioning and decreased hydroelectric output (Morrison, 2012; Walsh, 2012). In the fall of 2012, 8.5 million people lost power in the Northeast US, as a result of high windspeeds and extreme flooding associated with Hurricane Sandy (LeComte, 2013). And in the summer of 2003, a massive heat wave over much of Europe forced the temporary shut-down of several large thermal generation facilities in Germany and France as bodies of water used for cooling reached their legal maximum temperatures (De Bono et al., 2004).

We can choose to view events like these as isolated extremes. However, overwhelming evidence suggests that such deviations may increase in both severity and frequency over the coming decades. The Intergovernmental Panel on Climate Change (IPCC) indicates that the frequency and intensity of extreme heat events, the frequency of extreme rain events, the intensity of droughts and the maximum windspeeds of tropical cyclones are either likely or virtually certain to increase within the 21st century (IPCC, 2012).

Complementing these findings, a growing body of research suggests that these long-term changes are likely to influence the supply, demand, transmission and distribution of electricity in myriad ways. Increases in mean and extreme air and water temperatures and decreases in river flows are likely to affect the availability and efficiency of thermal generators, and the outputs of hydropower installations in certain areas (Koch and Vogele, 2009; Linnerud et al., 2011; Mideksa and Kallbekken, 2010). Increases in mean and extreme air temperatures may periodically reduce the capacities of power lines and heighten the risk of line failures (Rademaekers et al., 2011). Growth in the frequency and severity of windstorms may increase the occurrence of downed overhead lines, and rising sea levels combined with increased frequencies of extreme rain events may lead to periodic flooding of low-lying areas and subsequent disruption of power substations and other power system components. Higher average and extreme temperatures may increase demand for air conditioning and refrigeration, possibly leading to long-term increases in peak electricity loads (Petrick et al., 2010; Rothstein et al., 2008). These effects pose a very real threat to electricity infrastructures, from degrading their integrity and performance to inciting major blackouts.

Next to the impending threats of a changing climate is the reality that the electricity infrastructure itself is changing. New generation sources are coming online every year, and others are disappearing; new transmission and distribution lines are being constructed; new technologies are being developed; and new regulations are being implemented. For the most part, these changes happen slowly – technical infrastructure components are expensive and long-lived pieces of hardware – but they are happening continuously. Driven by rising standards of living, the accelerating pace of technological development, and concerns about the effects of fossil fuel-based generation on the global climate, the coming decades will likely see significant and large-scale changes in technological and institutional composition of the electricity infrastructure.

## 1.3 Climate change adaptation and infrastructure resilience

In dealing with vulnerabilities to climate change, the climate change community speaks of *adaptation* – "the process of adjustment to actual or expected climate and its effects in order to moderate harm or exploit beneficial opportunities" (IPCC, 2012). Adaptations may come in many forms, e.g.:

- *hard* adaptations, involving investments in physical/technical protections or redundancies
- *soft* adaptations, involving institutional or financial tools such as insurance products
- *pro-active* adaptations, directed at dealing with potential impacts before they occur
- *reactive* adaptations, directed at dealing with impacts after they have occurred

When it comes to electricity infrastructures, numerous forms of adaptation are possible – construction of dikes around vulnerable components to protect against flooding, modification of regulatory schemes to promote greater redundancy in the electricity grid, installation of cooling water towers to reduce the risk of cooling water issues during periods of extreme temperature, etc. Additionally, different adaptations may be geared to addressing different components of climate risk – threat, vulnerability, probability and consequence.

In considering possible adaptations for the electricity infrastructure, one reality must be highlighted – *100% security of supply is not feasible*. The electricity infrastructure is a *complex network*. The numerous interdependencies amongst the components of this network mean that disturbances in one corner of the system may have far-reaching impacts elsewhere within the system. This is demonstrated by a 2006 blackout in which a routine disconnection of a power line in Northwest Germany to allow for a ship crossing resulted in an alteration of load flows that sparked a power blackout extending to Germany, Poland, France, Italy, Spain, Portugal, Morocco, Belgium, Greece and elsewhere (UCTE, 2007). While added buffers and redundancies can help to reduce the likelihood of such events, the necessary investments are expensive. The competing objectives of cost and reliability tend to drive the long-term development of the system towards a point of *near-criticality* – a point at which eventual blackouts are inevitable (Dobson et al., 2007).

In light of this reality, *resilience* is increasingly seen as an essential characteristic of future infrastructure systems (EPRI, 2013; Garbin and Shortle, 2007; NIAC, 2009). The notion of resilience implicitly accepts the possibility of unforeseen disruptions and failures and focuses on the capacity of systems to handle them – to survive unexpected perturbation, recover from adversity and gracefully degrade – as well as an ability to adapt and learn over time (Madni and Jackson, 2009; McCarthy, 2007; Mili, 2011). Within the climate change adaptation community, increasing emphasis on the notion of "climate resilience" reflects a growing recognition of the importance of this approach (ADB; New York Department of State, 2011; Spelman, 2011; United Nations Development Programme, 2011).

## 1.4 Audience and contributions

This research sits at the intersection of multiple disciplines – electrical and energy engineering, systems engineering, climate change adaptation, complexity science, social simulation, power systems modeling and policy modeling. Given this breadth, portions of this thesis may be of interest to researchers from each of these disciplines, insofar as they represent specific (and in some cases novel) applications of familiar methods and tools. However, the main scientific contributions of this research are directed towards the climate change adaptation community, in particular the field of infrastructure adaptation.

The chief scientific contributions of this research to the field of climate change adaptation are four-fold. First, existing research has solidified a relatively well-defined understanding of the relationships between weather and other environmental variables and the performance/behavior of power system components and related human actors (Hekkenberg et al., 2009; Koch and Vogele, 2009; Linnerud et al., 2011; Mideksa and Kallbekken, 2010; Petrick et al., 2010; Rademaekers et al., 2011; Rothstein et al., 2008). Existing research has also defined temporally and geographically varying ranges of weather variables (climate scenarios) that are anticipated to occur under different socio-economic futures (Christensen et al., 2011; IPCC, 2007a, 2012; van den Hurk et al., 2006). The current body of research, however, leaves a gap at the *meso level* – at the level within which social and technical infrastructure components interact and component-level failures may cascade into network-level disruptions. This research seeks to address this gap by exploring relationships between environmentally-driven component disruptions and infrastructure network performance.

Second, the climate change adaptation community increasingly stresses the notion of *resilience*. The IPCC defines resilience as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions." (IPCC, 2007a). But this has very different implications depending on the manner in which we conceptualize our "system". What does resilience mean when it comes to a complex socio-technical system such as the electricity infrastructure, and how can this concept be operationalized in the context of climate change adaptation? Drawing from the field of socio-ecological systems, this research helps to solidify an understanding of infrastructure resilience from a viewpoint of infrastructures as complex socio-technical systems.

Third, existing research concerning the anticipated impacts of climate change on infrastructure networks – mostly in the field of transport – generally uses *current* infrastructure configurations as a starting point for assessment of potential vulnerabilities and identification of adaptation options (Chinowsky et al., 2013; Nguyen et al., 2011; Oslakovic et al., 2013; Oswald and Treat, 2013). However, given the long timespan over which the impacts of climate change may be relevant – decades to centuries – and anticipated major developments in electricity infrastructures over the coming decades – distributed generation, renewables integration, smart grids, electric vehicles, etc. – current configurations are not a valid starting point for assessments of electricity infrastructure vulnerability to climate change. Nor are they a valid basis for policy recommendations. Moreover, in the case of electricity, there exists little formalized understanding of the manner in which infrastructure networks develop in the long term, with most projections based upon a scenario approach that ignores the evolutionary processes underlying network development (National Grid, 2011; Tennet, 2011). Such an approach is inadequate given the fragmentation of control that characterizes today's electricity systems. This research addresses both of these issues by exploring long-term dynamics in the evolution of electricity infrastructures, and using this as a basis for a vulnerability assessment and recommendations for supporting resilience.

Fourth, existing research in the area of infrastructure adaptation to climate change – with a few exceptions (Hunt and Watkiss, 2011; Kirshen et al., 2008) – views different types of infrastructures (e.g. road, rail, electricity, gas) independently. However, it is increasingly recognized that different types of infrastructures are highly *interdependent*, and that these interdependencies may have significant consequences on the vulnerability of infrastructures to both environmental fluctuations and deliberate attacks (Pederson et al., 2006; Peerenboom and Fisher, 2007; Rinaldi, 2001; Svendsen and Wolthusen, 2007). Little knowledge exists about the consequences of infrastructure interdependencies on the vulnerability of such *multi-infrastructure systems* to climate change. This research explores these consequences, and seeks to identify options for supporting resilience within multi-infrastructure systems.

Next to these contributions to the field of climate change adaptation, this research contributes to the field of modeling and simulation, a field which currently struggles to deal with problems spanning *multiple spatial and temporal scales* and featuring *multiple valid perspectives*. Many of today's most challenging societal problems – including climate change adaptation, sustainability, poverty and others – share these features, and the modeling and simulation community needs improved approaches for addressing them. This research introduces the notion of *multi-model ecologies* – a novel way of conceptualizing systems of interacting and evolving models and datasets – which can help the infrastructures community to better address problems spanning multiple scales and featuring multiple valid perspectives.

Next to these scientific contributions, this research offers a societal contribution in the form of a set of recommendations for supporting the resilience of the Dutch electricity infrastructure to climate change. This contribution combines with the work of other researchers in the INCAH research program in contributing to a compilation of adaptation strategies for stakeholders. Together, these contributions provide a multi-infrastructure, multi-disciplinary set of guidelines for supporting the robustness and resilience of Dutch infrastructures to climate change.

## 1.5 Research questions and objective

The main question driving this research is: *How can we foster a climate resilient electricity infrastructure in the Netherlands?*

Framed by this question, the chief objective of this research is *to assess the vulnerability of the Dutch electricity infrastructure to extreme weather events within the context of climate change, and to identify robust options for supporting infrastructure resilience*. A secondary objective is to develop a framework, an approach and a set of modeling tools for supporting the development of climate resilient infrastructures. Underlying these objectives is a supposition that both the potential vulnerabilities of electricity infrastructures to climate change and options for supporting resilience can be found not only in the relationships of these components with their physical environment, but also in their linkages with one another and with their social context.

The main research question is divided into the following sub-questions:

1. How can infrastructure resilience be defined from a perspective of infrastructures as complex socio-technical systems?

2. How are the components of electricity infrastructures vulnerable to weather events, and what are the possible adaptation measures?

3. How can the extreme weather resilience of an electricity infrastructure be studied and quantified in a manner which captures the pertinent aspects of its functionality and accounts for the infrastructure's socio-technical complexity?

4. How may long-term changes in weather extremes affect the vulnerability of the Dutch electricity infrastructure, and what measures can effectively support infrastructure resilience?

5. How can we represent and explore the long-term development of electricity transmission networks in a manner which reflects the role of key societal drivers?

6. How might a low-carbon transition affect the vulnerability of the Dutch electricity infrastructure to climate change, and how can we harness this transition to support climate resilience?

7. Which infrastructure assets in North Rotterdam may be vulnerable in the case of a local dike breach, due to their dependence on the electricity infrastructure? Which measures can help to alleviate these vulnerabilities?

8. How can we identify strategies for enhancing infrastructure resilience under conditions of incomplete knowledge of possible interdependencies?

9. How can modeling and simulation be more effectively used to address multi-scale, multi-perspective societal challenges such as infrastructure adaptation to climate change?

## 1.6 Structure of the thesis

The remainder of this report consists of five parts. The first part introduces the theoretical and methodological foundations of this research. The second, third and fourth parts describe a set of three case studies that have been carried out based on these foundations. The fifth part provides a methodological and substantive synthesis of the findings of these case studies.

**PART I: FOUNDATIONS**

**Chapter 2:** Theoretical foundations

**Chapter 3:** Approach

**Chapter 4:** Climate change and electricity infrastructures – anticipated impacts and possible adaptations

**PART II: CASE STUDY 1**

**Chapter 5:** Assessing infrastructure resilience

**Chapter 6:** Assessing the extreme weather resilience of the Dutch transmission infrastructure

**PART III: CASE STUDY 2**

**Chapter 7:** Growing electricity networks

**Chapter 8:** Future development of the Dutch transmission infrastructure and consequences for resilience

**PART IV: CASE STUDY 3**

**Chapter 9:** Resilience in multi-infrastructure systems – exploration of the effects of interdependencies on infrastructure resilience

**PART V: SYNTHESIS**

**Chapter 10:** Multi-model ecologies – facilitating model integration and reuse in the study of infrastructures

**Chapter 11:** Conclusions

# Part I

# Foundations

# Chapter 2

# Theoretical foundations

This research is underpinned by several key theoretical concepts. In this chapter, we introduce these concepts and elaborate on their use in the context of this research. Specifically, this chapter aims (1) to establish a theoretically grounded perspective based upon which a suitable approach for addressing the research question can be formulated, and (2) to more precisely define and theoretically underpin the notion of *climate resilient electricity infrastructures* in order to provide needed clarity in pursuit of the research question.

This chapter is divided into three parts. The first part introduces the perspective of electricity infrastructures as complex socio-technical systems, and explores the theoretical basis for its application within the context of this research. The second part identifies distinct uses of the word *resilience* in systems literature, and seeks to arrive at a more precise framing of resilience and related concepts within the infrastructures context. The third part links the notion of climate change to the previously established framing of infrastructure resilience. A more thorough examination of climate change and its anticipated effects on electricity infrastructures is left to chapter 4.

## 2.1 Electricity infrastructures as complex socio-technical systems

An *infrastructure* may be defined as a set of technical and organizational structures responsible for the production and delivery of goods and services essential to economic productivity and human well-being. Infrastructures are the backbone of modern industrialized societies, and an essential ingredient to enhancing health and wealth in the developing world (Briceno-Garmendia et al., 2004; Leipziger et al., 2003). They include systems for the purification and delivery of drinking water, the movement of humans and physical goods by road, rail and air, the delivery of digital and analog communications, and the production and delivery of energy in the form of natural gas, petroleum, heat and electricity.

Infrastructures such as these may be viewed as *socio-technical* systems – sets of tightly linked technical and social components (Hughes, 1987; Ottens et al., 2006).

The technical components of the infrastructure include the pipelines, rails, roads and wires through/over which goods, humans and information are transported. The social components include the owners, operators, developers and maintainers of these technical components. The infrastructure's day-to-day operation and long-term development are a combined consequence of dynamics within the social and technical subsystems.

Electricity infrastructures are a distinct class of infrastructures responsible for the production and delivery of electrical energy. They have been called the largest machines in the world (Amin, 2002) – spanning cities, countries and even entire continents, and encompassing innumerable technical components from nuclear generators and wind turbines to electrical substations, transmission lines and sub-sea cables. The accompanying social infrastructure consists of the owners, operators and maintainers of these technical components, as well as the markets that mediate processes of production and delivery. This includes power producers, grid operators, electricity retailers and consumers of different types.

Driven by fundamental discoveries on the part of Alessandro Volta, Michael Faraday, Thomas Edison, Nicola Tesla and others, electricity infrastructures began to take shape in the late 19th and early 20th centuries. The first "true" electricity infrastructure came online in 1882, consisting of a single coal-fired generator linking the incandescent lamps of 59 customers within a New York neighborhood. Similar systems soon sprouted in major cities around the world, and were eventually expanded to link entire urban areas with a diversity of electricity consuming devices and multiple generators operating simultaneously. At first, each of these demand centers was managed independently and provided for its own demand. Gradually, however, these isolated grids were linked to provide backup power and improve stability, and were extended to connect progressively larger and more remote power generation facilities (Schewe, 2009). Today's electricity infrastructures link these formerly disparate networks into interconnected regional, national and even supranational power systems fed by an increasingly powerful and technologically diverse array of generators.

Dating back to Thomas Edison's Edison Illuminating Company and throughout most of the 20th century, the key tasks of electricity generation, transmission and distribution were concentrated within a single organizational entity, a vertically-integrated utility. In recent decades, however, processes of economic liberalization have induced vertical de-integration and a general shift from centralized to fragmented control of the technical infrastructure (Markard and Truffer, 2006; van Damme, 2005; Vries et al., 2006). In many countries, electricity transmission networks are currently owned, operated and planned by regulated, monopolistic entities called *transmission system operators (TSOs)* or *independent system operators (ISOs)*. Distribution grids are owned, operated and planned by separate private or public entities called *distribution system operators (DSOs)*. Generation facilities are owned and operated by yet another set of actors – *power producers* – and are organizationally distinct from TSOs and DSOs. The consequences of this vertical de-integration are visible in the current socio-technical structure of the Dutch electricity infrastructure (Figure 2.1).

As national infrastructures become more institutionally fragmented, supra-national infrastructures are becoming more institutionally unified. With the increasingly in-

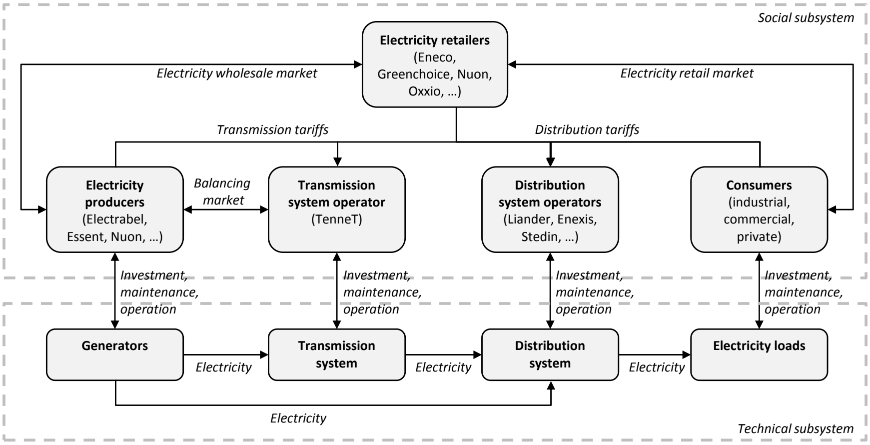


Figure 2.1: Current socio-technical structure of the Dutch electricity infrastructure.

terconnected nature of formerly disparate national infrastructures, the traditionally isolated nature of national electricity institutions (markets and grid operation) is changing. This trend is visible in the 2005 formation of ENTSO-e – the European Network of Transmission System Operators for Electricity – as well as in the development of a single Nordic electricity market and coupled markets in northwest Europe. It is also evident in Dutch TSO TenneT's 2010 takeover of a large portion of the German transmission system.

## Electricity infrastructures as complex systems

What is a complex system? A *system* may be defined as a set of elements or components connected so as to perform a unique function not performable by the elements alone. Regardless of their type, all systems have a *structure* – determined by the configuration of components and their connections in a given space – and exhibit *behavior* – a combined result of processes that transform inputs into outputs.

Though we might sometimes refer to certain real-world entities as "systems" (e.g. a stereo system, a solar system), it is important to note that not all systems are clearly defined entities in the real-world. As humans, we discriminate amongst entities in ways that are useful to us, but this does not imply that these entities are somehow isolated from their surroundings, nor that they are distinct entities at all. In other words, a system is something *we* define. It is a conceptualization whose borders are subjective and inherently porous, and whose "existence" is useful only insofar as it contributes to our understanding of the real world.

As much as we might sometimes like them to, not all of the systems we choose to define behave in convenient ways. The notion of *complexity* highlights the reality that many systems we define may not behave in accordance with our simplified notions of how these systems *should* behave (Allenby, 1998; Maier and Rechtin, 2002). While it may be mathematically convenient and cognitively appealing to imagine that a system responds linearly to a variation in the value of an input variable, such behavior is far from universal. A change in the value of an input variable may trigger a sudden, catastrophic shift in system behavior – a phase shift

– or a minor modification in initial state may incite a vastly different development trajectory (Capra, 2002; Kay, 2000).

While "non-intuitive" patterns such as these are common in natural and human systems, precisely what we mean when we call a system *complex* depends on our perspective, and many perspectives exist (Allen et al., 1999; Flood, 1990; Heylighen, 1999; Kolmogorov, 1963; Maier and Rechtin, 2002; Mikulecky, 2013). In this research, we choose to conceptualize the complexity of electricity infrastructures from two distinct perspectives: (1) as complex technical networks and (2) as complex adaptive systems.

### The electricity infrastructure as a complex technical network

A perspective of infrastructures as complex technical networks implies that, via the interconnectedness of their technical components, electricity infrastructures may exhibit non-intuitive behavior. This perspective draws from Heylighen (1999), who suggests that complexity relates to the degree of *variety* (distinction) and *dependency* (connection) in a system, and this in multiple dimensions. All other things equal, in other words, an increase in complexity is demonstrated by an increase in variety and/or connection in at least one dimension. With its single generator and 59 customers, Edison Illuminating Company's 1882 New York grid may have been complex, but – with hundreds of generators of different types, thousands of lines of different voltages and millions of customers with different demand profiles – today's electricity infrastructures are orders of magnitude *more* complex.

In operationalizing this perspective, we draw from *graph theory*, which, logically, entails the study of graphs – interconnected sets of vertices linked by (directed or undirected) edges. The study of complex systems as graphs has been employed in a range of fields from physics to linguistics to sociology. In the study of electricity infrastructures, graph theory allows for describing the characteristics of an electricity infrastructure's technical composition using a unique set of metrics – number of nodes, number of edges, mean degree, degree distribution, characteristic path length, clustering coefficient, etc. These metrics can provide us with hints as to the behavior and performance of the infrastructure under different circumstances, including its vulnerability (Holmgren, 2006; Winkler et al., 2010) and reliability (Rosas-Casals, 2009).

In viewing infrastructures as graphs, or networks, we need not limit ourselves to assessment of their static properties. By augmenting a graph theoretic conceptualization of electricity infrastructures with an electrical engineering conceptualization, we can study the dynamic performance of electricity networks. An example here is *Kirchoff's Circuit Laws* – a set of fundamental electrical engineering laws describing the distribution of electrical current in a circuit junction and the distribution of voltage within a closed conducting path. Combined with a network representation of an electricity infrastructure, and some knowledge about the properties of the infrastructure's components, Kirchoff's Laws enable the quantification of certain aspects of an infrastructure's dynamic behavior – fluctuations in real and reactive power flows over time, changes in voltage magnitudes at substations, potential capacity overloads, etc. Quantifying the behavior of an electricity infrastructure in this manner can provide us with further insight into its potential performance under different conditions, taking into account dynamic phenomena such as cascading failures (Dobson et al., 2003).

### The electricity infrastructure as a complex adaptive system

The second way in which we conceptualize infrastructure complexity is based on Universal Darwinism and the notion of complex adaptive systems. The theory of Universal Darwinism holds that the concept of evolution can be viewed as a generic algorithmic process of *variation*, *selection* and *heredity* that may be applied to systems beyond the biological realm (Dawkins, 1983). In the case of electricity infrastructures, *variation* occurs as new technologies (both physical and social) and modifications of existing technologies are introduced to the infrastructure; *selection* occurs as those technologies that do not produce sufficient social or financial benefit are removed or allowed to obsolesce; and *heredity* occurs as the application of successful technologies is expanded.

An example of this is the evolution of electricity generation over the past century. When electricity infrastructures first emerged, they were powered by relatively small, fossil fuel-fired generators – e.g. the 600 kilowatt coal-fired Pearl Street Station. Since this time, technological innovation (processes of *variation*) has resulted in the development of successively larger generators of various types providing improved efficiency and greater economies of scale, as well as a range of niche technologies – small-scale combined heat/power units, grid-independent photovoltaic generators and geothermal plants. At the same time, processes of *selection* have driven the extinction of inefficient and financially untenable technologies – e.g. the 175 horsepower Porter-Allen steam engines that powered Edison's Pearl Street Station – while processes of heredity have prompted the broad dissemination of successful technologies, such as highly efficient combined cycle turbines.

In seeking to describe infrastructures as evolving systems, we draw from the notion of *complex adaptive systems*. A complex adaptive system (CAS) may be defined as a "dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing", with behavior ultimately arising from the numerous decisions made each moment by each individual agent (Waldrop, 1992). From this perspective, complexity arises not only from the interactions amongst components, but also the ability of these components to make independent decisions based on local knowledge.

The CAS perspective aligns well with the structure of the social subsystem composing today's electricity infrastructures. Since the vertical de-integration of the electricity supply chain, ownership – as well as responsibility for the planning and operation – of the technical infrastructure is fragmented amongst a range of actors. Both the long-term development of the infrastructure, as well as its day-to-day functioning, are negotiated products of a multi-actor process in which each actor has incomplete knowledge and a unique set of interests and capabilities.

Holland (1992) suggests that CAS can be described in terms of three key characteristics. First, they *evolve* over time as system components learn and adapt. Second, they exhibit *aggregate behavior* that emerges from the interactions amongst components and cannot be simply derived from the independent actions of these components. Third, they *anticipate* through the decentralized development of rules that help them adapt to changing circumstances. Each of these characteristics can be identified in the social and technical dynamics of the electricity infrastructure. Electricity infrastructures *evolve* as producers invest and disinvest in generators, grid operators invest in grid components and consumers deploy new energy consuming devices. *Aggregate behavior* is visible in phenomena such as electricity price spikes, large-scale blackouts and sustained chaotic oscillations in power flows (Borenstein, 2002; Nedic et al., 2006; Venkatasubramanian and Ji, 1999). And *anticipation* is evident in the functioning of various types of markets – day-ahead markets, reserve markets, futures markets, etc. – which exist to coordinate the provision of power to consumers at a future point in time, as well as in the power flow models employed by grid operators to predict and correct for shortfalls in transmission capacity. The presence of these features within the electricity infrastructure testify to the validity of framing the electricity infrastructure as a CAS.

In the last several sections, we have elaborated on the notion of infrastructures as *complex socio-technical systems*. We have discussed the meaning of key concepts such as infrastructures, systems and complexity, and we have described the dual manner in which we conceptualize infrastructure complexity in this research. We now move on to the notion of *resilience*.

## 2.2 Resilience of electricity infrastructures

In this section, we explore the notion of resilience as it relates to electricity infrastructures. The concept of resilience has been applied in numerous fields of research, including psychology (Masten, 2001; Rutter, 1987), (social-)ecological systems (Adger, 2000; Folke, 2006; Gunderson et al., 2002; Pimm, 1991), business (Hamel and Vaelikangas, 2003; Linnenluecke and Griffiths, 2010) and engineering (Dekker et al., 2008; Sterbenz et al., 2010).

*Merriam Webster Dictionary* provides two definitions for resilience: (1) "the capability of a strained body to recover its size and shape after deformation caused especially by compressive stress", and (2) "an ability to recover from or adjust easily to misfortune or change" (Merriam Webster). The former of these definitions refers narrowly to a property of a physical object or material. The latter is broader and can be applied to a range of system types. When it comes to infrastructures, this broader definition of resilience implies an ability to recover from or adjust to both *sudden disturbances* such as deliberate attacks and weather extremes, and *gradual changes* such as evolving societal demands and climatic shifts.

To what degree are these properties relevant in the context of today's infrastructures? In the wake of 9/11 and resulting from several highly destructive recent natural disasters, there is growing recognition of the vulnerability of our infrastructures and the reality that they cannot be 100% protected 100% of the time (Dobson et al., 2007; Wald, 2013). Moreover, uncertainties about the trajectory of climate change and the increasingly rapid pace of technological development have forced infrastructure owners and managers to deal with the prospect of an unpredictable and turbulent future (Pahl-Wostl et al., 2007; Ukkusuri et al., 2007). Recognition of these realities has led to increased emphasis on resilience as a key property of future infrastructure systems (EPRI, 2013; Garbin and Shortle, 2007; NIAC, 2009).

From a systems perspective, the dictionary definition of resilience leaves much open – What is meant by *recover* and *adjust*? What *timescale* are we speaking of? What are the implications of *system complexity*? In order to address these questions, we first take a step back and frame the concept of resilience from a systems perspective. A system can be defined in terms of three characteristics – its *structure*, *functions* and *behavior*. A system also has a (subjectively) defined boundary and resides within an *environment*. As the dictionary definition suggests, resilience implies the occurrence of some sort of misfortune or change – we will call this a *disturbance* – which somehow interacts with the system. We assume that this disturbance emanates from the environment, rather than from within the system itself[1]. This framing is illustrated in Figure 2.2.

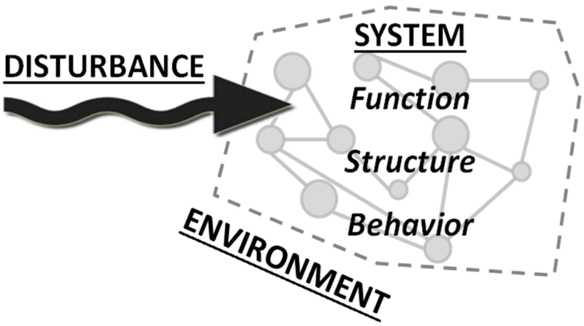


Figure 2.2: Framing of system resilience

## Perspectives on system resilience

According to the dictionary definition quoted above, resilience is about the ability of a system to *recover* or *adjust* in the face of a disturbance. However, a review of different definitions of resilience from systems literature suggests that there are multiple perspectives as to the precise implications of this ability in terms of the structure, behavior and function of a system. These perspectives can be broadly divided into three categories, summarized in Table 2.1.

Table 2.1: Categorization of perspectives on system resilience.

| | |
|---|---|
| **Perspective 1** | The ability of a system to *quickly recover* its original structure, behavior and level of function upon exposure to a disturbance. |
| **Perspective 2** | The ability of a system to *remain within a given regime* in terms of structure, behavior and level of function upon exposure to a disturbance. |
| **Perspective 3** | The ability of a system to *adjust structure, behavior and function* in order to sustain operations upon exposure to a disturbance. |

[1] There are different views on this – de Haan et al. (2011) suggest that disturbances may also derive from the internal relations within a system.

**Perspective 1**

The *first* perspective deals with the capacity of a system to recover quickly to its original state following a disturbance, with this state defined in terms of the system's structure, behavior and level of function. Inherent in this perspective is a temporal dimension. In other words, a disturbance is seen as potentially inciting a change in a system's structure, behavior or level of function. The system's resilience has to do with (and can be measured in terms of) its *return time* – how long does it take for the system to return to its original state? This inherently implies the existence of a single equilibrium in system behavior – a single stable state towards which the system will always tend to return. This perspective is in line with Pimm's definition of resilience in ecological populations (Pimm, 1991) and Folke's notion of "engineering resilience" (Folke, 2006), as well as with dominant twentieth century ideas about the dynamics of economic systems exposed to disturbances (Gunderson et al., 2002; Varian, 1992). Definitions of resilience in line with this perspective include:

- "The rate at which population density returns to equilibrium after a disturbance away from equilibrium." (Pimm, 1991)
- "The ability of a system to gracefully degrade and to quickly self-recover to a normal state." (Mili, 2011)
- "The rate at which a system approaches steady state following a perturbation." (Folke, 2006)

**Perspective 2**

The *second* perspective deals with the ability of a system to absorb a disturbance without deviating from a given set of boundaries in terms of structure, behavior and level of function. Like the first perspective, it accepts the possibility that a disturbance may cause a deviation in system state. In contrast to the first perspective, however, it lacks a temporal dimension. Instead of return time, it expresses and quantifies resilience in terms of the *magnitude* of disturbance a system can absorb without deviating significantly from its original state. This perspective relaxes the assumption that the system exists in a near-equilibrium state, accepting the possibility for catastrophic shifts to alternate steady states. Such catastrophic shifts are deemed inherently undesirable. Preferred is *graceful degradation* – gradual deterioration in performance (level of function) with increasing magnitude of disturbance.

Fittingly, this perspective has been employed to describe resilience in networks, specifically in terms of the degree to which a graph (structure) must be altered in order to destroy a particular property (function) (Sudakov and Vu, 2008). It has also been used to describe resilience in ecological systems (Folke, 2006; Gunderson et al., 2002), in emergency services (Kendra and Wachtendorf, 2003), in cyber systems (Vugrin and Turgeon, 2013) and in human societies (Allenby and Fink, 2005). Definitions of resilience in line with this perspective include:

- "Capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity." (Walker et al., 2006)

- "The magnitude of disturbance that can be experienced before a system moves into a different state and different set of controls." (Holling, 1973)

- "Ability to sustain a shock without completely deteriorating" (Kendra and Wachtendorf, 2003)

- "A graph G (from certain class) possesses a property P ... we define the resilience of G with respect to P, which measures how much one should change G in order to destroy P." (Sudakov and Vu, 2008)

### Perspective 3

The *third* perspective deals with the ability of a system to modify its state (structure, behavior and/or function) in order to sustain operations. This perspective is similar to the second perspective in that it excludes the temporal dimension and accepts the possibility for multiple stable states, catastrophic shifts and nonlinear behavior. The major distinction here is that a shift from one stable state to another is not viewed as invariably undesirable, but rather (sometimes) essential to preserve the system. This perspective derives amongst others from emerging work in the field of resilience engineering (Madni and Jackson, 2009), which emphasizes self-organization and the role of adaptive capacity – an ability to "recognize, absorb, and adapt to changes and disruptions" – in enhancing resilience (Dekker et al., 2008).

This perspective is very much in line with the notion of complex adaptive systems, in which system behavior is driven amongst others by the interests, knowledge and capabilities of its components (agents). Compared with the second perspective – which tends to stress the destructive role of humans in eroding system resilience (Gunderson et al., 2002) – the third perspective emphasizes a proactive role for human decision makers in adapting systems to new conditions. Resilient systems are ones which are able to self-organize towards new stable states in order to avoid catastrophic flips to undesirable ones. They are systems which are constantly reinventing themselves in order to survive, rather than seeking to dwell within an "outmoded" regime. These characteristics relate very strongly to the notion of *adaptability* as defined by (Folke, 2006), which stresses the role of humans in supporting and altering system structure and function. Definitions of resilience in line with this perspective include:

- "A resilient system is able effectively to adjust its functioning prior to, during or following changes and disturbances, so that it can continue to perform as required after a disruption or a major mishap, and in the presence of continuous stresses." (Hollnagel, 2009)

- "Identifying and then enhancing the positive capabilities of people and organizations that allow them to adapt effectively and safely under pressure." (Dekker et al., 2008)

- "The ability to dynamically reinvent business models and strategies as circumstances change, to continuously anticipate and adjust to changes that threaten their core earning power." (Hamel and Vaelikangas, 2003)

- "The ability of a system to recover from adversity, either back to its original state or an adjusted state based on new requirements." (McCarthy, 2007)

These three perspectives capture the chief distinctions amongst definitions of resilience found in systems literature. It is important to keep in mind that these perspectives are not mutually exclusive – some definitions span multiple perspectives, and some definitions must be viewed in the context of related concepts. Redfearn and Pimm (2000), for instance, define ecological resilience in terms of the first perspective above, but view resilience as closely entwined with the concepts of stability, persistence, resistance and variability. Walker et al. (2004) view ecological resilience itself as being composed of four related but distinct concepts:

1. **Latitude:** The maximum amount a system can be changed before losing the ability to recover.

2. **Resistance:** The ease or difficulty with which a system can be changed.

3. **Precariousness:** The proximity of a system to a given threshold.

4. **Panarchy:** The effects of states and dynamics at different scales.

Also in the infrastructures domain, resilience is sometimes perceived as a multi-dimensional concept. Vugrin et al. (2011), for instance, view resilience as consisting of two distinct components – *system impact* and *total recovery effort*. Resilience is defined as "the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system performance levels" (Vugrin et al., 2011). In the domains of both ecology and infrastructures, definitions of resilience vary and are context dependent. The perspectives described above provide us with some clarity as to the distinctions between these definitions, and can guide us as we seek to more clearly define and more fully underpin the notion of "climate resilient infrastructures".

## Attractors and resilience

The second and third perspectives introduced in the previous section both incorporate the idea that disturbances may cause a system to rapidly shift from one *stable state* or *equilibrium* to another. Before attempting to define the notion of resilience with respect to infrastructures, it is useful to take a brief sidestep and enhance our understanding of this key dynamic.

Another term for a stable state or equilibrium is an *attractor*. The concept of an attractor originates from mathematical studies of dynamical systems (Bhatia and Szego, 1967) and may be defined as a set of points towards which a system variable tends over time. Every point within this set resides within a *basin of attraction*, an area within the state space of the system within which the system tends towards the attractor. An important difference between a stable state or equilibrium and an attractor is that an attractor need not be a single point within state space (a so-called *fixed point* attractor). Other possible types of attractors include *limit cycles* (a.k.a. periodic attractors) – in which the system oscillates periodically between points – and *strange attractors* (Eckmann and Ruelle, 1985) – in which the trajectory of the system never repeats itself but remains within a given range of values.

An important feature of complex systems is the potential for a system's state space to contain *multiple* basins of attraction. Disturbances (or internal system phenomena) may cause the system to leap from one attractor to another. A well-established example of such "attractor flips" can be found in the dynamics of shallow lake ecosystems. The state of a shallow lake ecosystem can exist within one of several basins of attraction (Scheffer, 1999). At relatively low concentrations of nutrients, such ecosystems tend to exist in a basin of attraction characterized by clear water and a diversity of animal life and submerged plantlife. If the concentration of nutrients, e.g. phosphorus from fertilizer runoff, exceeds a particular threshold, the lake shifts into a new basin of attraction – one characterized by turbid water, phytoplankton blooms and a reduced diversity of submerged plant- and animal-life. This shift may occur suddenly and rapidly, and is not easily reversible.

The tendency of a system to remain within a given basin of attraction has to do with the interactions amongst components in the system. A clear lake ecosystem is maintained because of the structure of the food chain – high numbers of game fish enable effective phytoplankton grazing and lead to low incidence of algal blooms, which preserves high levels of dissolved oxygen, which in turn supports the further survival of a diversity of animal and plant life (Carpenter and Cottingham, 1997). Once an attractor flip has occurred, a similarly strong set of feedbacks acts to maintain the system within a turbid basin of attraction.

According to the second perspective identified in the previous section, resilience has to do with the ability of a system to remain within a given (desirable) basin of attraction. Disturbances that act to deteriorate the feedbacks within a system reduce resilience; they reduce the magnitude of disturbance that is necessary to cause a shift to a new attractor. Gunderson et al. (2002) suggest that, in the case of ecological systems, such deterioration may ironically often result from human attempts to preserve the state of a system. Often, the authors suggest, ecosystem management regimes focus on isolating and controlling particular variables of interest without sufficient attention to the complex web of interactions underlying these variables. Dynamics such as these can be found in many "maintained" ecological systems including managed forests and subsidized agriculture (Gunderson et al., 2002). And they may also play a role in increasing the vulnerability of electricity infrastructures to cascading failures (Dobson et al., 2007).

According to the third perspective introduced above, attractor shifts are not always undesirable, and indeed may be necessary in enabling the survival of the system. Gunderson et al. (2002) and Gunderson and Holling (2002) recognize this imperative in the management of ecological systems. Building on the traditional notion of ecosystem succession, the authors suggest that resilience in such systems is not about maintaining an ecosystem within a given state, but about allowing for periodic shifts amongst the phases of growth, conservation, collapse and reorganization (Gunderson and Holling, 2002) – in other words, periodic shifts amongst basins of attraction. The authors suggest that such *adaptive cycles* do not exist within isolation, but interact with similar cycles at different scales, some faster and some slower. These interactions act to introduce novelties within the system that allow for experimentation and promote adaptability without inciting catastrophic failure (Gunderson and Holling, 2002; Walker et al., 2004). While largely developed in the context of studying ecological systems, these insights into the relationships between attractors and resilience form a solid foundation for better understanding and defining the resilience of infrastructures.

## Attractors in infrastructure operation

Viewed through a lens of complexity, the state space of an electricity infrastructure can be conceptualized as a stability landscape composed of multiple basins of attraction, each corresponding to a particular *mode of operation* and characterized by a distinctly different set of structures. These modes of operation are defined by key variables such as total generator output, network frequency, mean ratio of line load to capacity, mean ratio of real to nominal voltage and mean demand satisfaction. These key variables are related by way of the myriad connections within the technical infrastructure. For instance, if total demand increases relative to generation, network frequency drops, causing total generator output to increase and network frequency to rise back to its original level. Like the relationships between e.g. fish population, nutrient loading and water turbidity in shallow lake ecosystems, the relationships between these key variables act to preserve the system within a particular basin of attraction.

One basin of attraction within this landscape can be thought of as representing the "normal functioning" of the infrastructure. In most of the industrialized world, this is a wide, deep basin characterized by a set of states nested around a network frequency close to 50 Hz, a demand-side voltage around 220 or 110v and a load demand satisfaction close to 100%.

While electricity systems in most industrialized countries spend the vast majority of time within this basin, the area within its boundaries does not represent the full range of possible system states. Every so often, we experience a catastrophic shift to a different attractor – a blackout. Like the flip to a eutrophied lake, this is a catastrophic shift to an attractor characterized by a vastly different set of conditions – 0% load demand satisfaction, a network frequency of 0 Hz and a demand-side voltage of 0v. A shift to this attractor often occurs when the system is already pushed to the edge of its "normal" basin of attraction, and suddenly experiences an unexpected disturbance. In the case of the 2003 Italian blackout, this disturbance took the form of a flashover to a tree on a major high-voltage link between Switzerland and Italy (Berizzi, 2004). In the case of the 2006 German blackout, it took the form of a seemingly benign ship crossing (UCTE, 2007).

Like the normal basin of attraction, the blackout basin is characterized by a set of feedbacks that act to maintain the system within this basin. Bringing the infrastructure back to its normal basin of attraction after a total blackout – a so called "black start" – is a complex procedure. Many generators can only be restarted with access to electricity from the network. And generators that do possess black start capability must be started such that power flows in different parts of the network are synchronized. Small deviations from this procedure can send the network tumbling back to the blackout attractor.

## Defining infrastructure resilience

If we frame the electricity infrastructure as a *complex technical network*, we may view these basins of attraction – for instance, the normal operation basin and the blackout basin – as the primary operational modes[2]. They are the areas of the state space towards which – due to the numerous feedbacks within the technical network – the system will tend. Framing the infrastructure in this manner, resilience is best defined with respect to the *system's capacity to remain within the normal basin of attraction*, reflecting the second perspective on system resilience (Table 2.1).

If we frame the electricity infrastructure as a *complex adaptive system* – resilience is no longer only a function of the relationships between the system's technical components. It is also affected by the *adaptive* abilities of the social agents embedded within the system, who can deliberately modify their actions to preserve or enhance system function. Resilience in this case is best defined in line with the third perspective (Table 2.1) – the ability of a system to adjust structure, behavior and function in order to sustain operations upon exposure to a disturbance.

Viewed another way, the third perspective on resilience relates to the capacity of the system (including its social components) to *manage shifts between attractors* in order to preserve system functionality. Or, in other words, resilience relates to the ability of the system to deliberately steer shifts from one basin of attraction to another – to undergo structural change – so as to prevent otherwise catastrophic failures. Such abilities are indeed apparent in the operational regimes of today's electricity infrastructures. System operators deliberately create partial blackouts – so called "rolling blackouts" – or voltage drops – brownouts – in times of emergency to prevent more undesirable, catastrophic flips to a total blackout (Constellation, 2013). In the future, demand response arrangements or islanding mechanisms may involve demand-side actors (consumers) in this process of adaptively steering the system between basins of attraction, further enhancing system resilience.

This perspective on resilience may also be applied to other infrastructures. An example from the Dutch rail infrastructure illustrates this. In the winter of 2009-10, the Dutch rail system suffered serious problems due to extreme winter weather – numerous trains were delayed or canceled because of repeated instances of unusually heavy snowfall and severe wind (Treinreiziger.nl, 2009). Over subsequent years, the operators of the Dutch railway took several actions to prevent this from occurring again. First, they installed heaters and covers on key switches to prevent them from freezing shut (NOS, 2012). Second, they implemented a new timetable – the so-called *Winterdienstregeling* – to be implemented during periods of extreme winter weather (Hofs, 2010). The *Winterdienstregeling* is like a brownout for the rail system. It is a secondary mode of operation in which trains ride less frequently and over shorter stretches – an alternative basin of attraction towards which the system can switch to preserve functionality under conditions that might otherwise incite a complete breakdown.

The manner in which we conceptualize our infrastructures affects the manner in which we define their resilience. If we view an infrastructure as a complex technical network – a system whose emergent behavior derives from the number of its parts

[2] Precisely what constitutes a basin of attraction is open to interpretation. Additional basins of attraction may be discerned, including for instance partially degraded states with the values of key variables lying partway between normal operation and complete blackout.

and the relationships between them – then resilience relates to the capacity of the system to remain within the desirable operational regime (basin of attraction). If we view an infrastructure as a complex adaptive system, then resilience relates to the capacity of the system to manage shifts *between* basins of attraction.

While this dual definition of resilience is not theoretically problematic, it may be confusing in the context of this research. For disambiguation purposes, we henceforth apply the phrase *infrastructure adaptability* in reference to the second definition of resilience (the third perspective in Table 2.1). We use the phrase *infrastructure resilience* in reference to the first definition (the second perspective in Table 2.1). This differentiation not only adds clarity as we proceed, but also is well aligned with the definitions of resilience and adaptability proposed by Folke (2006) with reference to social-ecological systems. The following definitions for infrastructure resilience and adaptability are proposed:

**Infrastructure resilience:** The ability of an infrastructure to *remain within a given basin of attraction* upon exposure to a disturbance.

**Infrastructure adaptability:** The ability of an infrastructure to *manage shifts between basins of attraction* to sustain operation upon exposure to a disturbance.

A key difference between infrastructure resilience and adaptability inherent in these definitions has to do with *structural change*. Infrastructure resilience does not require a structural change – the structure of the system is preserved (though it may require rebuilding structure). Infrastructure adaptability, on the other hand, inherently entails changes in structure. Via controlled shifts between different basins of attraction, the structure of the system (in terms of power flow patterns, generation distribution, etc.) undergoes change.

## Infrastructure (co-)evolution and transformability

Up to now, we have focused on the concept of resilience as it relates to infrastructure *operation* – that is, the behavior of an infrastructure on a timescale of minutes to days. As the dictionary definition of resilience introduced above implies, resilience also has to do with the capacity of a system to adjust to longer term changes in its environment, suggesting a timescale of months, years or even decades. This understanding of resilience is common amongst others in organizational science and business, stressing for instance "strategy that's forever morphing in response to emerging opportunities and trends" and "organization that's constantly remaking its future rather than defending its past" (Hamel and Vaelikangas, 2003).

Electricity infrastructures exhibit important long-term dynamics which may be framed within this understanding of resilience. The technical configuration and technological composition of the infrastructure change as new (types of) technical components are added and others become obsolete. Examples of this are the introduction of transmission networks and, more recently, of small-scale renewable energy generation technologies. Both of these developments have had a significant impact on the technical character of the infrastructure. Likewise, the infrastructure's social structures may change in the long term as a result of new regulatory or socio-economic developments, a primary example being the dramatic fragmentation of control following from electricity market liberalization.

Like shifts between operational regimes, long-term transformations in the socio-technical structure and composition of the infrastructure may be viewed as shifts between basins of attraction[3]. On this timescale, basins of attraction may be viewed as *stable combinations of technologies and institutions*. Defined in this way, the notion of a basin of attraction approaches the concept of a *socio-technical regime* in transition theory – a set of dominant practices, rules and shared assumptions within a socio-technical landscape (Rotmans et al., 2001). Verbong and Geels (2007) defines a socio-technical regime as consisting of three interlinked dimensions:

1. a *social* dimension – a network of actors and social groups (e.g. utilities, government bodies, consumers of different types)
2. an *institutional* dimension – formal, normative and cognitive rules that guide the activities of actors (e.g. regulations, standards, belief systems, behavioral norms)
3. a *technical* dimension – material and technical elements (e.g. physical resources, the grid, generators)

Defined in this manner, the current basin of attraction in most electricity systems of the industrialized world can be seen as one dominated by fossil fuel combustion technologies, a handful of large producers and a vertically operated power system. One can also imagine an alternative basin of attraction characterized by widespread distributed generation technologies, a social landscape dominated by a multitude of "prosumers" and a more horizontally operated grid composed of numerous flexibly coupled micro-grids. Like the networks of feedbacks in shallow lake ecosystems, the current basin of attraction is held in place by a web of stabilizing mechanisms – the vested interests of incumbent actors, cognitive routines that blind actors to external developments, sunk investments and technical complementarities between components (Verbong and Geels, 2007). These mechanisms contribute to a state of *lock-in* – a tendency to resist structural change (Kemp et al., 2007) – constraining possibilities for shifts to new socio-technical regimes.

Attractors on different timescales are not independent of one another. The operational performance of an infrastructure is constrained by its institutional and technological context. For instance, the ability of system operators to employ demand-side management as a strategy for mitigating peak electricity loads depends on the existence of a set of enabling technologies and institutions, such as smart meters and dynamic pricing. Likewise, the long-term development of an infrastructure may be significantly altered by events at the operational level – e.g. the 2011 tsunami and subsequent nuclear accident in Japan which has seemingly accelerated the shift of Germany away from nuclear energy (BBC, 2011). These sorts of cross-scale interactions are similar to the notions of *revolt* and *remember* in the model of panarchy introduced by Gunderson and Holling (2002) – with revolt implying an upward linkage between scales and remember implying a downward linkage.

[3] Use of the word *between* here is not meant to imply repeated back-and-forth movement, but rather shifts from one basin of attraction to another *new* basin of attraction. Unlike attractor shifts on an operational timescale – which may involve repeated movement amongst a handful of basins – shifts on an evolutionary timescale may often entail a degree of path dependence that inhibits backwards shifts.

From a perspective of electricity infrastructures as complex adaptive systems, we may view their long term development as a process of *evolution*. Moreover, if we view infrastructures as *evolving*, then we can also view the long-term developments that occur in response to changes in their environment as evolutionary processes. The low-carbon transition may be viewed as an evolutionary process occurring in response to public concerns about the consequences of carbon emissions on the global climate. Electricity market liberalization may be viewed as an evolutionary process occurring in response to changing ideas about the benefits of deregulation and competition in the context of infrastructures. These developments impose new constraints on selection processes in evolution, acting to drive the long-term development of the system in a new direction.

Moreover, the evolution of the electricity infrastructure occurs in concert with evolutionary processes at work in other (linked) systems. Such *co-evolutionary* processes play out, for instance, via the links between the electricity and gas sectors. The drive towards low-carbon fuels in the electricity sector has driven the demand for renewables such as wind. The intermittency of such energy sources is anticipated to expand demand for storage facilities in the gas sector and for flexible (quickly deployable) gas turbines in the electricity sector (van Foreest, 2010). Processses of change in the electricity infrastructure influence corresponding processes in the gas sector. Co-evolutionary processes are also evident in the linked development of the social and technical subsystems of the electricity infrastructure. The advent of electricity infrastructures transformed daily routines, social roles and economic opportunities in much of the world. In turn, this social transformation placed new requirements on the technical subsystem, including increased demand, altered loading patterns and enhanced reliability requirements.

From this perspective, *resilience* also has to do with the degree to which the (co-)evolutionary processes underlying a system's long-term development allow it to respond to changes in its environment through the development of fundamentally new structures and (perhaps) functions. However, this use of the term resilience may breed confusion in the infrastructures context, where it is useful to differentiate between an *operational* and an *evolutionary* timescale. For terminological inspiration, we turn again to research in the field of social-ecological systems. Next to resilience and adaptability, Folke (2006) uses the term *transformability* to describe "the capacity of people to create a fundamentally new social–ecological system when ecological, political, social, or economic conditions make the existing system untenable". Unlike adaptability, which entails structural change, transformability involves the emergence of *fundamentally new* structures, functions and basins of attraction. Insofar as it relates to a fundamental and multi-dimensional system change, the notion of socio-ecological transformability aligns well with the evolutionary perspective on resilience. We define *infrastructure transformability* as follows:

**Infrastructure transformability:** The ability of an infrastructure *evolve fundamentally new basins of attraction* to maintain or enhance performance in a changing environment.

## 2.3 Vulnerability and climate resilience

Before concluding this chapter, it is important to address two additional issues. First, it is essential that we more precisely define the notion of infrastructure *vulnerability* in the context of climate change. Second, we need to clarify the relationship of climate change with the framings of electricity infrastructures and infrastructure resilience elaborated above.

Vulnerability is defined by the IPCC (2012) as "the propensity or predisposition to be adversely affected". In the context of climate change, this translates to "the propensity or predisposition of an infrastructure to be adversely affected by climate change". Essentially, vulnerability may be understood as the inverse of resilience. It amounts to a *lack of* capacity to preserve structure, behavior or function in the face of a disturbance. In the context of infrastructures, it is a lack of capacity to successfully resist or effectively manage shifts between attractors.

How does climate change relate to the above-defined notions of infrastructure resilience, adaptability and transformability? Returning to the framing of system resilience illustrated in Figure 2.2, it seems logical to view climate change as a *disturbance* having the potential to affect system structure, function and behavior. However, it is important to recognize that climate change is not an *event*. Rather, it is a "change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer" (IPCC, 2012). In other words, it amounts to a change in *existing patterns of events* in terms of their frequency of occurrence, severity, etc.

If climate change is not an event, to what degree can it be framed as a disturbance in the context of system resilience? On a short timescale, framing climate change as a disturbance does not make sense, as climate change *itself* is not interacting with the system in question – in this case the electricity infrastructure. Rather, it is the *meteorological symptoms* of climate change that are of interest. Climate change literature provides a useful way of framing these meteorological symptoms in terms of two related but distinct concepts – extreme weather events and extreme climate events. These may be defined as follows (IPCC, 2001):

- An *extreme weather event* refers to an occurrence of weather that is rare (below/above the 10th/90th percentile) within its statistical reference distribution at a particular place (IPCC, 2001).

- An *extreme climate event* refers to an average of a number of weather events within a certain period of time which exceeds the normal range, for instance rainfall over a season (IPCC, 2001).

On a short timescale (minutes to months), climate resilience thus implies a capacity to preserve system function in the face of extreme weather or climate events.

On a long timescale (years to decades), framing climate change itself as a disturbance is more logical. On this timescale, a disturbance amounts to a deviation from existing or historical patterns – in this case changes in long-term meteorological conditions with the potential to disrupt the existing socio-technical regime. Climate resilience here implies a capacity to successfully adapt the socio-technical regime to this altered set of conditions.

Based on this discussion, we can say that the precise role of climate change in the framing of infrastructure resilience depends on the timeframe we are speaking about. In speaking of *infrastructure resilience* and *infrastructure adaptability* (short timeframe properties), extreme weather and climate events are the disturbances of interest. In speaking of *infrastructure transformability*, climate change itself is the disturbance of interest. A more thorough examination of climate change and its anticipated effects on electricity infrastructures is left to chapter 4.

## 2.4 Synthesis

The purpose of this chapter has been two-fold. First, this chapter has aimed to establish a theoretically grounded perspective as a basis for defining an approach. Second, it has aimed to more precisely define and theoretically underpin the notion of *climate resilient electricity infrastructures.*

With respect to the first aim, we extract the following elements from the sections above as a summary of the perspective to be employed in this research:

- The electricity infrastructure is viewed as a **socio-technical system**, consisting of tightly interconnected technical and social components.
- The electricity infrastructure is viewed as a **complex system**, the complexity of which is manifested both in the interconnectedness of its technical components and in the interests, knowledge and capabilities of its social components.
- The electricity infrastructure is viewed as an **evolutionary system**, exhibiting processes of variation, selection and heredity.
- In **operation**, the state space of the electricity infrastructure is viewed as consisting of **multiple basins of attraction**, corresponding to different operational regimes.
- In **evolution**, the state space of the electricity infrastructure is viewed as consisting of **multiple basins of attraction**, corresponding to different techno-institutional regimes.

With respect to the second aim, this chapter has identified different uses of the word resilience in systems literature, and has defined a terminology to disambiguate these uses in the infrastructures context. We use the phrase *infrastructure resilience* to refer to the ability of an infrastructure to remain within a given basin of attraction in infrastructure operation. We use the phrase *infrastructure adaptability* to describe the ability of an infrastructure to manage shifts between basins of attraction in infrastructure operation. And we use the phrase *infrastructure transformability* to refer to the ability of a system to evolve fundamentally new basins of attraction.

As defined, the properties of infrastructure resilience, adaptability and transformability are similar in that they all embrace the notion of infrastructures as complex systems with multiple basins of attraction. However, they are different in that they imply different strategies for managing infrastructures in the context of climate change. Resilience implies that our task is to keep the system within its original operational regime. Adaptability implies that we may develop and employ alternative modes of operation to sustain performance. Transformability implies that we should support the evolutionary capabilities of the system.

By drawing inspiration from the field of social-ecological systems, this terminology inherently recognizes certain parallels between technical and ecological systems, both in terms of the processes by which they change and their close relationship with the social world. While we must use them with caution, these parallels may also yield insights into opportunities for supporting the development of climate resilient infrastructures.

# Chapter 3

# Approach

This chapter introduces the approach to be employed in this research, including the research framework, scope, methodology, techniques and tools. The elements of the theoretical perspective introduced in the previous chapter form a basis for identifying several requirements which the approach must fulfill. These requirements may be defined as follows:

1. **The approach must entail representation of the electricity infrastructure as a *socio-technical system*.** It must account for the pertinent social and technical components and relationships between them.

2. **The approach must entail representation of the electricity infrastructure as a *complex system*.** It must capture the consequences of the large number and diversity of linkages within the technical subsystem, as well as the interests, knowledge and capabilities of actors in the social subsystem.

3. **The approach must entail representation of key *climate change impacts* on components of the electricity infrastructure.**

4. **The approach must entail representation of important *linkages* of the electricity infrastructure with other infrastructures.** First, it must account for the fact that the Dutch electricity infrastructure is increasingly linked with the electricity infrastructures of neighboring countries and embedded within a larger European context. Second, it must account for the fact that the electricity infrastructure is increasingly linked with other *types* of infrastructures, such as road infrastructures, rail infrastructures and natural gas infrastructures.

5. **The approach must account for the *evolutionary development* of the electricity infrastructure.** In other words, it must capture the long-term development of the infrastructure as a consequence of a repeated process of variation, selection and heredity.

6. **The approach must be capable of representing and assessing the effects of *measures* to enhance infrastructure resilience.**

## 3.1 Research framework

Based on this set of requirements, we now define a research framework, which solidifies a framing of the system with respect to the problem being addressed. This framework will serve as a basis for the development of a methodology and for the selection of case studies and techniques. The framework is illustrated in Figure 3.1..

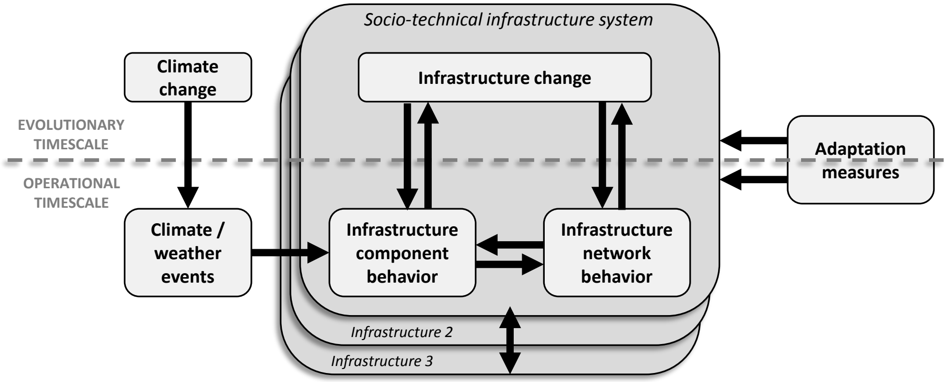


Figure 3.1: Illustration of the research framework

The elements of the framework are divided into two different timescales, an *evolutionary timescale* and an *operational timescale*. Within the evolutionary timescale are included elements relevant to a timeframe of years to decades. These include processes of *infrastructure change* and processes of *climate change*. Infrastructure change corresponds to long-term developments in the technical and institutional composition of the electricity infrastructure. Climate change corresponds to long-term shifts in patterns of variability in meteorological variables.

Within the operational timescale are elements relevant to a timeframe of minutes to months. This includes *weather and climate events*, corresponding to particular meteorological occurrences (e.g. rainstorms) or repeated observations of such occurrences (e.g. seasonal rainfall), respectively. Climate and weather events are conceptualized as affecting *infrastructure component behavior*. This may include, for instance, the electricity demand of a consumer, the efficiency of a thermal generator or the functionality of an electrical substation. It is important to emphasize that, within the context of this framework and this research, the term *infrastructure component* refers both to the technical elements of the infrastructure and the social components (actors). From a socio-technical perspective, both of these types of components are integral parts of the infrastructure system. Moreover, both exhibit *behavior*, and this behavior may change as weather and/or climate conditions change.

The behavior of infrastructure components may affect *infrastructure network behavior* – the behavior of the network as a whole. For instance, the failure of a single key substation may cut off a large portion of the network, or the overloading and subsequent disconnection of a power line may incite a massive redistribution of flows within the network. Moreover, the behavior of the network as a whole may have an impact on the behavior of components (downward causation). A redistribution of power flows at the network level, for instance, may result in the overloading and subsequent disconnection of further components.

Linkages between components across timescales (across the dotted line in Figure 3.1) correspond to the relationships between long- and short-timescale phenomena. Climate change, for instance, may affect the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events (IPCC, 2012). Likewise, long-term changes in the technical or institutional composition of the infrastructure may affect the behavior of components, or of the network as a whole. The construction of a cooling tower (infrastructure change) at the site of an existing thermal generation plant, for instance, may reduce its vulnerability to cooling water restrictions, enhancing its capacity to function under extreme temperature conditions (infrastructure component behavior).

The elements *infrastructure change*, *infrastructure component behavior* and *infrastructure network behavior* are all embedded within the *socio-technical infrastructure system*, consisting of the components and relationships of the social and technical subsystems of the electricity infrastructure. As illustrated in Figure 3.1, this infrastructure system is linked with other infrastructure systems. These other infrastructure systems may include other electricity infrastructures (e.g. those of neighboring countries) or other types of infrastructures (e.g. road or rail). These interconnections reflect the possibility for disturbances within one infrastructure to spill over to others, as well as the possibility for these infrastructures to stabilize one another. Failures in the electricity infrastructure may cascade across national borders, or leap to road and rail infrastructures by cutting power to traffic lights and contact wires. Or they may be rectified as power shortfalls in one system are compensated by excess capacity in another.

*Adaptation measures* – defined here as efforts to enhance the resilience, adaptability or transformability of the infrastructure – may affect elements on both an operational and an evolutionary timescale. Adaptation measures aimed at an evolutionary timescale affect the manner in which the infrastructure evolves. An example is capacity mechanisms in electricity markets, which seek to ensure sufficient investment in generation capacity, enabling the system to cover periodic generator failures. Adaptation measures aimed at an operational timescale affect the manner in which the infrastructure is operated. An example here might be a temporary relaxation of cooling water restrictions, allowing generators to continue functioning at full capacity under extreme temperature conditions.

## 3.2 Research scope

The scope of this research is defined as follows:

- In terms of socio-technical scope, this research focuses on **electricity infrastructures**, with limited consideration of linkages with other types of infrastructures. On the technical side, this research incorporates the processes of electricity generation, transmission/distribution and consumption. On the social side, the research incorporates the activities of actors associated with these processes, including power producers, TSOs, DSOs and consumers. Relatively more focus is placed on the *network* aspects of the infrastructure (transmission and distribution) than on the production and consumption aspects.

- In terms of geographical scope, this research focuses on the area of **the Netherlands**[1], with limited consideration of important linkages with neighboring regions. This scope has been selected as it offers a convenient bounding of the socio-technical infrastructure system while capturing the core areas of interest to the involved stakeholders.

- In terms of climate change, this research focuses on **extreme weather events**, in particular floods, windstorms and heat waves. This focus has been selected due to the particular relevance of (these types of) extreme weather events to the functioning of electricity infrastructures. Extreme climate events and non-extreme weather and climate events are excluded from the study. Moreover, this research does not directly address the scientific basis for climate change, relying rather upon existing peer-reviewed work in this area.

- Temporally, this research focuses on developments between the years 2010 and **2050**. This focus has been selected to balance the decadal dynamics of climate and infrastructure change with the progressive uncertainty of long-term prognostications.

- In measuring infrastructure performance, this research focuses on the concept of **resilience**, as defined in chapter 2 (and further formalized in chapter 5). The concepts of adaptability and transformability are not dealt with in depth. Other potentially relevant measures of infrastructure performance (e.g. robustness, flexibility, survivability) are not considered. This focus has been selected given the growing importance of resilience within climate change adaptation and infrastructures research and practice.

## 3.3 Research methodology

The research methodology describes the sequence of steps that is followed to address the research questions stated in chapter 1. This methodology is illustrated in Figure 3.2. At the highest level, the research methodology consists of three phases, a *literature study* phase, a *case study* phase and a *synthesis* phase – each addressing a subset of the research questions. The purpose of the literature study phase is to generate an inventory of knowledge concerning (1) the anticipated effects of climate change on electricity infrastructure components, and (2) possible adaptation measures to alleviate the effects of these impacts. The knowledge developed during the literature study phase serves as input to the case study phase. This second phase aims to assess the performance of the Dutch electricity infrastructure under extreme weather conditions, and to explore the effectiveness of options for fostering infrastructure resilience. The results from the case study phase serve as input to the synthesis phase, which focuses on combining and repackaging these results in

[1] The Netherlands here refers to the *country* of the Netherlands, not the *Kingdom* of the Netherlands, and excludes the extra-European special municipalities of Bonaire, Sint Eustatius, and Saba.

the form of specific insights and recommendations for supporting the development of climate resilient electricity infrastructures.

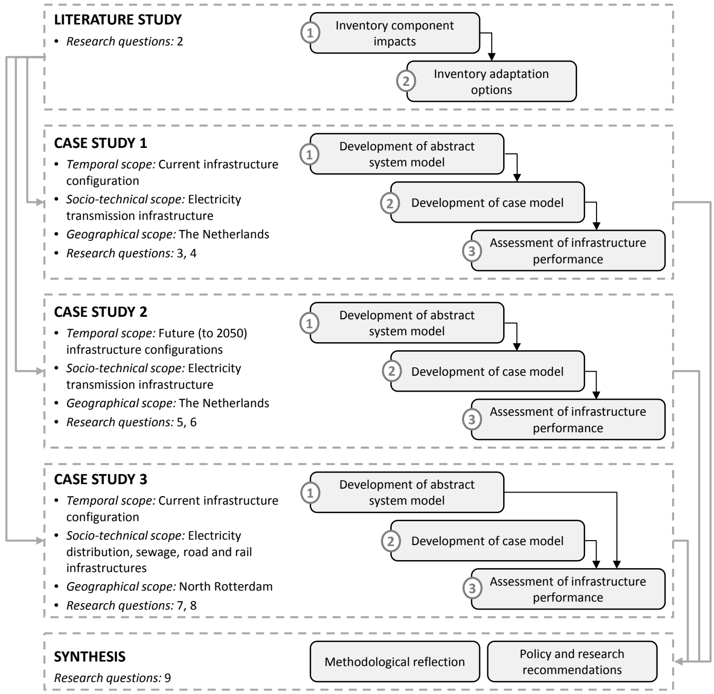


Figure 3.2: Illustration of the research methodology

The core of this research takes place in the case study phase. This phase is divided into three distinct case studies, each addressing a different (set of) research question(s), and each differentiated according to their temporal, socio-technical and geographical scopes. The first case study focuses on assessing options for supporting the resilience of the *current* Dutch electricity infrastructure to certain categories of extreme weather events. This case study begins by developing an understanding of the dynamics by which component-level impacts may affect network-level behavior, and explores how these dynamics can be represented in a model. This knowledge is then used as a basis for exploring the network-level consequences of various extreme weather events within the context of the Dutch electricity infrastructure. The focus of this case study is on the electricity *transmission* infrastructure, and excludes consideration of impacts and adaptations at the level of the distribution infrastructure.

The second case study extends on the first by incorporating considerations of *infrastructure change*. This case study begins by developing an understanding of the mechanisms by which electricity infrastructures (particularly transmission infrastructures) evolve, and exploring how this evolutionary process can be represented in a model. Building on this, this case study goes on to explore possible development trajectories of the Dutch electricity infrastructure to 2050, and assesses the consequences of these trajectories in terms of infrastructure performance.

The third case study investigates the role of the electricity infrastructure in the context of a *multi-infrastructure system* – a socio-technical system consisting of multiple infrastructure types – and the consequences of this in terms of resilience. This case study begins by describing the method and results of a study of the consequences of infrastructure interdependencies on the flood resilience of a multi-infrastructure system in the North Rotterdam area of the Netherlands. The second part of the case study deals with the very real issue that many interdependencies may be unknown to an infrastructure operator, and assesses different strategies for dealing with this source of uncertainty for the case of a hypothetical electricity network operator.

Each case study is further divided into three parts, with each part contributing knowledge to the next. The first part of each case study involves the development of an *abstract system model* – a generic, exploratory model built for the purpose of generating improved understanding of how the system and its relevant dynamics can be effectively represented. The second part of each case study involves the development of a case model, which (with the exception of the 3rd case study) builds on the abstract model, but gears it specifically to the study of the Dutch infrastructure. The third part of each case study entails the use of the case model to assess the performance of the infrastructure under different conditions.

The synthesis phase of this research aims to summarize the main insights from the case studies, and to extract specific policy and research recommendations. In addition, this phase entails a methodological reflection geared towards addressing the final research question – How can modeling and simulation be more effectively used to address multi-scale, multi-perspective societal challenges such as infrastructure adaptation to climate change?

## 3.4 Modeling methodology

The chief technique employed in this research is that of *modeling and simulation (M&S)*. M&S refers to the development of mathematical (usually computer) representations of real-world systems for the purpose of yielding insight into the behavior of these systems. M&S is particularly useful in situations in which it is practically, morally and/or financially infeasible to perform suitable experiments on the real-world system. All of these are true in the case of the problem and target system of this research. The technique of M&S has a long history in the engineering and physical sciences, and is increasingly used in the study of social systems.

The use of M&S in this research is characterized by a cyclical development process, illustrated in Figure 3.3. This process is inspired partially by the *CoSMoS process* (Andrews et al., 2010), a methodology for developing simulation models of complex systems, and by the methodology of Nikolic et al. (2013b) for constructing agent-based models of large-scale socio-technical systems. It involves a set of seven steps, which may be summarized as follows:

1. **Research definition** is the first step in the modeling process. It involves the creation of a *research context*, which is composed of (1) the research aim and scope, (2) relevant actors and knowledge sources, and (3) anticipated research outcomes.

2. **System analysis** is the process of creating a *conceptual system model*, a qualitative but structured picture of the relevant elements and relationships in the studied system with respect to the previously identified research aim and scope. System analysis is ideally a social process involving the problem owner(s), other stakeholders and domain experts.

3. **Model design** is the process of creating a *formalized model*, an explicit design of the simulation model. It is a process of formalizing the concepts identified in the conceptual model in preparation for software implementation. Each of the components of the formalized model is a refined or revised version of one or more of the components in the conceptual model.

4. **Software implementation** involves translation of the formalized model into a working simulation. The end product of the software implementation phase is a computer model which includes all elements necessary for running the simulation, including (at a minimum) the simulation code, data inputs and the experimental setup

5. **Verification** involves ensuring that the computer model, formalized model and conceptual model align with one another. It is a process of confirming that there are no outstanding errors or omissions in the computer representation of the system.

6. **Experimentation** involves running the simulation code in accordance with the experimental setup defined in the software implementation phase. The product of the experimentation phase is a *results model*, which includes (1) output data, (2) results visualizations and (3) a listing of key assumptions.

7. **Results interpretation** involves evaluating the degree to which the results achieve the stated purpose of the modeling exercise, and the degree to which the assumptions are suitable in light of this purpose. If it is determined that either the purpose of the model has not been sufficiently met, or that the assumptions are unacceptable, another iteration of the process is carried out. Ultimately, the product of the results interpretation step is a set of research outcomes, which become part of the research context.

8. **Validation** involves confirming the validity of the model and its results. Ensuring the validity of a model is not a single step within the modeling process (and thus is not illustrated in Figure 3.3) but is embedded throughout the process. A number of means have been proposed for the validation of simulation models, including validation through prediction (the model proves its accuracy through repeated testing), validation through retrodiction (the model is able to replicate historical patterns) and validation through structural similarity (the structure of the model is sufficiently similar to the system's real-world structure) (Gross and Strand, 2000). However, in the case of large-scale societal problems such as climate change adaptation, methods such as these tend to be insufficient. Their predictive accuracy cannot be tested through real-world experimentation; historical records are an insufficient guide to possible futures; and micro-structural richness and abundance of causality inhibits the

useful comparison of structure. While it may often be impossible to prove the validity of such models, it is possible to provide evidence that indicates towards their validity under certain conditions. This evidence may take many forms: historic replays may indicate that a simulation produces historically accurate patterns, or domain experts may confirm that particular patterns correspond with expectations. In combination, these diverse bits of evidence can be used to create a case supporting the validity of a given model. This approach to validation is inspired by the *validity argument* approach of Polack (2010).

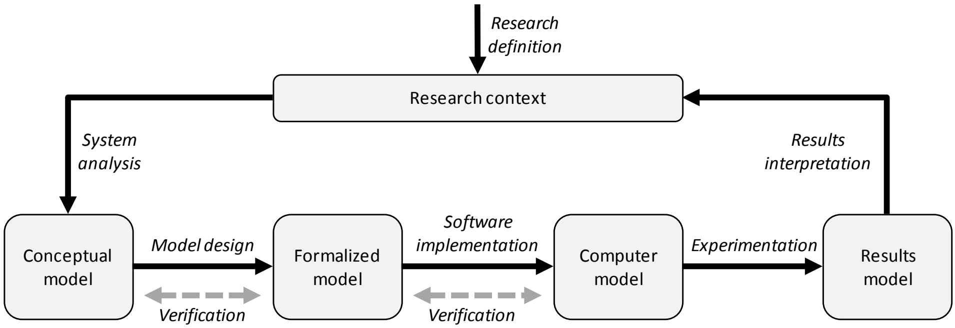


Figure 3.3: Illustration of the model development process employed in this research.

To some degree or another, stakeholders have been involved in the model development processes of each of the case studies. In the case of the second and third case studies, stakeholders and the data they provided facilitated processes of research definition, system analysis, model design, results interpretation and validation. In the case of the first case study, the stakeholder was loosely involved during the model design phase, and data from the stakeholder was used for validation purposes. For the first and second case studies, the involved stakeholders were representatives from the Dutch transmission system operator TenneT. The third case study involved stakeholders from the municipality of Rotterdam, the Dutch Ministry of Infrastructure and the Environment (Rijkswaterstaat) and the electricity/gas distribution system operator Stedin.

## 3.5 Techniques and tools

In carrying out the methodology described above, this research makes use of several M&S techniques and tools. In the following paragraphs, we provide a brief introduction to the main techniques and tools used in this research. A more thorough description of these techniques is provided in the relevant case studies.

### Power system modeling

Power system modeling encompasses a range of techniques for representing the technical operation of electric power systems. The power system modeling techniques employed in this research include power flow analysis, cascading failure analysis, contingency analysis and structural vulnerability analysis:

- *Power flow analysis* is a tool commonly employed by power system engineers in planning expansions and optimizing the use of existing infrastructure. It is a numerical technique which takes the properties and configuration of a power system as input and uses Kirchoff's laws to calculate power flows and voltages in the specified system.

- *Cascading failure analysis* (Baldick et al., 2008) is a technique for studying the propagation of failure cascades in an electrical power system. The form of cascading failure analysis used in this research employs power flow analysis to iteratively calculate potential component overloads in a power system and the resulting redistributions of power flows.

- *Contingency analysis* (Gomez-Exposito et al., 2009) is a technique used to ensure the real-time security of power systems and to identify necessary investments for maintaining a desired level of security. It involves the evaluation of system performance under a set of statistically likely contingencies to identify potential overloads.

- *Structural vulnerability analysis* (Albert et al., 2004; Chen et al., 2009; Holmgren, 2006; Wang and Rong, 2009) is a method for assessing the structural robustness of an electricity network to component failures. Beginning with a graph representation of a power system, structural vulnerability analysis assesses how the successive removal of nodes/edges affects the overall performance of the infrastructure.

The chief tools employed for power system modeling in this research include MATLAB, GNU Octave and MATPOWER. MATLAB is a numerical computing software commonly used for data analysis, data visualization and simulation. GNU Octave is similar to MATLAB except that it is free and open source. MATPOWER is a MATLAB- and GNU Octave-compatible power system simulation package for solving power flow and optimal power flow problems (Zimmerman et al., 2011).

## Agent-based modeling

Agent-based modeling (ABM) is a computer simulation technique centered around the concept of *agents* – autonomous software entities with the fundamental ability to make independent decisions (Macal and North, 2007). The advantage of ABM relative to more top-down, equation-based techniques (e.g. system dynamics, general equilibrium modeling) lies in its ability to draw linkages between micro-level decision making processes and macro-level *emergent* phenomena. In the process of developing an agent-based model, agents are conceptualized to represent actors or other intelligent or semi-intelligent entities in a real-world system, such as individuals, organizations or nations. These agents are assigned attributes and decision processes mimicking those of the real-world entities they represent, and then are released and allowed to interact within a defined digital simulation environment.

Insights are gained by observing the patterns which emerge from these interactions under different conditions.

ABM has been productively employed in fields from ecology (Grimm and Railsback, 2005) to economics (Tesfatsion et al., 2006) to climate change adaptation (Acosta-Michlik, 2008; Asseng et al., 2010; Balbi et al., 2010; Barthel et al., 2008; Baynes and Heckbert, 2010; Bell, 2011; Berman et al., 2004; Bharwani et al., 2005; Bone et al., 2011; Entwisle et al., 2008). A number of claims have been made with regard to the advantages of ABM in climate change mitigation and adaptation research, including improved representation of human decision processes (Pahl-Wostl, 2002), better capture of socio-economic dynamics (Downing et al., 2000), and enhanced opportunities for validation (Moss et al., 2001). Regardless of the validity of these claims, ABM is particularly applicable in this research due to its ability to represent complex decision-making processes and bounded rationality on the part of the actors that compose the electricity infrastructure, enabling the capture of (technical) evolutionary processes and rich representation of the factors that drive them. In this respect, agent-based modeling offers a distinct advantage over optimization techniques, which ignore the path dependencies and bounded rationalities central to the CAS perspective.

To facilitate the development of and experimentation with the agent-based models in this research, we use the software *Netlogo* (Wilensky, 2012). Netlogo is a commonly used agent-based modeling platform in the social simulation community, and has been referenced in more than 70 academic articles in the social science domain since 2003[2]. Runtime linkage of Netlogo and MATPOWER is enabled by way of a custom-developed Netlogo extension called *MatpowerConnect*, described in chapter 5.

## GIS modeling

GIS (geographic information system) modeling refers to the use of computer systems and software to manipulate and analyze geographic data. Given the essentiality of spatial factors in determining the vulnerability of infrastructure components to certain types of extreme weather events, GIS modeling is an indispensable tool throughout the case studies of this research. GIS modeling is employed most extensively in the first and third case studies, in particular in order to assess the vulnerability of electrical substations and other infrastructure components to flooding. In the context of these case studies, we employ several different tools with spatial analysis capabilities, including QGIS, R, Risicokaart.nl and Google Earth.

## Exploratory modeling

Exploratory modeling is a technique in which the results of a model are viewed as indications of possible futures rather than as predictions of a single definitive future (Bankes, 1993). At the foundation of exploratory modeling is the idea of investigating multiple hypotheses about the constitution of a system (Agusdinata, 2008). These multiple hypotheses are then explored by way of numerous computational

[2] Based on a search of the titles, abstracts and keywords of articles appearing in publications of the social sciences and humanities domain (using the Scopus database).

experiments – simulation runs corresponding to different sets of assumptions about how the world works, and testing different policy strategies. Coupled with high performance computing, application of exploratory modeling can enable the testing of a model across a large parameter space over thousands of simulation runs.

A key advantage of this technique is its capacity to effectively deal with the types of uncertainty inherent in issues of climate change adaptation and mitigation. The uncertainties associated with climate change are difficult to effectively characterize with traditional probability distributions, whether objectively or subjectively determined (Lempert et al., 2004). Exploratory modeling deals with this by essentially admitting to the existence of multiple plausible representations of the world, and simulating them in succession. Through the testing of different policy strategies, exploratory modeling can aid the identification of robust policies – policies that generate desirable outcomes across a range of possible futures. Furthermore, it can help to locate scenarios under which these strategies may perform poorly, helping to inform the development of effective hedging strategies (Lempert et al., 2004).

## 3.6 Synthesis

In the introduction to this chapter, a set of requirements for the approach were defined. Before closing this chapter, we reiterate these requirements and clarify how they are fulfilled by the elements of the approach.

**Requirement 1: The approach must entail representation of the electricity infrastructure as a socio-technical system.**

The research framework accounts for this requirement through the explicit incorporation of *infrastructure components*, defined to include both the social and technical elements of the infrastructure. The research methodology accounts for this requirement by incorporating a socio-technical representation of the electricity infrastructure in all case studies. The chosen techniques account for this by allowing for the rich representation of both social (agent-based modeling) and technical (power system modeling) elements.

**Requirement 2: The approach must entail representation of the electricity infrastructure as a complex system.**

The research framework accounts for this requirement by incorporating the behavior of social and technical components as well as the embeddedness of these components within a (social or technical) network. The research methodology accounts for this requirement by incorporating case studies specifically aimed at exploring the different dimensions of infrastructure complexity. The chosen techniques account for this requirement by enabling the capture of electricity infrastructures as complex technical systems (power system modeling) and complex adaptive systems (agent-based modeling), and the exploration of their behavior under different situations.

**Requirement 3: The approach must entail representation of key climate change impacts on components of the electricity infrastructure.**

The research framework accounts for this requirement by explicitly incorporating the relationship between *climate/weather events* and *infrastructure component behavior*. The research methodology accounts for this requirement both in the literature study phase and in the case study phase. The literature study phase involves developing an inventory of climate/weather event impacts on infrastructure components. The first case study involves exploring ways of representing these impacts in a computer model. The chosen techniques allow for representing climate change impacts on both social infrastructure components (agent-based modeling) and technical infrastructure components (power system modeling).

**Requirement 4: The approach must entail representation of important linkages of the electricity infrastructure with other infrastructures.**

The research framework accounts for this requirement by explicitly incorporating linkages between different socio-technical infrastructure systems. The research methodology accounts for this requirement in particular in case study 3, which involves exploring infrastructure resilience in the context of multi-infrastructure networks. The chosen techniques allow for representing both social and technical linkages between infrastructures.

**Requirement 5: The approach must account for the evolutionary development of the electricity infrastructure.**

The research framework accounts for this requirement by explicitly incorporating processes of infrastructure change in representing socio-technical infrastructure systems. The research methodology accounts for this requirement in case study 2, which involves exploring evolutionary pathways of the development of the infrastructure. The chosen technique of agent-based modeling allows for the representation of evolution as a socially-driven, bottom-up process.

**Requirement 6: The approach must be capable of representing and assessing the effects of measures to enhance infrastructure resilience.**

The research framework accounts for this requirement by explicitly incorporating adaptation measures and their effects on the socio-technical infrastructure system, both on an evolutionary and an operational timescale. The research methodology satisfies this requirement via the literature study and each of the case studies. The second part of the literature study involves developing an inventory of possible adaptation measures. The selected technique of exploratory modeling enables the assessment of different measures for supporting resilience by allowing for the execution of multiple simulation runs under different policy conditions and/or assumptions.

# Chapter 4

# Climate change and electricity infrastructures

## Anticipated impacts and possible adaptations

This chapter seeks to qualify the multifarious relationships between climate change and electricity infrastructures. The chapter is divided into four sections. The first two sections elaborate on the anticipated effects of climate change on weather patterns and sea levels, first at the global level and then at the regional. The third section inventories the anticipated effects of climate change on components of the electricity infrastructure. Particular attention is paid here to the potential impacts of *extreme weather events*. The final section specifies a typology of adaptation measures for enhancing the climate resilience of electricity infrastructures. Particular attention is paid to possible measures for mitigating the effects of extreme weather events.

## 4.1 Anticipated effects of climate change on global weather and sea level

Precise predictions of future climatic conditions are impossible for multiple reasons. The climate system is complex, featuring an innumerable number and large diversity of interacting variables operating on different levels and across different timescales. Today's computer models are incapable of capturing these relationships to a sufficient degree, and the inherently chaotic nature of meteorological systems (Lorenz, 1972) implies that precise predictions may never be possible. Moreover, the long-term development of climatic conditions is heavily dependent on natural and anthropogenic factors external to the climate system, such as ocean circulation patterns, vegetative cover and greenhouse gas emissions. The long-term development of these factors is itself impossible to predict, not only due to the internal complexity of these systems, but also because of their reflexive relationships with climate and human systems.

The fact that we cannot precisely predict the long-term trajectories of meteorological variables does not imply that we cannot make meaningful projections. Climate projections at a global level are made using numerical models called *general circulation models (GCMs)*. GCMs represent physical processes in the atmosphere, ocean, cryosphere and land surface to provide geographically and physically consistent estimates of regional climate change (IPCC, 2013). The results of any GCM carry many uncertainties, both concerning the relevant elements of the modeled system and the relationships between them, as well as on the growth trajectory of GHG emissions. In the use of GCMs, the effects of these uncertainties are normally accounted for in two ways. Uncertainties concerning the growth of GHG emissions (scenario uncertainty) are normally accounted for through the use of multiple scenarios. In the most recent Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), these scenarios take the form of so-called *Representative Concentration Pathways (RCPs)* – "internally consistent sets of time-dependent forcing projections which could potentially be realized with more than one underlying socio-economic scenario" (IPCC, 2013). Uncertainties concerning the representation of the modeled system (structural uncertainties) are accounted for by averaging results across multiple independently-developed GCMs (ensembles). Uncertainties concerning the effects of climatic variability on annual and decadal scales (statistical uncertainty) are accounted for by running multiple simulations with the same model (Christensen et al., 2011).

The most scientifically rigorous climate change projections are summarized in the Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC), published every five to six years since 1990. The most recent IPCC Assessment Report estimates an increase in global mean surface temperatures of 0.3 to 4.8°C for 2081–2100 (relative to 1986–2005), and a global mean sea level rise of 0.26 to 0.82 m for the same period and reference years (IPCC, 2013). The Report projects (by 2100) increases in annual mean precipitation in high latitude regions, mid-latitude wet regions and in the equatorial Pacific Ocean, as well as decreases in many mid-latitude and sub-tropical dry regions (IPCC, 2013).

Next to these changes in mean temperature and precipitation, the IPCC also projects marked changes in global weather extremes, including:

- more frequent, intense and longer lasting hot temperature extremes (heat waves) over most land areas (IPCC, 2012, 2013)
- less frequent cold temperature extremes (IPCC, 2012, 2013)
- more frequent and more intense extreme precipitation events over most mid/high-latitude land masses and wet tropical regions (IPCC, 2012, 2013)
- less or equally frequent, but more intense (higher maximum wind speed) tropical cyclones (IPCC, 2012)
- more intense droughts (due to reduced precipitation and/or increased evapotranspiration) in regions including southern Europe and the Mediterranean, central Europe, central North America, Central America and Mexico, northeast Brazil and southern Africa.

## 4.2 Anticipated effects of climate change on regional weather and sea level

Due to their global scope, GCMs entail a relatively low horizontal resolution, on the scale of 250 and 600 km (IPCC, 2013). To obtain improved regional scale projections, GCMs are often complemented with regional climate models (RCMs), which provide a more realistic representation of aspects such as topography and geography and a finer resolution, on the scale of 25 to 50 km (Christensen et al., 2011).

Results from combined GCMs/RCMs provide more detailed climate projections for (northwestern) Europe and the Netherlands. One such set of projections has been generated by the *ClimateCost* project (ClimateCost, 2013), which focuses on the European level. Results from this project estimate higher changes in summer temperature in Europe compared with the global average, especially for southern Europe (Christensen et al., 2011). Projected changes in winter temperatures are in line with the global average, except in northern Europe which demonstrates larger changes (Christensen et al., 2011). In terms of precipitation, the results suggest (under most scenarios) a likely increase in winter precipitation in northern and western Europe, and a decrease in southern Europe (Christensen et al., 2011).

These projections for the development of mean temperatures and precipitation levels in Europe are complemented by the findings of Beniston et al. (2007) concerning anticipated changes in extreme weather events at the European level. In particular, this study suggests an increasing intensity of extreme hot temperatures greater than the increase in moderate temperatures, with regions such as France and Hungary experiencing as many days above 30°C as currently experienced in Spain and Sicily (Beniston et al., 2007). For central and northern Europe, the study projects increases in heavy winter precipitation as well as increases in extreme wind speeds (Beniston et al., 2007). These changes, combined with more north-westerly wind directions, are anticipated to result in increases in storm surges along the North Sea coast, including in the Netherlands (Beniston et al., 2007). For southern Europe, the study projects a reduction in the frequency of heavy precipitation events as well as earlier and longer lasting Mediterranean droughts (Beniston et al., 2007).

At the level of the Netherlands, the most comprehensive climate projections are provided by the Royal Netherlands Meteorological Institute (KNMI). The most recent set of KNMI projections were released in 2014. KNMI's 2014 projections for 2050 are shown in Table 4.1. In general, these projections suggest that mild winters and hot summers will become more common; winters will become wetter and extreme precipitation amounts will increase; the intensity of extreme rain showers in the summer will increase; changes in wind speed will be small relative to natural variability; and sea level will continue to rise (Tank et al., 2014). Contrary to Beniston et al. (2007), Tank et al. (2014), KNMI (2009) and van den Hurk et al. (2006) find only small changes in the frequency and intensity of strong northerly winds.

Table 4.1: Quantitative summary of KNMI's climate change projections for the Netherlands for 2050 (Tank et al., 2014). $G_H$ $G_L$, $W_H$ and $W_L$ refer to different scenarios in terms of global temperature rise and change in air circulation patterns.

| | **Attribute** | **KNMI scenario** | | | |
|---|---|---|---|---|---|
| | | $G_L$ | $G_H$ | $W_L$ | $W_H$ |
| | Global temperature rise | +1°C | +1°C | +2°C | +2°C |
| | Change in air circulation patterns | low | high | low | high |
| Winter | average temperature | +1.1°C | +1.6°C | +2.1°C | +2.7°C |
| | coldest winter day per year | +1.0°C | +1.5°C | +2.1°C | +2.9°C |
| | average precipitation amount | +3% | +8% | +8% | +17% |
| | number of wet days (≥0,1 mm) | -0.3% | +1.4% | -0.4% | +2.4% |
| | 10-day precipitation sum exceeded once in 10 years | +6% | +10% | +12% | +17% |
| | highest daily mean wind speed per year | -3% | -1.4% | -3% | -0% |
| Summer | average temperature | +1.0°C | +1.4°C | +1.7°C | +2.3°C |
| | warmest summer day per year | +1.4°C | +1.9°C | +2.3°C | +3.3°C |
| | average precipitation amount | +1.2% | -8% | +1.4% | -13% |
| | number of wet days (≥0,1 mm) | +0.5% | -5.5% | +0.7% | -10% |
| | daily precipitation sum exceeded once in 10 years | +1.7–10% | +2.0–13% | +3–21% | +2.5–22% |
| | potential evaporation | +4% | +7% | +4% | +11% |
| Sea level | absolute increase | +15–30 cm | +15–30 cm | +20–40 cm | +20–40 cm |

## 4.3 Anticipated impacts of climate change on components of the electricity infrastructure

A growing body of research has elucidated the (anticipated) impacts of extreme weather and climate events on the (technical and social) components of the electricity infrastructure. In this section, we present the results of a comprehensive review of these impacts, which can be divided into four categories – impacts on electricity *generation*, impacts on electricity *transmission and distribution*, impacts on electricity *demand* and *indirect* impacts. In this section, we do not differentiate between impacts that are more or less likely to affect the *Dutch* electricity infrastructure.

### Impacts on electricity generation

Climate change is anticipated to affect electricity generation in a number of ways. A key phenomenon in this context is the so-called *energy-water nexus* – the set of interdependencies between water availability/quality and energy production/demand. One key such interdependency is the relationship between reservoir levels and hydropower. Changes in hydrologic cycles (e.g. precipitation levels and freeze-thaw cycles) can affect river flows and reservoir levels and, in turn, hydropower output (Mideksa and Kallbekken, 2010). Absolute reductions in precipitation levels in certain areas are not the only issue. The projected intensification of hydrological cycles can affect the stability of stream flows – higher high flows and lower low flows – in turn affecting the stability of power output (Ebinger and Vergara, 2011). As a result of these changes, Lehner et al. (2005) suggest a 20-50% decline in hydropower potential in East-Central and Southern Europe, but an increase of 15-30% in Russia and Scandinavia.

A second dimension of the energy-water nexus is the relationship between surface water levels/temperatures and the cooling water needs of thermal power plants. Thermal power plants, including fossil fuel-fired plants and nuclear plants, require a source of cooling to condense steam back into water. Normally, this cooling function is provided by water extracted from adjacent water bodies (surface water or sea water). Effective cooling requires sufficient quantities of cooling water to fulfill this function. These quantities can be enormous – cooling water for thermal power plants accounts for 37% of total freshwater extracted across Europe (Mima et al., 2011) – which can problematic in times of drought.

Effective cooling also requires cooling water of sufficiently low temperature. Higher cooling water temperatures reduce the efficiency of thermal power plants, and restrictions on maximum surface water temperatures may in certain places limit possibilities for cooling water use under extreme temperature conditions. These effects are already visible today. During the 2003 European heat wave/drought, a drop in the level of inland waterways and an increase in their temperature incited the temporary shut-down of several nuclear generators in France, and necessitated the issuance of temporary legal exemptions from water temperature limits for other plants (De Bono et al., 2004). Looking to the future using a combined hydrological/electricity generation model, van Vliet et al. (2012) project an average summer decrease in power plant capacity of 6.3–19% in Europe and 4.4–16% in the United States for 2031–2060, as well as a three-fold increase in the probability of extreme (>90%) reductions in thermal generation.

A third dimension of the energy-water nexus has to do with the potential impacts of floods on thermal power plants. Flooding of power plant grounds may lead to the failure and contamination of electrical and electronic components. Reports of power plant damage following recent flood incidents provide insight into the likely extent of damage. The 2008 flooding of a coal and natural gas fired power plant in Iowa, USA – in which waters rose greater than 1 m above the turbine room floor – incited the shutdown of all generation units, seriously damaged the boilers and turbine generators, and forced the replacement of all power distribution equipment and many mechanical systems (Enercon, 2008).

Flooding of nuclear plants can be even more disastrous. The IAEA cites numerous possible effects of flooding at nuclear installations (International Atomic Energy Agency, 2004): (1) failure of safety related systems such as emergency power supply systems which may be essential for reactor cooling, (2) deceased structural capacity of walls, (3) reduced effectiveness of communication and transport networks on and around the plant site, which can jeopardize the implementation of safety measures, and (4) dispersion of radioactive material to the environment. The 1999 flooding of the Le Blayais nuclear power plant in France – caused by a massive windstorm – for instance, resulted in a partial loss of power supply to all four of the plant's generation units, disabled cooling water pumps and disrupted the operation of the plant's safety system (Gorbatchev et al., 2000).

Problems with power plant flooding may be exacerbated by the fact that many of today's thermal plants are located in coastal locations. These locations are often advantageous from a cooling water perspective, but are more exposed to storm surges. Given the anticipated rise in sea levels over the coming decades and changing weather patterns which may exacerbate storm surges in certain areas (Beniston et al., 2007), climate change is likely to enhance these risks.

Beyond the energy-water nexus, electricity generation may be affected by ambient air temperature. The efficiency of gas turbines, in particular, may be significantly reduced under high temperature conditions – caused by a temperature-induced reduction in air density which reduces mass flow into the compressor, and by the positive relationship between temperature and power consumed by the compressor (Kehlhofer et al., 2009). Steam turbines and combined cycle plants, on the other hand, generally experience a slight increase in efficiency with increases in ambient temperature (Kehlhofer et al., 2009).

Another impact on electricity generation may entail changes in the availability of wind resources, though there is still quite some uncertainty on this aspect. Pryor and Barthelmie (2013) suggest that multi-year annual mean wind power densities over Europe and North America will be relatively stable to 2100, whereas Mideksa and Kallbekken (2010) suggest that Northern Europe and the North Sea will likely benefit from higher wind speeds, and the US will experience lower wind speeds. Independent of long-term changes in resource availabilty, there is some evidence for increased magnitude of wind speed extremes over northern Europe, possibly with the potential to incite greater rates of fatigue, automatic shut-downs, and/or turbine damage (Pryor and Barthelmie, 2013). The negative impacts of increased wind extremes may, however, be somewhat balanced by reduced turbine icing and sea ice loading, common problems in the offshore turbine installations of northern Europe (Pryor and Barthelmie, 2013).

Table 4.2 summarizes anticipated climate change impacts on electricity generation.

Table 4.2: Summary of extreme weather/climate event impacts on electricity generation

| **Extreme weather/climate event** | **Affected components** | **Description of impact** |
|---|---|---|
| Drought; heat wave | Thermal power plants | Cooling water issues due to surface water temperature restrictions and/or water shortages |
| Heat wave | Thermal power plants | Reduced generation efficiency due to heightened cooling water temperatures |
| Flood | Fossil fuel-fired plants | Shutdown; damage to electric systems and machinery |
| Flood | Nuclear plants | Shutdown; failure of safety systems, possible structural failure, possible dispersion of radioactive material |
| Seawater intrusion | Thermal power plants | Contamination and possible corrosion of electrical components |
| Drought; heat wave | Hydropower | Reduced resource availability (reservoir levels and/or river flows), resulting in reduced power output |
| Windstorm | Wind turbines | Automatic shutdown, component fatigue, turbine damage |

## Impacts on electricity transmission and distribution

With respect to electricity transmission and distribution, the anticipated effects of climate change are mixed. It is well established that the capacity of overhead transmission and distribution lines is reduced under higher temperatures, as resistivity increases and convective cooling decreases. Higher temperatures also contribute to *line sag* – the vertical displacement of an overhead power line – a result of thermal expansion on the part of the conducting material, usually aluminum or copper. Although the sagging of an overhead line is not a problem in itself, it can increase the likelihood of a flashover to the ground or trees, resulting in line failure. The potentially significant consequences of a sag-induced flashover are apparent in the 2003 Italian blackout – the largest blackout ever to occur in Italy – which resulted in 180GWh of lost load (Corsi and Sabelli, 2004).

Increases in the frequency, severity or nature of windstorms may also pose a threat to electricity transmission and distribution systems by increasing the occurrence of downed overhead lines. Potentially detrimental interactions between overhead power lines and wind take several forms. One such form of interaction is *conductor galloping* – a high-amplitude, low-frequency oscillation of overhead power lines due to wind. Conductor galloping most frequently occurs during conditions of moderate to strong steady winds and under conditions in which ice or snow has accrued on the line. In many cases, conductor galloping is not problematic. However, under certain conditions, it can result in flashovers, circuit failures, fatigued conductors and fractured or collapsed tower components (Lilien and Havard, 2008). Insofar as climate change is anticipated to result in an increase in heavy winter precipitation and extreme wind speeds in northern Europe (Beniston et al., 2007), it may also increase possibilities for overhead line damage in this region due to conductor galloping. This, however, needs to be balanced with the general warming trend, which will likely reduce the timeframe during which temperatures are low enough to allow for ice/snow accretion on overhead lines.

Next to conductor galloping, another potentially detrimental wind effect is *high-intensity wind events* or *downbursts* – local convective downdrafts and tornados produced by thunderstorms (Holmes, 2008). Such events are normally quite localized, but can result in the simultaneous failure of multiple towers in a small area (Oliver et al., 2000). More widespread damage may be caused by extratropical cyclones, such as the Lothar and Martin storms which passed through northern Europe in 1999. This particular pair of storms caused "the greatest devastation to an electricity supply network ever seen in a developed country", toppling 120 high-voltage pylons and one quarter of the total high-tension transmision lines in France (IPCC, 2012).

A final form of interaction between wind and overhead power lines is in the form of *airborne debris*. A particular issue here is trees and branches. Studies have shown that tree-related failures increase exponentially when wind speeds exceed 100 km/hr (Kumagai, 2012). Insofar as climate change is expected to result in an increase in summer storm activity in the Netherlands (Tank et al., 2014), there exists a theoretical possibility for greater damage to overhead lines due to both high-intensity wind events and airborne debris.

Next to high temperatures and extreme wind, a third potential impact of climate change on electricity transmission and distribution is via the flooding of electrical substations. While overhead power lines and underground cables are relatively insulated from the direct consequences of flood events, substations contain high concentrations of sensitive electrical and electronic equipment – power transformers, breakers, capacitors and computers. Even very small quantities of moisture and dirt contamination can cause some of this equipment to fail[1] (Kumagai, 2012). Seawater intrusion is a potentially more serious threat, due to its corrosive effect on electrical components. Restoring power to a substation after flooding can be a lengthy and arduous task. A submerged breaker, for instance, requires complete disassembly and thorough cleaning of each part, and acquiring a new transformer can take anywhere from 18 months to a couple of years (Kumagai, 2012).

Next to extreme heat, wind and flooding, drought poses several threats to electricity grid components. Firstly, drought may affect the capacity of underground cables. Dry soil conditions increase the resistivity of underground cables and decrease power transfer capacity. The capacity rating of a cable may be reduced by up to 29% if the surrounding soil becomes thoroughly desiccated. In addition to this capacity effect, soil desiccation under drought conditions can lead to increased underground soil movement, which may damage underground cables. This phenomenon led to a loss of power to 4,000 people in the Bordeaux region of France in August of 2003 (Rademaekers et al., 2011). Drought-induced desiccation of soils can also affect the stability of dikes, in particular peat dikes. This, in turn, increases risk of flooding, which can affect electrical substations as described above. A 2003 incident in the Dutch village of Wilnis illustrates the potential for drought-induced dike failure.

Table 4.3 summarizes anticipated climate change impacts on electricity transmission and distribution.

## Impacts on electricity demand

The chief anticipated effects of climate change on electricity demand lie in changes in energy use for heating and cooling purposes. Insofar as climate change is anticipated to result in a general increase in both winter and summer temperatures, it will reduce demand for heating and increase demand for cooling. According to Mima et al. (2011), the reduction in heating demand for Europe as a result of climate change alone is estimated to amount to 10% by 2050 and 20% by 2100. The study projects the largest reductions in western Europe, an area which is defined to include the Netherlands (Mima et al., 2011). Isaac and van Vuuren (2009) project even steeper reductions in heating demand, by about 25% in continental and Atlantic Europe between 2000 and 2050, and 18–43% between 2050 and 2100. While these studies agree that the Netherlands may experience significant reductions in future heating demand, it needs to be taken into account that nearly all space heating in the Netherlands comes from natural gas combustion (International Energy Agency, 2012). The effect on electricity demand will thus likely be much more modest.

With respect to cooling, demand change on a percentage basis is expected to be much larger. Currently, it is estimated that only about 5% of residential households

[1] sometimes this failure can be spectacular and catastrophic, as demonstrated by the explosion of a flooded Manhattan substation during Hurricane Sandy in 2012 (see video here: `http://www.youtube.com/watch?v=T_-TI9RXiZ8`)

Table 4.3: Summary of extreme weather/climate event impacts on electricity transmission and distribution

| **Extreme weather/climate event** | **Affected components** | **Description of impact** |
|---|---|---|
| Heat wave | Overhead lines | Reduced capacity |
| Heat wave | Overhead lines | Increased line sag, resulting in increased risk of flashover and circuit failure |
| Windstorm (moderate to severe steady wind) | Overhead lines | Conductor galloping, resulting in increased rate of fatigue and risk of flashover, circuit failure and/or fractured/collapsed tower components |
| Windstorm (downburst) | Overhead lines | Toppled towers and downed lines in the affected area |
| Windstorm | Overhead lines | Circuit failure due to airborne debris |
| Flood | Substations | Shutdown of affected substations |
| Flood / seawater intrusion | Substations | Contamination (and possibly corrosion) of various electrical and electronic components; likely component failures |
| Drought | Underground cables | Reduced capacity |
| Drought | Underground cables | Increased risk of cable damage/failure due to soil movement |

and 27% of commercial buildings in Europe are equipped with air conditioning, leaving significant room for future growth. Isaac and van Vuuren (2009) (as referenced in (Dowling, 2013)) estimate an increase in cooling demand of about 260% in Continental Europe and Atlantic Europe between 2000 and 2050, and an increase of more than 4000% elsewhere in Europe. Given that air conditioning is largely electricity powered, these changes will likely result in accompanying increases in electricity demand – estimated at about 3% per year in Europe to 2100 (Mima et al., 2011).

Historically, aggregate electricity demand in the Netherlands has been characterized by a winter peak and a summer trough – a negative relationship between temperature and electricity demand. Analyzing daily electricity demand and average temperature data between 1970 and 2007, Hekkenberg et al. (2009) identifies a shift in the Netherlands towards a *positive* relationship between temperature and electricity demand in the months of May, June, September and October. According to the authors, the identified trend suggests that an increase in temperature of 1°C during these months currently results in an increase of aggregate demand by more than 0.5%. Moreover, the authors find that the intensity of this relationship is *accelerating* over time, implying the gradual emergence of a new summer peak in electricity demand, driven by the increased use of cooling (Hekkenberg et al., 2009).

Already, certain countries, notably in southern Europe, experience a *dual peak* in electricity demand – in the winter and the summer. In some of these countries (e.g. Greece), the magnitude of the summer peak exceeds that of the winter peak, implying that the capacity of the infrastructure must be sized in accordance with the summer demand peak (Hekkenberg et al., 2009). With higher summer temperatures, increased use of cooling and reduced winter heating demand, it is likely that the seasonal demand profiles of more northern countries will drift in this direction over the coming decades. Even though, in many places, emerging summer demand peaks may not exceed existing winter peaks, they may affect the socio-technical organization of the infrastructure by forcing a shift in planned maintenance and other operational practices.

Changes in electricity demand may be incited not only by gradual shifts in average temperatures, but also by extreme events, in particular extreme heat events. Based on an analysis of media reports during the 2003 European heat wave, Rothstein et al. (2008) identify a dual impact of heat waves on electricity consumption – (1) an increase in the intensity of electricity demand and (2) changes in the course of the electricity load curve. Higher total demand for electricity is tracked to a higher utilization of air conditioners, fans, refrigerated and freezers. Changes in the load curve are attributed to alterations in the daily routines of individuals, including an earlier beginning and ending of working days and greater participation in open air leisure activities.

Next to increased demand for cooling, extreme heat events (as well as droughts) may increase electricity demand for pumping water. Currently, approximately 3.5% of electricity consumption in Europe is used for water supply and treatment. Climatic changes are anticipated to increase this number to approximately 5% by 2050 (Mima et al., 2011). It is not clear to what degree these numbers may be applicable in the unique water management situation of the Netherlands, where increased evapo-transpiration seems likely to *decrease* water pumping requirements.

Table 4.4 summarizes anticipated climate change impacts on electricity demand.

Table 4.4: Summary of extreme weather/climate event impacts on electricity demand

| **Extreme weather/climate event** | **Affected components** | **Description of impact** |
|---|---|---|
| Heat wave | Residential and commercial consumers | Increased electricity demand for cooling applications |
| Heat wave | Residential and commercial consumers | Possible shifting of the demand curve |
| Drought | Drinking water infrastructure | Increased electricity demand for pumping water |
| Rainstorm; flood | Wastewater infrastructure | Increased electricity demand for pumping water |

## Indirect impacts

In addition to the direct impacts of climate change and extreme weather/climate events on components of the electricity infrastructure, other more indirect impacts may be important. One type of indirect impact comes in the form of actor responses to extreme events. In some cases, these responses may fall into the category of adaptations, in the sense that they may be intended to lessen the negative consequences of future similar events on infrastructure components. Examples here include regulatory and investment discussions following the 2003 European heat wave (Rademaekers et al., 2011), as well as investments in distributed generators and substation flood protections in the wake of Hurricane Sandy (Con Edison, 2013; Kristof, 2012).

In other cases, responses to an event may be beneficial to the actor, but ultimately increase the vulnerability of the infrastructure. Anecdotal evidence from the

2003 heat wave suggests that the event prompted not only heightened use of existing air conditioning units, but also an increase in the *uptake* of residential air conditioning units (Tagliabue, 2003). Such choices may be entirely logical and beneficial from the perspective of a consumer, but can produce long-term shifts in demand patterns with the potential to exacerbate the fragility of the system under extreme temperature conditions. Grothmann and Patt (2005) suggest that decisions such as these are largely motivated by a cognitive factor known as *relative risk perception* – the perceived probability of being exposed to climate change impacts and the appraisal of how harmful these impacts may be, relative to the appraisal of other problems. An important impact of extreme weather and climate events is their tendency to enhance relative risk perception on the part of actors – an actor exposed to a flood is more likely to take mitigating action. However, according to Grothmann and Patt (2005), the degree to which this increase in risk perception actually translates into action depends on the *perceived adaptive capacity* of the actor – the degree to which he thinks he is capable of carrying out an adaptive response. In other words, this effect is not necessarily automatic, but is dependent on the (perceived) resources available to the actor.

A second type of indirect impact has to do with supply chain effects. The components of an electricity infrastructure may be wholly unharmed by an extreme event, but costs may rise and/or performance may drop if key portions of the supply chain are cut off. Floods and droughts may pose a particular threat in this respect, insofar as they are capable of disrupting supply routes and destroying crops. Flooding may disrupt mining operations or coal supply routes – a phenomenon which was observed during the Queensland floods of 2011. While most coal-fired power plants maintain an on-site reserve of fuel, prolonged flooding incidences that disrupt supply can increase costs and eventually force the shut-down of a plant. Similarly, both droughts and floods may destroy biofuel crops, currently a growing component of the energy mix in many countries.

A third type of indirect risk has to do with ecological factors. In particular, changing climatic conditions may result in increased habitat ranges for certain species, whose activities may in turn endanger components of the electricity infrastructure. An example is the current outbreak of the mountain pine beetle in western North America, which has decimated pine tree populations in parts of western Canada and the United States. Historically, pine beetle populations in these areas were limited by cold winters, but an increase in winter temperatures in recent years has allowed them to survive through the winter and expand their range to higher elevations and more northern latitudes (University of British Columbia). In their wake, pine beetles leave large swaths of dead trees, whose structural weakness makes them more susceptible to falling on power lines. As a result, pine beetles have been cited as a cause in at least one recent power outage (Gesick, 2013), and concerns about more widespread impacts have incited the initiation of a massive tree clearing project by the US Forest Service (U.S. Forest Service, 2013).

Supply chain effects, changes in the risk perception of actors, and ecological changes are just a few of many possible indirect effects of climate change on electricity infrastructures. It is impossible to comprehensively inventory these impacts, as they may be highly uncertain and difficult to discern, and may play out over long periods. An example is the hypothesized role of climate change in inciting recent uprisings in the Middle East (Reuters, 2011). These uprisings in turn are claimed to have reduced investments in oil and gas projects as regional governments have shifted their focus elsewhere (Sternberg, 2013). According to the International Energy Agency, this dearth in investment is anticipated to result in an increase in energy prices by 2016 (Reuters, 2011). While such cause-effect chains may be difficult to discern, their impacts may nonetheless be significant.

Table 4.5 provides a partial overview of anticipated indirect impacts of climate change on the electricity infrastructure.

Table 4.5: Partial overview of possible indirect impacts of extreme weather/climate events on components of the electricity infrastructure

| **Extreme weather/climate event** | **Affected components** | **Description of impact** |
|---|---|---|
| Heat wave | Residential and commercial consumers | Enhanced risk perception: Increased adoption of cooling devices, possibly leading to a longer term shift in demand patterns |
| All | Residential and commercial consumers | Enhanced risk perception: Increased adoption of distributed generation to provide backup power |
| All | Power producers; grid operators | Enhanced risk perception: Investment in protective measures for power plants, power lines and/or substations |
| All | Regulators | Enhanced risk perception: Regulatory action to reduce component vulnerabilities to similar events |
| Drought; flood | Coal power plants | Supply chain effects: disruption of coal mining, refining and/or delivery operations |
| Drought; flood | Biofuel power plants | Supply chain effects: destruction of bio-energy crops |

## 4.4 Typology of adaptation measures

This section introduces a typology of adaptation measures. Adaptation measures are broadly defined here as *technical or institutional mechanisms for supporting the development of a climate resilient electricity infrastructure*. Given the scope of this research, we focus here mostly on adaptations for dealing with *extreme weather events* such as heat waves, droughts, windstorms and floods.

Given the large number and diversity of possible adaptation measures, we seek here not to comprehensively identify such measures, but rather to identify different *categories* of measures. These categories have been identified based on a limited review of relevant literature from the climate change adaptation, power systems and energy policy domains. This review identified a broad range of adaptation measures, from which were extracted three broad categories of adaptation measures – targeted infrastructure investments, infrastructure management strategies and infrastructure development strategies – each with several subcategories. The developed typology, including examples of measures falling within each (sub)category, is illustrated in Table 4.6. The sections below elaborate on the elements of this typology and provide examples of implemented adaptation measures.

Table 4.6: Typology of adaptation strategies for electricity infrastructures. Relevant extreme weather conditions for each strategy are indicated in parentheses after the examples.

| **Category** | **Sub-category** | **Examples** |
|---|---|---|
| Targeted infrastructure investments | Generation | Indirect/dry cooling systems for thermal power plants (heat waves, droughts)<br>Construction of new thermal power plants in coastal areas (heat waves, droughts)<br>Distributed solar photovoltaics (heat waves, droughts) |
| | Transmission and distribution | Undergrounding of transmission and distribution lines (windstorms)<br>Wind-resistant transmission/distribution towers (windstorms)<br>Construction of dikes and levees to protect substations (floods)<br>Elevation of substation equipment (floods)<br>Relocation of substations to high ground (floods) |
| | Loads | Backup generators, possibly combined with energy storage (multiple)<br>Micro-grids (multiple) |
| Infrastructure management strategies | Network management strategies | Balancing markets (multiple)<br>Overhead line monitoring (heat waves)<br>Self-healing grids (multiple) |
| | Demand-side management strategies | Direct load control (heat waves)<br>Commercial/industrial programs (heat waves)<br>Frequency regulation (heat waves)<br>Time-of-use-pricing (heat waves)<br>Demand bidding (heat waves) |
| | Maintenance strategies | Vegetation management (windstorms)<br>Shift in generator maintenance timing (heat waves) |
| Infrastructure planning strategies | Capacity strategies | Generation capacity mechanisms (heat waves)<br>Probabilistic transmission planning (windstorms, floods) |
| | Decentralization strategies | Feed-in tariffs/net metering for distributed/renewable installations (multiple) |
| | Diversification strategies | Feed-in tariffs/net metering for distributed/renewable installations (multiple)<br>Nuclear energy credit guarantees (multiple) |
| | Demand reduction strategies | Building codes (heat waves)<br>Building design guidelines (heat waves, floods)<br>Energy efficiency standards/labels for air conditioning units (heat waves) |

## Targeted infrastructure investments

The first category of adaptation measures entails *targeted infrastructure investments* – investments in individual infrastructure components intended to reduce their vulnerability to extreme weather events. Targeted infrastructure investments are *hard* adaptations in the sense that they entail purely technological solutions. Three categories of targeted infrastructure investments can be distinguished – investments in generators, investments in transmission and distribution components, and investments in loads.

Examples of targeted investments in *generation* include the construction of new thermal plants with indirect cooling or dry cooling systems. Where direct cooling systems rely on a steady, once-through flow of water through a power plant's condensers, indirect and dry cooling systems recirculate cooling water through the plant resulting in less water use (World Nuclear Association, 2013). An alternative with similar benefits is the construction of new thermal power plants in the vicinity of coastal areas, where cooling water is more abundant. All of these strategies have the potential to reduce the vulnerability of power plants to drought or heat wave induced cooling water shortages.

Next to these strategies, it has been suggested that widespread installation of distributed solar photovoltaics – in addition to providing a less carbon intensive form of electricity production – can help electricity systems to better cope with the heightened demand and reduced thermal generation capacity that often accompany severe heat waves. By taking advantage of the same weather forces that may simultaneously drive heightened demand and reduced thermal generator output, solar photovoltaics are able to offer additional capacity to the power system precisely when it is needed. It has been shown, for instance, that distributed solar photovoltaics could have significantly reduced the risk of catastrophic failure during the 2003 North American blackout, a case in which high regional air-conditioning demand created unusually large power transfers and stress on the grid (Letendre and Perez, 2006).

Examples of targeted investments in *transmission and distribution* include the undergrounding of lines and the construction of more wind-resistant towers, both at the transmission and the distribution level. Measures such as these can help to reduce the vulnerability of lines to windstorm-induced damage such as conductor galloping, downbursts and airborne debris. In the Netherlands, most lines of the distribution system have already been undergrounded, as have many of the lines of the transmission system up to 150kV. Undergrounding of higher voltage connections is more challenging due both to the high cost and technical difficulties with voltage control (TenneT, 2009). Further examples of targeted investments in transmission and distribution include various options to protect substations from flooding – construction of dikes and levees, elevation of equipment above anticipated flood levels, or relocation of substations to higher ground (Abri-Samra and Henry, 2011).

Examples of targeted investments at the level of *loads* include the installation of backup generators, energy storage devices and micro-grids. Backup generators are traditionally based on diesel or natural gas combustion, but increasingly fuel cells are being applied to ensure a steady supply of power to critical equipment. Though usually more expensive, fuel cells have the advantage that they may run for several days without refueling, have fewer moving parts than combustion engines (thus requiring less maintenance) and can be remotely monitored (Satyapal, 2012). When used in combination with energy storage devices such as batteries, backup generators can ensure a steady supply of power to even the most sensitive medical and electronic equipment in the event of grid failure (National Electrical Manufacturers Association, 2013). Micro-grids are separately managed sub-networks that are capable of functioning in "islanding mode" – independently from the main grid. The benefit of micro-grids during extreme weather events was observed during Hurricane Sandy, when several university campuses in the New York area, including Princeton and New York University, were able to maintain power by cutting themselves off from the main grid and relying on their own generators (Princeton University Office of Communications, 2012; Wald, 2012).

## Infrastructure management strategies

A second category of adaptation measures is *infrastructure management strategies*. This category of measures may be distinguished from targeted infrastructure investments in that it entails strategies for *managing infrastructure operation* to cope with extreme weather events, as opposed to specific hardware investments. While such adaptations are *soft* in the sense that they largely concern rules, guidelines and procedures, the implementation of adaptations of this category may also require certain technological capabilities and thus *hard* investments. Three categories of infrastructure management strategies may be distinguished – network management strategies, demand-side management strategies and maintenance strategies.

*Network management strategies* include strategies for managing network performance during extreme weather conditions. Many such strategies already exist, and are essential for dealing with day-to-day imbalances in the electricity network as well as extreme conditions. One well-established such mechanism is *balancing markets*, which are used by transmission system operators to ensure constant equity between the magnitude of demand and supply. In the Netherlands, the balancing market is a single-buyer market, with various parties offering both regulating and reserve capacity to the transmission system operator (TenneT, 2011).

Increasingly, network operators are pursuing strategies that would allow them to more effectively use the infrastructure at their disposal. One such strategy is *dynamic line rating*, which involves the use of meteorological data to calculate the real-time dynamic loadability of transmission lines (TenneT, 2012a). In addition to obviating the need for costly grid expansions, such a capability could facilitate improved management of grid capacity under extreme weather conditions. A step further is the concept of the *self-healing grid*, a system of sensors, automated controls, and advanced software which uses real-time data to detect and isolate faults, and to quickly reconfigure the network to minimize customer impact (Cooper Power Systems, 2013). In addition to isolating service disruptions, self-healing grid technologies can provide operators facing stability-threatening events with greater real-time awareness and an ability to adapt to changing conditions (Sun et al., 2012).

*Demand-side management* strategies entail various mechanisms for improving the responsiveness of loads to the availability of generation capacity. Historically, the only mechanisms available to grid operators for curtailing demand under extreme conditions included load shedding and brownouts. Demand-side management strategies aim to limit the use of these sorts of heavy handed solutions by establishing voluntary arrangements with consumers. Such arrangements include, for instance, direct load control, commercial/industrial programs, frequency regulation, time-of-use pricing and demand bidding (Strbac, 2008). Each of these mechanisms entails a different form of arrangement between consumers and grid operators, but they all may help to reduce demand under extreme conditions when certain types of generation may be depressed. While not yet in widespread use, demand-side management mechanisms have already been used to preserve power system stability during extreme weather events. During a 2013 heat wave in North America, for instance, the demand of certain commercial, industrial and residential customers was strategically curtailed to preserve system function and stabilize prices (EnerNOC, 2013). Amongst others, this was facilitated by way of an institutional arrangement in which small consumers were offered fixed financial compensation ($1.50/kWh) for reducing consumption during a specified period (Lowfoot, 2013).

*Maintenance* strategies include various strategies for ensuring the robustness and reducing the exposure of infrastructure components to extreme weather events. Chief amongst these is *vegetation management* – the trimming/removal of vegetation in the vicinity of power lines. Vegetation management is essential to reducing power system vulnerability to extreme weather events such as windstorms and heat waves, which can threaten power lines with flying debris and increased sag levels. Following the 2003 North American blackout – which partially resulted from inadequate vegetation management – the North American Electric Reliability Corporation (NERC) developed new vegetation management standards, and required all utilities to implement a compliant tree trimming or vegetation management plan (Federal Energy Regulatory Commission, 2013). On the flip side, maintenance activities can also *worsen* infrastructure vulnerability under certain conditions. During the 2003 European heat wave, France suffered a severe power shortage, due not only to cooling water related issues at its inland plants, but also due to the unavailability of some of its coastal plants for maintenance. To avoid such issues in the future, Electricité de France (EDF) implemented an adaptation measure in the form of shifted maintenance schedules to avoid the unavailability coastal power plants during future heat waves (Caneill, 2013).

## Infrastructure planning strategies

*Infrastructure planning strategies* entail measures for (incentivizing) the planning and design of the infrastructure system in a manner which enhances climate resilience. Infrastructure planning strategies are distinct from targeted infrastructure investments in that they deal with the *procedures and incentive mechanisms* driving the development of the infrastructure, rather than with specific investments. They are distinct from infrastructure management strategies in that they entail measures for guiding the *long-term development* of the infrastructure, rather than its operational management. Three broad categories of infrastructure planning strategies may be distinguished – capacity strategies, decentralization strategies, diversification strategies and demand reduction strategies.

*Capacity strategies* entail procedures and mechanisms for ensuring sufficient generation and transmission capacity in an electricity system. The degree to which liberalized electricity markets offer adequate incentives for investment in generation capacity is questionable, in particular for peaking units. This can lead to a situation in which an electricity system has insufficient capacity to provide for demand under certain non-normal circumstances or events, including extreme weather conditions. *Generation capacity mechanisms* are institutional mechanisms that are used to incentivize investments in generation to ensure generation adequacy. There exist a variety of possible mechanisms, including capacity subscriptions, reliability contracts, capacity payments and strategic reserves operated by the TSO. The

Netherlands does not currently have any form of capacity mechanism in place.

Another form of capacity strategy is the rules and procedures that drive investments in electricity transmission. Investments in many electricity systems, including the Dutch transmission system, have long been driven by a deterministic "n-1" or "n-2" planning criterion, which stipulates that the capacity of components in an electricity network must be sufficient to accommodate the failure of any one (or two) components. These planning criteria help to ensure system stability, also in the case of extreme weather events. However, it has been suggested that they may be insufficient in that they do not account for the *probability* of component failure (Li and Choudhury, 2007). When it comes to weather-induced failures, different types of extreme weather conditions will likely pose different risks to different (types of) infrastructure components. Wind poses a particular risk to overhead power lines in exposed areas. Flood poses a particular risk to substations and generation facilities located in low-lying coastal locations. Extreme heat poses a particular risk to thermal power plants in inland locations. These types of heightened risks are not accounted for in deterministic planning. For this reason, a *probabilistic* approach to transmission system planning has been proposed as a complement to the traditional deterministic approach (Li and Choudhury, 2007), and may be beneficial in helping the system to cope with extreme weather events in a changing climate.

Where capacity strategies can help to ensure a sufficient magnitude of capacity in generation and transmission, *decentralization strategies* can facilitate resilience by ensuring geographic dispersion of this capacity. Given that different types of extreme weather events may affect different geographical areas in different ways, decentralization of generation can help to ensure that geographically concentrated extreme weather events do not result in catastrophic power failures. One successful mechanism for supporting investments in distributed generation has been the German Renewable Energy Sources Act, which obliged grid operators to pay small-scale producers a fixed tariff. While decentralization of production by way of distributed generation may help to reduce vulnerability to extreme weather events, it can also introduce instabilities into the system, in particular due to the intermittent nature of renewable energy sources. These instabilities may also be exacerbated by extreme weather events – for instance, the sudden cut-out of wind turbines during extreme wind conditions can momentarily disrupt the balance of supply and demand (Lin et al., 2012).

Where decentralization strategies facilitate resilience by promoting geographic dispersion of power system assets, *diversification strategies* support resilience by ensuring technological diversification of the power generation portfolio. As suggested above, different types of extreme weather events may affect different generation technologies in different ways. A technologically diverse generation portfolio can help to reduce the risk of catastrophic failure under extreme weather conditions, and can help to limit fuel, electricity, and $CO_2$ price risks. The complementarity of solar photovoltaics and thermal generators during heat waves exemplifies the potential advantages of technological diversification under extreme weather conditions. However, the degree to which liberalized electricity markets stimulate technological diversification is questionable (Roques et al., 2008). For this reason, various mechanisms have been proposed to encourage technological diversity in generation, including feed-in tariffs and net metering to incentivize renewable investments and credit guarantees to incentivize nuclear investments (Roques et al., 2008).

It is important to point out, however, that none of these strategies – capacity strategies, decentralization strategies or diversification strategies – on their own are necessarily sufficient. Implementation of capacity strategies without efforts to decentralize and/or diversify generation – or vice versa – runs the risk of enhancing system resilience in the case of certain types of extreme events, while preserving or increasing vulnerability in the case of others. Ideally, capacity, diversification and decentralization strategies should complement one another in order to ensure that the system is resilient to a range of threats.

*Demand reduction strategies* entail mechanisms for encouraging long-term reductions in electricity demand. Given the significant role of the built environment in shaping the nature and magnitude of electricity demand, a key demand reduction strategy involves the implementation of incentives and standards to promote the design of new buildings and the retrofitting of existing buildings to reduce cooling demand. Such measures could include building codes or regulations, design guidelines or planning permissions (Mima et al., 2011). Current examples include the minimum energy performance standards established in the European Union's *Energy Performance of Buildings Directive* (European Parliament, 2003) and the *High Performance and Sustainable Buildings Guidance* of the US Department of Energy (US Department of Energy, 2008). A complementary set of mechanisms is air conditioning energy efficiency standards and labeling programs, such as the energy labeling scheme established by the *EU Energy Labeling Directive* (European Parliament, 2010)

## 4.5 Synthesis

In this chapter, we have sought to more precisely qualify the relationship between climate change and electricity infrastructures. In the first two sections, we explored the anticipated effects of climate change on weather patterns and sea levels. In the third section, we created an inventory of the anticipated effects of climate change on components of the electricity infrastructure. In the last section, we specified a typology of adaptation measures for dealing with these impacts. Before closing this chapter, it is useful to reflect on the relevance of the identified effects and adaptations within the specific context of *The Netherlands*. In terms of extreme weather events, projections suggest the following changes in the Netherlands:

1. More frequent and more intense extreme precipitation events (IPCC, 2012, 2013), both in the winter and the summer (Tank et al., 2014)

2. Less frequent and less intense cold temperature extremes (IPCC, 2012, 2013; Tank et al., 2014)

3. More frequent, intense and longer lasting hot temperature extremes (Beniston et al., 2007; IPCC, 2012, 2013; Tank et al., 2014)

4. Increases in extreme windspeeds, possibly complemented by an increase in the frequency and intensity of north-westerly storms with the potential to generate coastal storm surges (Beniston et al., 2007)

Next to these changes in extreme weather events, projections indicate a rise in sea levels of 15-40 cm by 2050, depending on the scenario (Tank et al., 2014).

What do these changes imply for the Dutch electricity infrastructure? Increases in the intensity of extreme precipitation events and storm surges, as well as the projected rise in sea levels, indicate towards an increased risk of flooding in coastal and riverine areas of the Netherlands. Insofar as such events may force the shutdown of thermal power plants or electrical substations, they represent an undeniable risk to these components. However, the degree to which such failures may result in network-level disturbances is unclear, as it may be highly dependent on the specific scenario and on the effectiveness of local flood defences. These aspects will be considered in the second part of this thesis.

The effect of anticipated increases in extreme windspeeds is uncertain. As described above, extreme winds may interact with overhead power lines via phenomena such as conductor galloping, downbursts and airborne debris. The exposure of the Dutch infrastructure to such events is significantly diminished by the fact that nearly all conductors of the distribution grid, and an increasing proportion of those of the transmission grid, are located below ground. Moreover, the anticipated reduced frequency of cold weather extremes may lessen the frequency of situations in which conductor galloping is likely. Potentially more relevant for the Dutch situation may be downbursts and extratropical cyclones. Given that such weather events are likely to occur with greater frequency and severity in the future (IPCC, 2007b), it is not unlikely that the frequency of wind-related failures may grow.

The threat of more frequent, more intense and longer lasting hot temperature extremes may be particular reason for concern. The Netherlands has experienced a handful of heat waves in recent years, and – while these events did not result in the same sort of catastrophic issues seen elsewhere in Europe – their consequences were not insignificant. Heat waves may be seen as a sort of "perfect storm" for electricity infrastructures – they cripple supply and reduce transmission capacity while simultaneously driving up demand. While artificial cooling currently comprises a relatively small proportion of electricity demand in the Netherlands – evidenced by the lack of a summer load peak – research by Hekkenberg et al. (2009) indicates a strong likelihood that this number will grow in the future. It is an open question to what degree the future Dutch infrastructure will be able to cope with such a situation. This will be addressed in the coming chapters.

The largest uncertainties associated with the electricity infrastructure impacts of climate change have to do with *indirect impacts*. Climate change may have a variety of effects beyond those discussed in this chapter – for instance on the structure and organization of social and ecological systems. These effects may in turn have tangible consequences on the functioning of the electricity infrastructure. Given in particular the dependence of the technical infrastructure's development and operational performance on highly developed forms of social organization – markets and regulatory systems – and its increasing dependence on the socio-technical infrastructures of other countries and regions, it is not unlikely that threats may emanate from these sources as well. For the most part, consideration of these aspects is beyond the scope of this study.

Options for adapting electricity infrastructures to cope with the effects climate change are numerous. They span from low-tech measures that are already widely used to high-tech dreams of a self-healing and self-regulating infrastructure. And they span from targeted technical investments to broad regulatory incentives. Moreover, it must be kept in mind that the consequences of many adaptations may extend beyond that of enhancing the infrastructure's climate resilience. Some adaptations may have negative side effects – e.g. demand-side management strategies may unnecessarily infringe on the privacy of consumers. Others may have positive co-benefits – e.g. widespread installation of distributed solar photovoltaics can reduce the carbon intensity of the electricity infrastructure. In many cases, the risks posed by anticipated changes in weather extremes may not be enough to incite the implementation of (potentially expensive) adaptation measures. For many actors in the electricity industry, the challenge of mitigation looms much larger than that of adaptation. In such cases, the promise of positive synergies may prove key to implementation. In the chapters that follow, particular attention is paid to such measures.

# Part II

# Case study 1

# Chapter 5

# Assessing infrastructure resilience

## 5.1 Introduction

This chapter introduces the first case study of this research. The purpose of this case study is to assess options for supporting the resilience of the Dutch electricity infrastructure to extreme weather events. As indicated in chapter 3, the scope of this case study is characterized by a focus on: (1) the electricity *transmission* infrastructure, (2) the *current* configuration of the infrastructure and (3) the geographic area of *the Netherlands*.

In this chapter, we describe the development of and experimentation with an *abstract model*. This model is abstract in the sense that it is *fact-free* – it is not informed by real-world infrastructure data, nor does it incorporate any factual knowledge of the relationships between meteorological variables and infrastructure components. The purpose of this model is (1) to generate improved understanding as to how the system in question can be effectively represented with respect to the scope and purpose of this case study, and (2) to arrive at a robust method for quantifying the notion of infrastructure resilience in the context of this research.

Before delving into the core content of this chapter, we define the requirements of the model to be developed. These requirements may be extracted from the set of requirements defined at the end of chapter 2, with certain items removed in order to reflect the limited scope of this case study. The model developed in this chapter must:

1. entail representation of the electricity infrastructure as a socio-technical system.
2. entail representation of the electricity infrastructure as a complex system.
3. entail representation of key climate change impacts on components of the electricity infrastructure.
4. be capable of representing and assessing the effects of measures to enhance infrastructure resilience.

## 5.2 Approach – resilience assessment

The model developed in this chapter builds on work in the area of *vulnerability assessment*, which may be defined as the process of identifying, quantifying and ranking the vulnerabilities in a system. Vulnerability assessment is an approach with a long history and has been applied to a wide range of domains, from supply chains (Chang et al., 2012) to ecosystems (Metzger et al., 2008) to infrastructures (Murray et al., 2004; Ten et al., 2008). In the study of infrastructures, the aim of a vulnerability assessment may entail either identifying and prioritizing vulnerable *system components*, or assessing *whole-system performance* under exposure to specific hazards or threats. The former of these aims is illustrated by a study of the climate change vulnerability of the Washington State transportation infrastructure (Washington State Department of Transportation, 2011), which employs vulnerability assessment to identify and rate the vulnerability of specific infrastructure assets such as rail lines, highway corridors and ferry terminals. The latter is illustrated by Haidar et al. (2006), who use vulnerability assessment to evaluate the system-level performance of an electricity infrastructure under different event contingencies.

Vulnerability assessment is just one of several approaches to assess infrastructures in the context of external threats. A second approach is *risk assessment*, which entails the quantification or qualification of risk associated with a given threat. Risk is normally defined in terms of two components: (1) the magnitude of the potential loss associated with a given threat, and (2) the probability that such a loss will occur. Due to its ability to explicitly account for uncertainty, as well as its shared theoretical underpinnings with economic analyses, risk-based approaches are often favored by decision makers, also in the context of climate change and infrastructures (Yohe, 2010).

Complementary to vulnerability and risk assessment is *resilience assessment*. Resilience assessment has been applied in different ways to evaluate infrastructures and other types of systems in the context of different threats (Francis and Bekera, 2014; Ouyang and Duenas-Osorio, 2012; Vugrin and Camphouse, 2011). While resilience assessments may take many forms, a unique component of many resilience assessment methodologies compared with vulnerability and risk assessment relates to *system recovery* – the return of a system to its previous state following a disturbance. Vugrin et al. (2011), for instance, introduce a framework for infrastructure resilience assessment based on two central components: (1) system impact and (2) total recovery effort. As defined by Vugrin et al. (2011), system impact relates to the magnitude of impact that a disturbance has on system productivity, and total recovery effort refers to the efficiency with which the system recovers from a disruption.

In this chapter, we adopt the approach and terminology of resilience assessment. Our purpose in employing this approach is to enable the evaluation of a broad range of measures for supporting infrastructure resilience to extreme weather events. In operationalizing this approach, we focus on the first component of resilience assessment – system impact. In doing so, we seek to align our approach with the definition of infrastructure resilience introduced in chapter 2 – the ability of an infrastructure to remain within a given basin of attraction upon exposure to a disturbance. This definition will be our departure point as we seek to develop a method for quantifying resilience for use in this research.

In adopting this approach to resilience assessment, we explicitly exclude the dimensions of recovery effort and probability. As such, our quantification of resilience should be viewed as a *vulnerability-based* estimate, rather than a comprehensive evaluation of resilience and risk. This limitation should be kept in mind in interpreting the results in this and subsequent chapters. We will address the implications of this limitation in more detail at the end of this chapter.

## 5.3 Model design

In order to capture both the social and the technical dimensions of the system in question, we design this model as a hybrid agent-based / power systems model with distinct but interacting social and technical subsystems. The elements and properties of the modeled system and its environment are outlined in Table 5.1.

### Representation of the social and technical subsystems

The social subsystem is reflected in the representation of three types of agents, together with certain key decision-making capabilities of each. These agents include *producers* of electricity, *consumers* of electricity and a *transmission system operator (TSO)*. These agents have been chosen as they reflect the key decision making entities with respect to the implementation of resilience-enhancing measures affecting the electricity transmission infrastructure.

The technical subsystem of this model is reflected in the representation of four types of electricity infrastructure components: *generators* (power production facilities), *loads* (power consumption facilities), *power transmission lines* and *power substations*. Together, these elements comprise a unified electricity infrastructure, with generators and loads linked by way of a network of transmission lines and substations. The components and configuration of the technical subsystem are illustrated in Figure 5.1. Each of the technical components represented in the model is controlled by a particular agent – producers control generators, consumers control loads and the TSO controls substations and power lines. In this initial model, each producer or consumer agent is defined to control a single generator or load, respectively. The precise nature of control exerted by each agent over his technical component(s) is described in more detail below.

The structure and properties of the technical subsystem are defined in accordance with the *IEEE 30 bus test case* (Christie, 1993a). IEEE power system test cases are standardized abstractions of certain real world power systems that have historically been used as cases for testing power systems analysis tools and techniques, including methods and algorithms for calculating optimal generator dispatch (Xie and Ilic, 2008), planning reactive power compensation (Fernandes et al., 1983) and identifying critical nodes in a power system (Nasiruzzaman et al., 2012). The IEEE 30 bus case represents a portion of the Midwestern US power system as of December, 1961. The purpose of utilizing the IEEE 30 bus case here is not to produce any specific insights with respect to the Midwestern US power system, but rather to enable a realistic technical representation of a generic power system. The IEEE 30 bus test case defines the following properties of the technical infrastructure represented in

Table 5.1: Elements included in the abstract model of case study 1 and their associated properties.

| Elements | Property | Description |
|---|---|---|
| **Elements of the social subsystem** | | |
| *Producers* | Producer-generators | The set of generators owned by the producer |
| *Consumers* | consumer-satisfaction | The degree to which a consumer's demand for power is met at a particular point in time |
| | consumer-demand | The default level of power demand of the consumer |
| | consumer-loads | The set of loads owned by the consumer |
| | Backup-generation? | Whether or not the consumer has an ability to shift to backup generation |
| *TSO* | TSO-substations | The set of substations owned by the TSO |
| | TSO-power-lines | The set of power lines owned by the TSO |
| | TSO-increase-capacity? | Whether or not the TSO has an ability to increase (double) line capacity |
| **Elements of the technical subsystem** | | |
| *Generators* | generator-number | The ID number of the generator |
| | generator-substation | The substation to which the generator is connected |
| | generator-power-output | The default real power output of the generator |
| *Loads* | load-power-demand | The power demand of a load |
| | load-power-received | The amount of power received by a load during a given timestep |
| | load-substation | The substation to which the load is connected |
| *Power lines* | line-load | The magnitude of real power flow across the line during a given timestep |
| | line-capacity | The maximum magnitude of real power flows that can be accommodated by a power line |
| | line-from-bus-number | The number of the first substation to which a line is connected |
| | line-to-bus-number | The number of the second substation to which a line is connected |
| | line-status | Whether or not the link has failed |
| *Substations* | substation-number | The ID number of a substation |
| **Elements of the environment** | | |
| *Extreme event* | extreme-event-magnitude | Number of lines directly affected (failed) as a result of the extreme event |

this model: (1) the configuration of loads, generators, substations and power lines – in other words, how many of each component exist and how they are connected with one another; (2) the default power demand of each load; and (3) the generation capacity of each generator.

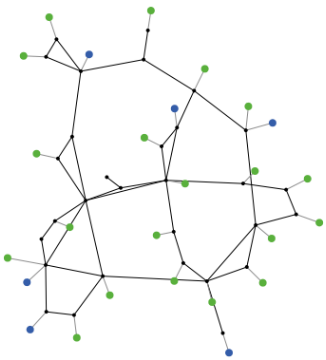

Figure 5.1: Image of the instantiated technical subsystem in the abstract model of case study 1. Blue circles represent generators; green circles represent loads; black dots represent substations; and black lines represent power lines.

## Model narrative

Each timestep during the course of a simulation (1 timestep = 1 day) consumers demand electricity and producers use their generators to supply this electricity. The amount of electricity demanded by each consumer is generally constant, set in line with the specifications of the IEEE 30 bus test case. The amount of electricity generated by each producer is set such that the combined output of all generation units equals the total demand of consumers, and such that each generator operates at an equivalent fraction of its capacity. Electricity is transported from producers to consumers by way of the network of power lines and substations, comprising an abstract power grid. The power flows through the lines in this network are calculated each timestep. These values can be conceptualized to represent the mean power flow magnitudes over the lines of the modeled infrastructure over the period of a single day.

Each timestep, there exists a certain probability of an *extreme weather event*. This event manifests itself in the failure of one or more power lines of the technical subsystem. In this abstract model, we do not specify what type of an extreme weather event this might be, nor the mechanism(s) of its interaction with the technical subsystem that may result in these failures. Two important and (purposely) unrealistic assumptions are made with respect to the occurrence of these events: (1) each timestep there exists a 50% likelihood that an extreme weather event will occur, and (2) the magnitude of events – expressed as the number of power lines failed – is uniformly distributed. In other words, at any given timestep, there is a 50% chance of an extreme weather event, and an equivalent probability that this event will result in the simultaneous failure of one line or 12 lines or 36 lines, etc. These probabilities have been chosen to facilitate the exploration of behavioral patterns across the state space of the modeled system, rather than to replicate real world conditions.

The failure of a line lasts one timestep. In other words, a line that fails during timestep 12 will be functional again (repaired) at the beginning of timestep 13. This makes each timestep effectively independent of the previous. While this designed lack of path dependency ignores certain aspects of reality, it is a sufficient approximation given the scope of this case study.

By inciting the failure of power lines, extreme weather events may affect the *performance* of the modeled infrastructure – defined here in terms of the system's capacity to meet the electricity demand of consumers. This may occur via several mechanisms. First, the direct failure of a power line due to an extreme weather event may cut off a load or generator from the remainder of the infrastructure, inhibiting the ability of (sufficient) power to physically reach one or more loads. Second, each line in the network has a set capacity, defined as the maximum amount of power it is able to transport during the course of a single timestep. The capacity of the lines in the modeled system are set to 10% above their load under default conditions – conditions in which no extreme event has occurred. This method of assigning capacities is intended to facilitate the exploration of behavioral patterns across the state space of the modeled system, rather than to replicate realistic processes of line capacity determination. When an extreme event has occurred, the direct failure of lines may result in a redistribution of power flows, causing the loads on other lines to exceed their set capacities and subsequently fail as well. This process may be iterative, with the overloading of one power line resulting in a further redistribution of power flows and subsequent failures. This is the classic dynamic of a cascading failure.

In order to mitigate the disintegration of the infrastructure, the agents in the system are endowed with the capability to implement two *adaptation measures*. These measures include (1) an ability on the part of the TSO agent to increase line capacity and (2) an ability on the part of consumer agents to switch to backup generation. The first of these measures involves an immediate increase in the capacity of each power line in the modeled system by 100% at the start of the simulation. The fact that it is the TSO agent who carries out this measure is practically inconsequential, but aligns well with our conceptualization of the system.

The second measure entails independent action on the part of consumers. This measure assumes that consumers have access to a source of backup generation that is capable of providing for the majority (75%) of their power demand. Upon experiencing a power shortfall equal to 50% of their demand or more, a consumer will temporarily (for one timestep) disconnect from the grid and switch to backup generation. By including these measures in the modeled system, we do not intend to imply that such mechanisms are feasible or desirable in the real-world. Rather, we use them here as a proxy for more realistic adaptation measures, some of which will be explored in the following chapter.

The performance of the modeled system is gauged in terms of the *fraction of demand served* – the proportion of power demanded by consumer agents that is actually received. This is determined based on the results of the power flow calculations, which provide the power injections to each node in the network, enabling us to discern the volume of power flowing to each consumer. In this manner, the fraction of demand served reflects the state of the network as well as the sufficiency of generation capacity at any point in time. The value of this metric varies between zero and one, with one indicating that all power demand has been fully met, and zero indicating that all power demand has gone fully *unmet*.

## 5.4 Software implementation

In order to adequately represent the dynamics and functionality of the social and technical subsystems, as well as the interactions between them, this model employs several pieces of software. The social subsystem is captured in the agent-based modeling platform Netlogo (Wilensky, 2012). The functionality of the technical subsystem is represented using the MATLAB-based power system simulation package Matpower (Zimmerman et al., 2011).

Runtime communication between these pieces of software is enabled by way of a custom-developed Netlogo extension, the *MatpowerConnect* extension. This extension takes as input the properties and configuration of a power system instantiated in Netlogo and provides as output data about real and reactive power power flows, and voltage magnitudes and angles, under the specified conditions. The extension uses Matpower's M-files for solving the power flow equations, but runs these files in the freely available, open source MATLAB clone *GNU Octave*. This run-time linkage of power systems software and social simulation software is a novel contribution of this research. By enabling a rich and combined representation of social and technical dynamics in relation to electricity infrastructures, we hope that this tool may offer benefit in other research contexts as well.

The MatpowerConnect extension consists of two key components. The first of these is a set of Java classes, which (1) opens a GNU Octave session, (2) translates the Netlogo inputs into a form understandable to GNU Octave, (3) passes these inputs to GNU Octave, (4) accepts outputs from GNU Octave, (5) passes these back to Netlogo and (6) closes the GNU Octave session. The second key component is a MATLAB M-file which accepts inputs from the Java classes and and calls on Matpower to solve the power flow equations. This M-file – *PowerFlowWrapper.m* – also adds an important layer of functionality to the MatpowerConnect extension by enabling the simultaneous processing of multiple networks. Upon receiving an input from Netlogo, PowerFlowWrapper.m first identifies and separates the constituent networks and processes these sequentially using Matpower. This means that multiple networks (or isolated components within a single network) can be effectively handled by the extension. While the above-noted Java classes are compressed into a JAR file, PowerFlowWrapper.m is uncompressed and can easily be edited by any user familiar with the MATLAB language. This allows users to modify and extend this code, and to take advantage of Matpower's advanced features, including AC power flow calculations and optimal power flow analysis.

In its current form, the MatpowerConnect extension imposes some limitations in performing power flow analyses. While Matpower is capable of performing both AC and DC power flow analyses, as well as optimal power flow calculations, the extension currently limits users to performing DC power flow analyses. The DC power flow problem is a simplified version of the AC problem which ignores the reactive power component of a power flow and assumes negligible line resistance. Under certain conditions, DC power flow analyses are less accurate than AC analyses. However, due to their nonlinear nature, AC power flow analyses are slower and are prone to non-convergence compared with DC analyses. In limiting the user to a DC power flow analysis, we have chosen the faster and more robust, but less accurate option.

The Netlogo file and the files of the MatpowerConnect extension can be downloaded here: https://github.com/ABollinger/MatpowerConnect

## 5.5 Experiments and results

We have performed a set of three experiments with the developed model. Each experiment consists of 100 model runs of 100 timesteps (days) each under identical parameter conditions. Since there is no path dependence in the model (the state of the modeled system is identical at the start of each timestep), each experiment can essentially be seen as 10,000 independent model runs. The difference between the experiments relates to which of the aforementioned adaptation measures is active:

- Experiment 1: No adaptation measures implemented
- Experiment 2: TSO increases line capacity
- Experiment 3: Consumers have the ability to switch to backup generation

How do disturbances of different magnitudes affect the behavior of the modeled system? Figure 5.2 shows the relationship between disturbance magnitude and two aspects of system behavior, aggregated across all 10,000 timesteps of each experiment (each point represents the results of one timestep). In the case of experiment 1, we observe a generally positive correlation between the magnitude of disturbance (expressed in terms of the number of lines directly affected by the disturbance) and the total number of lines failed. The nonlinearity of this relationship is due to the magnifying effect of cascading failures, in which a small disturbance alters power flow patterns in such a way that other lines become overloaded and subsequently fail. This pattern is also reflected in the relationship between fraction of demand served and the magnitude of disturbance, where we observe that relatively small disturbances may lead to large drops in the fraction of demand served.

In experiment 2, we observe a more linear relationship between the disturbance magnitude and the total number of lines failed, and between the disturbance magnitude and the fraction of demand served. In this case, the added line capacity serves as a buffer that reduces the occurrence of failure cascades, thus generally reducing the consequences of disturbances. It is important to point out, however, that the added capacity does not completely eliminate the occurrence of failure cascades. Under certain circumstances, the direct failure of one or more *critical* lines (due to the disturbance) may result in large redirection of power flows that overwhelms the capacity of alternative routes. Additionally, it is interesting to point out that this added capacity is most beneficial in the case of disturbances of low to moderate magnitude. In the case of events of high magnitude, the additional available capacity is not longer able to compensate for the direct failure of lines.

In experiment 3, we observe a relationship between disturbance magnitude and total lines failed that is essentially identical to that in experiment 1, suggesting that failure cascades play an important role here. Compared with experiment 1 we see a quite different relationship, however, between the disturbance magnitude and the fraction of demand served. While the network itself is quite fragile, the ability of consumers to switch to backup generation limits the downsides of this in terms of the fraction of demand served. Unlike the adaptation in experiment 2, this adaptation

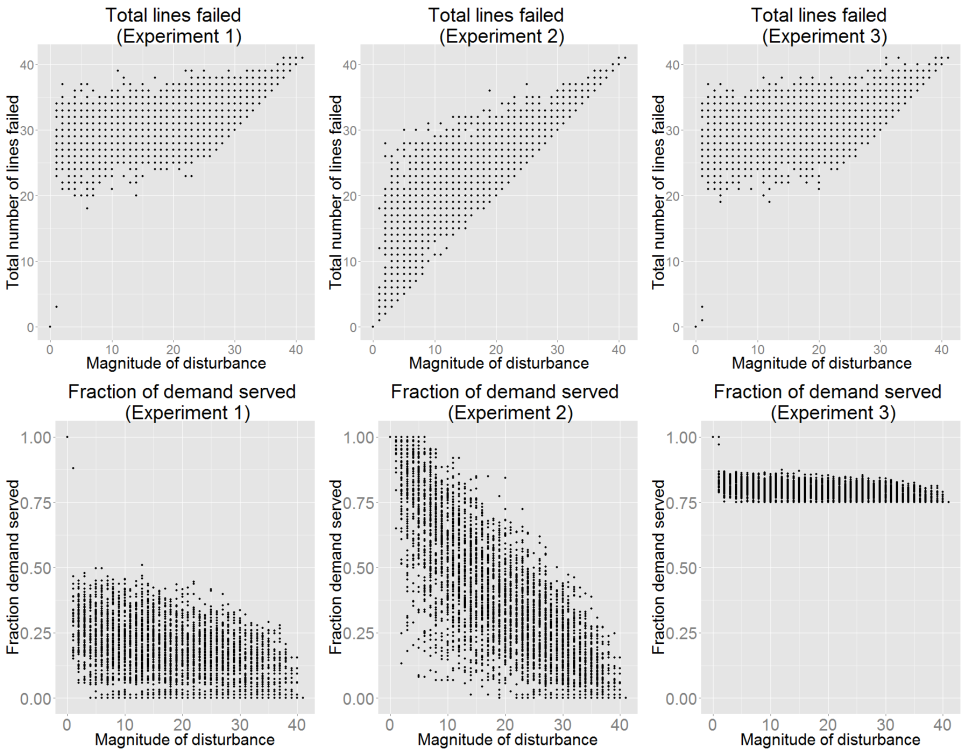


Figure 5.2: Relationship between magnitude of disturbance and the behavior of the modeled system across each of the experiments. Each point represents the results of a single timestep.

performs equally well under events of low and high magnitude. However, it is unable to completely mitigate the effects of low magnitude events – a notable capability of the adaptation in experiment 2.

Complementing the results in Figure 5.2, Figure 5.3 shows the fraction demand served vs. the mean magnitude of power flows. In the results of experiment 1, we see that the behavior of the system tends to cluster in four areas/points – a point characterized by high mean power flows and high fraction demand served, a point characterized by *slightly* lower mean power flows and fraction demand served and a pair of adjacent areas characterized by very low power flows and fraction demand served. In the results of experiment 2, we see that these very distinct clusters have disappeared, though we still see areas of higher and lower density. Again here, we observe a very clear positive correlation between mean power flows and fraction demand served, but less clear clustering of behavior along this trajectory. In the results of experiment 3, we see the re-emergence of essentially the same clusters that were visible in the results of experiment 1, though shifted in the direction of high fraction demand served. In fact, the fraction demand served does not drop below 0.75 in the third experiment.

Why do we see these patterns? The positive correlation between mean power flows and fraction demand served is logical. When all the lines in the system are functioning (none have failed), the system is able to fully meet the power demands

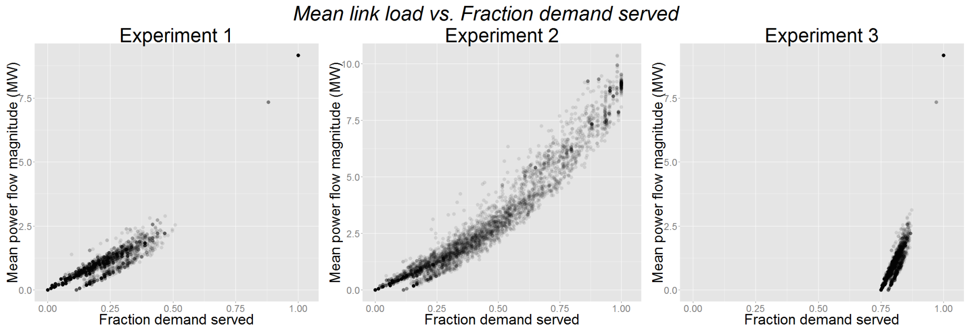


Figure 5.3: Mean power flows across the lines of the modeled system vs. fraction demand served for each of the three experiments. Each point represents the results at a single timestep.

of consumers by pushing relatively high volumes of power through the network from generators to loads. As the structural integrity of the system degrades, more and more consumers and generators are cut off from the network, reducing both the ability of the system to meet demand as well as the magnitude of power flows. The observed rightwards shift in the curve in the results of experiment 3 can be attributed to the adaptation measures taken by consumers, who shift to backup generation when their level of demand satisfaction drops below 0.75. The use of backup generation allows the system to maintain relatively high levels of consumer satisfaction even under conditions in which the network may be highly compromised.

The clusters observed in the results of experiments 1 and 3 may be attributed to the structural characteristics of the technical subsystem. As noted above, each power line of the modeled infrastructure is characterized by a particular capacity. If the power flows through the line exceed this capacity, the line fails. The failure of this line may furthermore incite the failure of other lines. The observed clustering occurs because of these recurring patterns of failure. This dynamic will be explored in more detail in the following section.

In this section, we have identified and explained some key aspects of the developed model's behavior under different circumstances. Our results show that the modeled infrastructure demonstrates a range of behavior in terms of both power flows and power delivery (fraction demand served). And they show that the implemented adaptation measures have a clear and significant effect on the behavior of the modeled infrastructure. Both of the tested measures produce a marked difference in the magnitude of power flows and the fraction demand served.

Though a highly abstract representation, the developed model allows us to explore the performance of an electricity infrastructure exposed to a generic set of disturbances, taking into account the distribution of demand and supply, the structure of the network and capacity constraints within the network. While the model captures (in an abstracted manner) the key dynamic of cascading failures, it does not explore other dynamic aspects, such as the recovery time following a disturbance, nor does it represent the elements that are responsible for these dynamics. This is an important limitation to keep in mind. In the next section, we will address possibilities for using the developed model to arrive at a quantification of infrastructure resilience in line with the definitions outlined in chapter 2.

## 5.6 Quantifying infrastructure resilience

In chapter 2, we introduced the notion of *infrastructure resilience*, which we defined as "the ability of an infrastructure to remain within a given basin of attraction upon exposure to a disturbance". In order to make the concept of resilience useful in the context of this research, it is essential that we redefine it in quantitative terms. In this section, we test several options for quantifying infrastructure resilience. Our aim is to arrive at a suitable metric for comparing different infrastructure configurations in terms of their performance under various extreme weather conditions. In the paragraphs that follow, we seek to draw from the results of the model introduced above to arrive at a method for quantifying resilience which is: (1) feasible to implement in the context of this study, (2) useful in the sense that it provides practical insight into the behavior of the system and (3) aligned with the aforementioned definition of infrastructure resilience. Before doing so, however, we return briefly to the notion of attractors.

### Identifying attractors in the behavior of the modeled infrastructure

The notion of an *attractor* was introduced in chapter 2 as "a set of points towards which a system variable tends over time". Given the centrality of this notion to the aforementioned definition of resilience, it is important, before seeking to quantify resilience, that we first assess the practicality of identifying attractors and bounding basins of attraction in the modeled system.

In theory, attractors may be found in any combination of variables of the modeled system – the demand of consumers, the power produced by generators, the distribution of power flows, etc. In the previous section, we identified a clear clustering of certain variables under certain conditions, indicating the existence of attractors in certain dimensions of the model's behavior. In this section, we begin with a hypothesis that attractors may be identified in the *patterns of power flow* of the modeled system. Each timestep of each run, each line of the modeled system is determined to transport a particular amount of power. The magnitudes of these flows are determined by the power flow equations and cascading failure algorithm embedded in the model's code, which in turn are fed by data describing the real-time distribution of supply and demand, the configuration of the network and the failed components.

On one hand, given the significant randomness embedded in the model, it seems logical to assume that a large degree of randomness may be visible in these patterns of power flow. This would be observable in the model results in the form of a large diversity of power flow magnitudes across the lines of the modeled system over the 10,000 timesteps of each experiment. On the other hand, it also seems feasible that the numerous relationships embedded within the system might generate feedbacks that drive power flow patterns towards particular regions of state space. This would be reflected in a more limited range of power flow magnitudes observed across the lines of the modeled system.

Which of these patterns do we see? To answer this question, we first look at several results from the first experiment. Figure 5.4 shows a histogram of the power flow magnitudes across two randomly selected lines of the modeled system, over all

10,000 timesteps of experiment 1. As these plots illustrate, we see a high frequency of occurrences at the highest and lowest magnitudes, and seemingly a handful of occurrences in between. This seems to indicate that the power flow magnitudes of these lines restrict themselves to only a handful of values/regions.

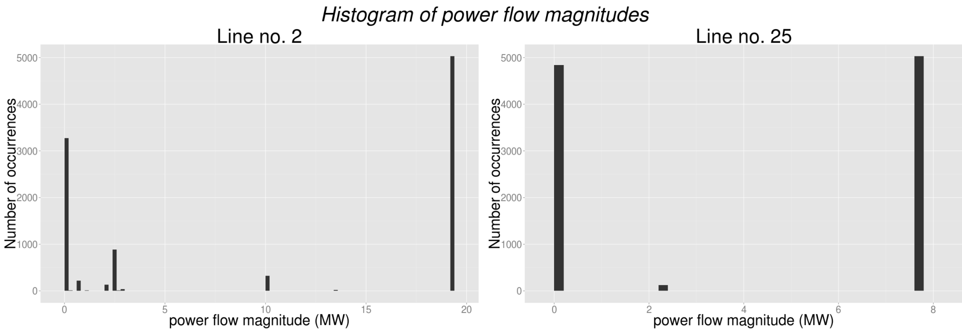


Figure 5.4: Histogram of power flow magnitudes across two randomly selected lines of the modeled infrastructure.

In order to more conclusively test this hypothesis, we now look at the full range of observed power flow magnitudes across *all* lines of the modeled system over all 10,000 timesteps of the first experiment. This is illustrated in Figure 5.5 (left panel). If the results were highly random, we would expect to see a plot filled with numerous (thousands of) black dots representing a range of power flow magnitudes across each line. Clearly, this is not what we see. The plot indicates that each line exhibits only a handful of characteristic power flow magnitudes. Some lines of the system exhibit a larger diversity of power flow magnitudes than others, but all feature a highly limited range possible states. This suggests that the system has a marked tendency to move towards a handful of regions in its state space – a set of clearly defined attractors expressed in the form of different patterns of power flow.

Why does the system exhibit this tendency? As discussed in chapter 2, attractors result from relationships and feedbacks within a system which cause it to gravitate towards particular areas of state space. An increase in nutrient levels in a shallow lake ecosystem past a particular threshold results in phytoplankton blooms which lead to a decrease in dissolved oxygen levels which reduce game fish populations which, in turn, affect phytoplankton levels. In the case of the developed model, these relationships are expressed in the form of *failure cascades* – the failure of one line automatically results in a chain of additional failures. Moreover, the precise patterns of these cascades seem to repeat themselves under a diversity of conditions, resulting in a limited range of possible power flow patterns.

Do we see similar regularities in the results of the other experiments? Figure 5.5 (center and right panels) shows similar results for experiments 2 and 3. While in the case of experiment 3 we see that the power flow magnitudes across most lines of the modeled system are limited to a handful of values, the results of experiment 2 exhibit much less regularity – the observed magnitudes span most of the range between the maximum and the minimum of each line. Why do we see this difference between the results of experiments 1 and 3, and those of experiment 2? As mentioned above, the regularity observed in experiment 1 is due to repeated patterns of cascading failure. Experiment 2 corresponds to a situation of vastly increased line capacities compared with the other two experiments. Due to these higher capacities, the direct failure of lines due to the occurrence of extreme events is less prone to drive the overloading of other lines – the key set of relationships driving the emergence of the previously observed regularity has been severed. As a result, clearly discernible basins of attraction no longer exist.

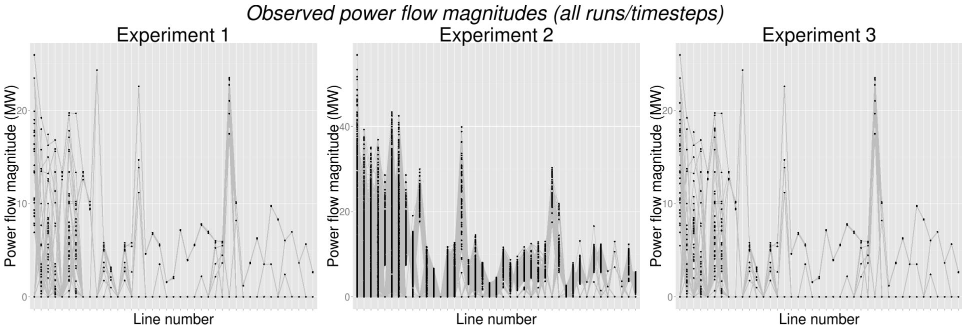


Figure 5.5: Power flow magnitudes occurring across all lines of the modeled infrastructure over all 10,000 timesteps of each experiment. Black dots represent an occurrence of a given power flow magnitude across a given line. Gray lines connecting two dots indicate that the associated magnitudes occurred during the same timestep.

The results of this analysis demonstrate that it is indeed possible to identify attractors in the output of the modeled system. Especially in the case of experiments 1 and 3, we are able to see clear tendencies of the system to move towards particular areas within the state space. We can thus confirm our hypothesis that attractors may be identified in the patterns of power flow of the modeled system. On the other hand, we have found that there are situations (experiment 2) in which clear attractors cannot be readily identified, at least within the context of the system's power flow patterns. We cannot necessarily claim that attractors do not *exist* in these cases. However, we can say that it is practically difficult to discern the boundaries between basins of attraction. In the following section, we address the consequences of this difficulty in terms of quantifying resilience in line with our current definition.

## Quantifying the resilience of the modeled infrastructure – method 1

If we adhere to our conceptualization of attractors as distinct patterns of power flow, our aforementioned definition of infrastructure resilience may be restated in more precise terms as follows: *the mean magnitude of a disturbance which causes the system to shift to a distinctly different pattern of power flow*. By seeking to quantify resilience in terms of a *magnitude of disturbance*, we align our definition with that of Holling (1973), who defines resilience as "the magnitude of disturbance that can be experienced before a system moves into a different state and different set of controls".

Using the results of experiment 1, this revised definition can be used to arrive at a quantification of the modeled infrastructure's resilience. By calculating the mean distance moved through state space – the mean change in power flows across each line in the modeled system – with each discrete increase in disturbance magnitude, we can identify shifts to distinct patterns of power flow. As illustrated in Figure 5.6 (left pane), we see a radical jump in movement through the state space – a shift in the qualitative pattern of power flows – in the results of experiment 1 at events of magnitude 1. Based on this, we can reasonably assert that the modeled infrastructure as represented in experiment 1 has a resilience of *1*. Or, more precisely, this suggests that the original basin of attraction of the modeled infrastructure – the basin characterizing the infrastructure in the absence of disturbance – features a resilience of 1. Theoretically, we could go on to define similar levels of resilience for each distinct basin of attraction identified to exist within the state space of the modeled infrastructure.

Before embarking on this task, however, it is important to step back and reflect – in light of our findings in the previous section – on the practicality of this method for quantifying infrastructure resilience. While this method is both in line with our stated definition of resilience and feasible to implement in the developed model, it suffers from an important limitation. Namely, it may not always be straightforward to objectively discern between "distinct" patterns of power flows. How large a leap through the system's state space constitutes a shift *between* basins of attraction, as opposed to movement *within* a given basin of attraction? Answering this question inevitably necessitates the subjective determination of a threshold magnitude of movement, potentially reducing the scientific and practical value offered by this method of quantification. For instance, looking at the mean change in power flows with each discrete increase in disturbance magnitude in the results of experiment 2 (Figure 5.6, middle pane), we do not see any clear points of transition to distinctly different power flow patterns. If we are to quantify resilience in a meaningful way, our method of quantification must be able to handle cases in which clear boundaries between basins of attraction do not exist.

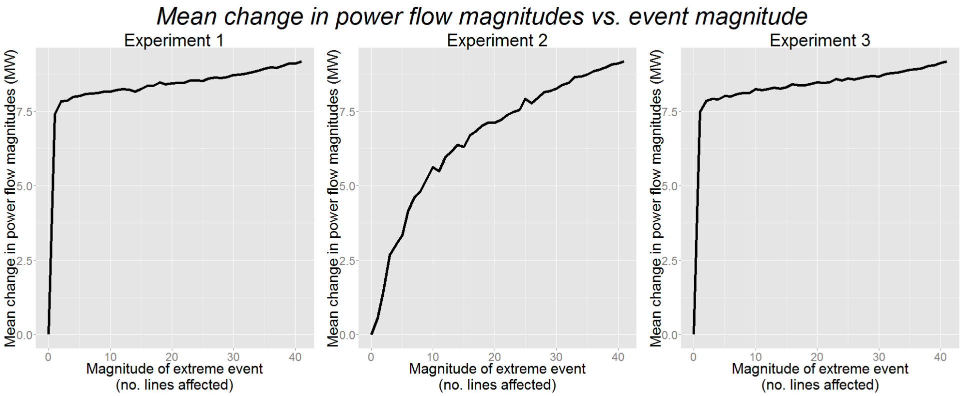


Figure 5.6: Mean change in power flow magnitudes across all lines of the modeled infrastructure with each discrete increase in event magnitude (relative to the zero magnitude case).

One way of sidestepping this difficulty is to quantify resilience in *absolute* terms – that is, in terms of the absolute movement of the system through state space resulting from a given disturbance. This method of quantification turns the previous one on its head – a system demonstrating *less* movement through state space under a given set of conditions would be deemed *more* resilient. As illustrated in Figure 5.6, the power flow patterns of the system represented in experiment 1 change drastically with disturbances of magnitude 1, and less drastically after that. The power flow patterns of the system represented in experiment 2 change steadily with increasing disturbance magnitude. And the power flow magnitudes of the system represented in experiment 3 change in a very similar way to those in experiment 1. By taking the mean of the change in power flow magnitudes across events of all magnitudes, we can express the resilience in terms of a single number, which comes out to 8.26 for experiment 1, 6.55 for experiment 2 and 8.26 for experiment 3.

This method of quantification is useful insofar as it allows us to describe in absolute terms how the behavior of the system changes with increasing disturbance magnitude. Moreover, we are no longer dependent on defining (potentially subjective) boundaries between basins of attraction. However, quantification of resilience exclusively in terms of power flow patterns has certain shortcomings. Most importantly, it ignores an important dimension of infrastructure behavior – the degree of service provision.

## Quantifying the resilience of the modeled infrastructure – method 2

Conceptualizing the resilience of the modeled system in terms of changes in power flow patterns is undoubtedly useful, as it can allow us to discern between different "modes of operation" of the system. However, infrastructures are constructed and operated for the express purpose of providing a particular *service* to humans – electricity infrastructures provide electricity; drinking water infrastructures provide drinking water. If our quantification of resilience ignores this pertinent dimension of infrastructure behavior, it risks practical irrelevance. Quantifying resilience in terms of power flow patterns exhibits this shortcoming.

Moreover, quantifying resilience exclusively in terms of power flow patterns may limit our ability to evaluate the effects of certain types of adaptations. Namely, a network-based metric will not work in evaluating non-network measures, for instance that evaluated in experiment 3. This can be observed in Figure 5.5, which portrays a similar power flow profile for experiments 1 and 3, despite significant and meaningful differences system configuration and behavior. A method that captures the degree of service provision is essential to enabling the effective comparison of different infrastructure configurations.

In order to address these shortcomings, we describe here an alternative method of quantifying resilience which makes use of the system performance metric defined above – the *fraction demand served*. To reiterate, this metric describes the degree to which the electricity demand (in terms of real power) of consumers in the modeled system is met under the given conditions. In other words, it quantifies the *degree of service provision*, exactly that aspect which was missing from our previous method of quantification. The degree of service provision of an infrastructure could also be quantified in other ways, e.g. in terms of the stability of voltage, the number of customers without power or the mean duration of service outage. Quantification in terms of fraction demand served, however, is readily measured in the developed model and is sufficient for the purposes of this research.

Figure 5.7 shows the mean fraction demand served (system performance) for events of each possible magnitude for the infrastructure configurations represented in each of the three experiments. As these plots illustrate, each infrastructure configuration exhibits a different pattern of performance degradation. The configuration in experiment 1 shows a highly nonlinear pattern of degradation, with performance severely degraded even after an event of magnitude 1. The configuration in experiment 2 shows a more linear pattern of degradation, with performance decreasing steadily with increasing event magnitude. The configuration in experiment 3 also shows a highly nonlinear pattern of degradation, similar to that in experiment 1, but bottoming out at a fraction demand served value of 0.75.

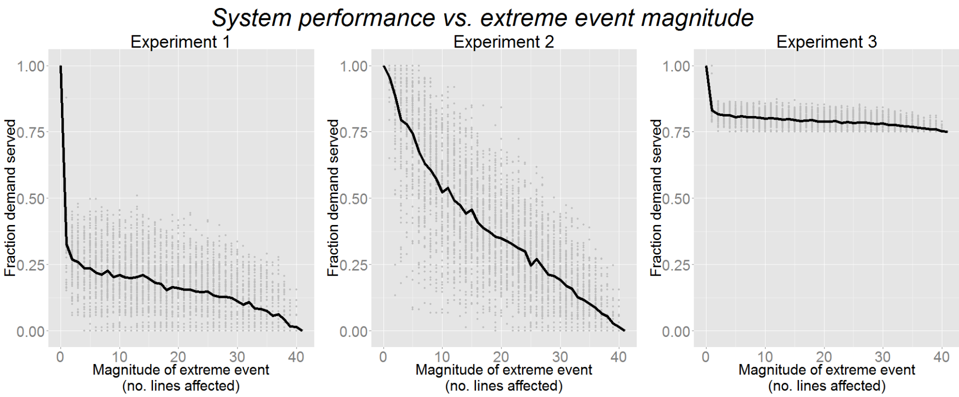


Figure 5.7: Fraction demand served in the modeled infrastructure for each possible extreme event magnitude. The black line illustrates the development of *mean* fraction demand served with increasing event magnitude. Gray dots represent the *individual* recorded values of fraction demand served at each event magnitude.

In some cases, the plots in Figure 5.7 may not suffice to convey the resilience of the modeled system in a sufficiently compressed manner. It would be more useful to be able to express the resilience of a system in the form of a single number. There are several possibilities for doing this, the simplest of which would be to define resilience as the *mean* fraction demand served across events of all possible magnitudes. For the infrastructure represented in experiment 1, this comes out to 0.17. For that in experiment 2, it is 0.38. For that in experiment 3, it is 0.79. From this perspective, we could reasonably claim that the infrastructure represented in experiment 3 is the most resilient of the tested configurations.

Compared with the method of quantification described in the previous section, the method described here demonstrates the advantage that it incorporates the key aspect of *degree of service provision*. No longer are we just describing changes in the system's "mode of operation", but rather the degree to which the system fulfills the function for which it was designed and built. However, this method of quantification, too, is not without its shortcomings. Most importantly, it treats events of different magnitudes as equally likely. While this assumption holds in the case of the model described here, it is usually not the case. In the next section, we introduce a third method of quantifying resilience which seeks to address this shortcoming.

## Quantifying the resilience of the modeled infrastructure – method 3

In the model introduced in the first part of this chapter, extreme events of all magnitudes were considered equally likely. It was deemed equally probable that an event would result in the failure of 2 lines as it was that an event would result in the failure of 15 lines. While we have thus far not specified the *type* of extreme weather event causing these failures, it is safe to assume that events of larger magnitude will occur with less frequency than those of smaller magnitude. If our method of quantifying resilience is to serve as a useful tool in supporting desired infrastructure qualities in the face of (meteorological) disturbances, it seems logical that this method should account for this aspect of reality.

It has been well established that many types of natural disasters – including earthquakes, tornadoes, hurricanes and floods – generally follow what is known as a *power law* size-frequency distribution. Adherence of these phenomena to such a distribution implies that the frequency of the event varies as a power of its magnitude:

$$f(x) = c \times x^{\lambda}$$

where $x$ is the event magnitude, $c$ and $\lambda$ are constants, and $\lambda$ typically has a negative value. The value of $\lambda$ in this equation determines how rapidly the frequency of events deteriorates with increasing event magnitude. Studies in the United States have shown that hurricanes feature a $\lambda$ of approximately -0.58, tornadoes of -1.39 and floods of -1.35 (Barton and Nishenko, 2013).

If we assume that the magnitude of an event is directly correlated with the number of failed power lines, we can can reasonably apply a power law size-frequency distribution to account for the effects of different magnitude frequencies. Choosing the arbitrary values of $c = 0.5$ and $\lambda = -0.5$ and artificially setting size zero frequency to 0.99, we arrive at the size-frequency distribution illustrated in Figure 5.8. After normalizing the values within this distribution (by dividing them by the mean frequency), we can multiply them by the respective system performance values illustrated in Figure 5.7 to arrive at a *frequency-adjusted* representation of system resilience.

As in the previous section, we can compress the information in these plots to a single number for each experiment by calculating the mean value across events of all possible magnitudes. This produces values for the three experiments of 0.31 (experiment 1), 0.57 (experiment 2) and 0.83 (experiment 3). As these values demonstrate, this approach to quantification has the effect of increasing the resilience values observed in all the experiments compared with the previous method, as well as reducing the spread between these values.

Relative to the previous methods of quantifying resilience, the method described here offers the advantage that it accounts for differing frequencies of events of different magnitudes. This advantage may be highly relevant in practice, where financial limitations demand that resources be distributed efficiently. Moreover, this method can more explicitly account for the effects of a changing climate, which may be represented as a shifted or skewed size-frequency distribution for certain types of extreme weather events.

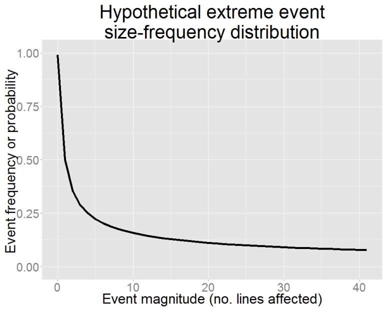


Figure 5.8: Hypothetical size-frequency distribution of extreme events, based on a modified power law relationship.

## Quantifying resilience – summary

In this section, we have highlighted three methods for quantifying the resilience of the modeled infrastructure. As stated above, we have sought to define a method which is (1) feasible to implement in the context of this study, (2) useful in the sense that it provides practical insight into the behavior of the system and (3) aligned with the definition of infrastructure resilience introduced in chapter 2.

Our attempt to identify attractors in the behavior of the modeled infrastructure demonstrated a difficulty in arriving at a method of quantification fulfilling the third of these criteria. Namely, it highlighted the challenge under some conditions of discerning the boundaries between different basins of attraction. In our first method, we sought to deal with this challenge by quantifying resilience in terms of the *absolute* movement of the system through state space. This allowed us to successfully enumerate the resilience of the infrastructures represented in each experiment. The results suggested that the infrastructure represented in experiment 2 is the most resilient.

In our second method, we sought to address a shortcoming of the first in terms of its neglect of the key aspect of *service provision*. Instead of quantifying resilience in terms of patterns of power flow, we chose here a quantification based on the *fraction demand served* at each possible event magnitude. Results using this method suggested that the infrastructure in experiment 3 is (by far) most resilient. The third method of quantification entailed a modified form of the second and sought to capture the additional dimension of *frequency-size distribution*. Results using this method of quantification were found to be similar to those using the second method, but suggested less spread between the resilience of the infrastructures represented in the different experiments. For clarity and reference purposes, we summarize these methods in Table 5.2[1].

All of the developed methods fulfill the defined criteria to some degree, though none is ideally suited to serve as a sole method of quantification in the context of this study. The first method neglects the aspect of service provision; the second neglects the aspect of event frequency; the third is slightly less feasible due to its requirement

[1]The equations in this table assume that the minimum possible magnitude of extreme events is zero. The normalized frequency referred to in method 3 is defined as the frequency of an event divided by the mean frequency of events of all possible magnitudes.

of a size-frequency distribution data, which may not always be available.

Additionally, it is important to recognize that the requirements for the developed model and tested quantification methods leave out certain pertinent elements and determinants of infrastructure resilience. For instance, neither the model nor the tested quantification methods capture the dynamics of infrastructure recovery. Moreover, the developed model leaves out financial and regulatory aspects, which may be key in determining which adaptations are financially and institutionally feasible and/or beneficial.

Table 5.2: Summary of resilience quantification methods introduced in this chapter.

| |
|---|
| **Method 1:** Resilience is the *mean change in power flow patterns across the range of possible extreme event magnitudes* $$R_I = \sum_{m=0}^{M} \frac{\sum_{n=1}^{N} \lvert P_{n_m} - P_{n_0} \rvert}{M}$$ where: $R_I$ is the resilience of the infrastructure, $m$ is the extreme event magnitude, and $P_{n_m}$ is the power flow magnitude over power line $n$ under conditions of an extreme event of size $m$. |
| **Method 2:** Resilience is the *mean fraction demand served across the range of possible extreme event magnitudes* $$R_I = \frac{\sum_{m=0}^{M} \Theta_m}{M}$$ where: $R_I$ is the resilience of the infrastructure and $\theta_m$ is the mean fraction demand served under conditions of an extreme event of size $m$. |
| **Method 3:** Resilience is the *mean change in frequency-adjusted fraction demand served incited by the range of possible extreme events* $$R_I = \frac{\sum_{m=0}^{M} f_m \times \Theta_m}{M}$$ where: $R_I$ is the resilience of the infrastructure, $f_m$ is the normalized frequency of events of magnitude $m$, and $\theta_m$ is the mean fraction demand served under conditions of an extreme event of size $m$. |

## 5.7 Synthesis

This chapter has described the design, implementation and analysis of an abstract model with the dual purpose of:

1. Generating improved understanding as to how the system in question can be effectively represented with respect to the scope and purpose of this case study.

2. Arriving at a robust method for quantifying the notion of infrastructure resilience in the context of this research.

With respect to the first purpose, the developed model represents the electricity infrastructure as a socio-technical system exposed to and capable of reacting to (extreme weather) disturbances emanating from its environment. We have shown that the chosen manner of representation is capable of capturing key aspects of infrastructure behavior, such as cascading failures, and is capable of incorporating and demonstrating the effects of various adaptation measures. From this perspective, the constructed model offers a solid starting point for proceeding with the development of a more realistic, fact-driven model, described in the next chapter. While incorporating aspects of both the social and technical dimensions of the infrastructure, the developed model's treatment of the social subsystem is very limited, a decision driven by the scope of this case study. This model and the software implementation used, however, provide a solid basis for developing the social dimension further.

With respect to the second purpose, we have used the developed model to arrive at several methods for quantifying resilience. These methods are summarized in Table 5.2. Each method demonstrates certain strengths and weaknesses, with none in isolation offering a sufficient form of quantification with respect to our stated requirements. For practical reasons, we will only apply the second method in the remainder of this case study, and in the subsequent case studies.

The modeling approach and quantification methods developed in this chapter have dealt with the resilience of the infrastructure to extreme weather events. In the context of climate change, this approach and these methods may be used to explore how changes in the frequency and severity of extreme weather events may affect infrastructure performance. Moreover, they may be used to explore how specific adaptation measures and/or other infrastructure developments may affect the resilience of the infrastructure to extreme weather events. In this context, the developed modeling approach and quantification methods may help to guide infrastructure planners and managers in preparing the electricity infrastructure for the effects of climate change.

However, the limitations of this approach should be kept in mind. As stated at the beginning of this chapter, the results based on this approach should be viewed as vulnerability-based estimates of resilience, given the exclusion the key aspects of recovery dynamics and probability. In this context, the developed approach may be effectively used for the rapid evaluation and identification of promising measures or system developments for further study amongst a range of possibilities. It is not currently suited, however, to generating definitive and comprehensive evaluations of specific investments. Extensions of the approach to incorporate these excluded aspects may help to alleviate this limitation, but are beyond the scope of the current study.

This chapter has focused on the notions of infrastructure vulnerability and resilience, and has not further addressed nor sought to quantify the notion of infrastructure *adaptability*, which was also introduced in chapter 2. Before closing this chapter, it is worth briefly reflecting on the consequences of our findings in this chapter in terms of our understanding of infrastructure adaptability. Compared with resilience, adaptability entails an explicit recognition that the social elements of an infrastructure may exert some control over the attractors that exist and the attractors to which the system may shift under different conditions. And it reflects the idea that managed shifts between attractors may be desirable insofar as they can help to preserve a higher level of system performance than might otherwise be feasible. This phenomenon was observed in experiment 3, in which consumer agents independently shifted to a backup energy source when service provision dropped – essentially shifting the system as a whole towards an alternate attractor.

The potential difficulties associated with discerning between basins of attraction do not mean that adaptability is necessarily an irrelevant concept in the context of this study. In fact, the multiple methods of quantifying resilience which we have defined above may help us to identify cases in which the system demonstrates adaptability, which in turn can help us to identify measures for *supporting* adaptability. Likewise, the difficulties with discerning between basins of attraction do not necessarily mean that the notion of attractors itself is wholly irrelevant. In cases in which clear attractors can be distinguished, knowledge of the conditions leading to the emergence of these attractors can help us to develop more targeted intervention strategies for supporting resilience. As we move forward over the coming chapters, these are important possibilities to keep in mind.

# Chapter 6

# Assessing the extreme weather resilience of the Dutch transmission infrastructure

## 6.1 Introduction

As a low-lying coastal country situated at the mouth of three major European rivers, the Netherlands may be particularly exposed to certain effects of a changing climate. Historically, the electricity infrastructure of the Netherlands is one of the most reliable in Europe, and has proven relatively invulnerable to extreme weather events. In 2012, weather was cited as the primary cause of only 0.6% of total interruptions (Netbeheer Nederland and Movares Energy, 2013). Still, the Dutch electricity infrastructure is far from impervious to the effects of extreme weather (KEMA, 2010; Stedin, 2012; Tennet, 2014), and climate change may exacerbate these effects.

How may long-term changes in weather extremes affect the vulnerability of the Dutch electricity infrastructure, and what measures can effectively support infrastructure resilience? In addressing these questions, historical data is an insufficient guide, as the infrastructure is constantly developing, and past meteorological conditions may not accurately reflect the range of future possibilities. Moreover, it is insufficient to deal with the infrastructure as a set of isolated components, as its interconnectedness may play an important role in affecting its resilience (Bollinger et al., 2014) – disturbances in one corner of the system may have far-reaching impacts elsewhere within the system.

This chapter describes the second part of the first case study of this research. Here, we present the results of a model for assessing the resilience of the Dutch electricity infrastructure to extreme weather events. The starting point for this model is a representation of the current Dutch electricity infrastructure, including major generators, transmission lines, substations and distribution grids, as well as the manner in which these components are interconnected. The model represents key sensitivities of these components to extreme weather events, as well as the processes by which weather-induced disturbances may propagate through the network in the form of cascading failures. In performing this assessment, we focus on two types of extreme weather events with particular relevance to the Dutch situation – *floods* and *heat waves*.

We continue in the next section with a description of the focal system of this chapter – the Dutch electricity infrastructure. After this, we introduce the technique of *structural vulnerability analysis* – used as a basis for developing a model to address the questions above – and summarize the design and software implementation of the developed model. Finally, we present the results of the developed model in the form of an assessment of the proposed measures, utilizing the metric developed in the previous chapter.

## 6.2 System description – the Dutch electricity infrastructure

In this section, we describe the focal system of this chapter – the Dutch electricity infrastructure – in terms of both its technical and its social subsystems. The Dutch electricity infrastructure is responsible for delivering electricity to approximately 8.1 million customers spread throughout the geographical area of the Netherlands (Energie-Nederland and Netbeheer Nederland, 2011). In 2010, annual electricity consumption in the Netherlands amounted to approximately 109 TWh, with a peak transmission grid load of about 14.7 GW (Energie-Nederland and Netbeheer Nederland, 2011). On the technical side, the infrastructure is composed of dozens of large generation facilities complemented by numerous smaller-scale fossil-fuel- and renewables-based installations. Nearly all consumers and generation facilities are connected to a centralized grid, composed of nearly 310,000 km of lines and including hundreds of distribution grids linked by a transmission grid, which itself is linked with the grids of several neighboring countries (Energie-Nederland and Netbeheer Nederland, 2011). On the social side, the infrastructure is composed of numerous actors, including consumers, producers, retailers, distribution system operators and a single transmission system operator. In the paragraphs that follow, we describe in more detail the socio-technical composition and operational aspects of the Dutch electricity infrastructure.

### The technical subsystem

As of 2010, electricity generation in the Netherlands comprised 42 generators with a production capacity greater than 60 MW (Energie-Nederland and Netbeheer Nederland, 2011), as well as numerous smaller generators. Compared to other countries in Europe, combined heat and power (CHP) facilities are quite common in the Netherlands, providing for about 32.5% of total production (European Environment Agency, 2012). The majority of Dutch CHP production takes place in the context of the chemical and greenhouse industries. The current technological composition of the Dutch generation portfolio comprises approximately 16.5 GW natural gas-fired power plants, 5.9 GW coal-fired power plants, 2.4 GW wind and 0.5 GW nuclear (European Wind Energy Association, 2013; TenneT, 2013b). The largest power plant in the Netherlands is currently the Eemscentrale in Eemshaven with a nameplate capacity of 2400 MW (Enipedia, 2014).

The majority of electricity produced in the Netherlands is used for commercial and industrial purposes, with household consumers comprising approximately 24% and heavy industry approximately 28% of total consumption (Energie-Nederland and Netbeheer Nederland, 2011). Between 2000 and 2010, growth in electricity demand in the Netherlands amounted to approximately 1.1% per year (Energie-Nederland, 2012). Electricity consumption in the Netherlands generally peaks in the cold, dark winter months, with the peak load on the grid usually occurring in December or January (Energie-Nederland, 2012). On a daily basis, demand in the Netherlands generally peaks in the early evening hours (around 17:00) and dips during the night (TenneT, 2013c).

The components of the Dutch electricity grid can be divided into a transmission system and a distribution system. As of 2010, the transmission system included 8,829 km of lines operating at four different voltage levels – 110 kV, 150 kV, 220 kV and 380 kV (Energie-Nederland, 2012). Most of the transmission system in the northern part of the Netherlands operates at 110 and 220 kV, with the system in the remainder of the country operating at 150 and 380 kV. The reason for this difference has to do with the historical development of the grid, and nowadays 380 kV lines are slowly replacing their 220 kV counterparts. The distribution system of the Netherlands comprises approximately 145,000 km of lines contained within 238 distribution grids operating at voltages of 0.4 kV to 50 kV (Energie-Nederland, 2012; TenneT, 2009). While many lines of the transmission grid are above ground, nearly the entire length of the distribution system (99.88% as of 2007) is underground (Energie-Nederland, 2012), making this system less susceptible to meteorological circumstances.

The Dutch electricity infrastructure is linked with the infrastructures of neighboring countries by way of a handful of extra high-voltage interconnectors. These interconnectors link the Dutch grid directly to the grids of Germany, Belgium, the United Kingdom and Norway. Amongst these countries, the most interconnection capacity is with Germany, with three interconnectors comprising a total of 4,715 MVA of interconnection capacity (TenneT, 2009). An additional interconnector with Germany is currently under construction. In all years between 2000 and 2010, the Netherlands was a net importer of electricity, with an average net import volume of 15.2 million MWh per year (Energie-Nederland, 2012).

## The social subsystem

The social subsystem of the Dutch electricity infrastructure and its links with the technical subsystem are illustrated in Figure 6.1. The largest electricity producers in the Netherlands are currently GDF-Suez, E.ON Benelux, EPZ, Essent/RWE and Nuon. The largest of these in terms of generation capacity is GDF-Suez, with a total capacity in the Netherlands of 4,549 MW (GDF-Suez Nederland). There are a handful of distribution system operators (DSOs) in the Netherlands, including Liander, Stedin, Enexis, Westland Infra, DELTA and others. These DSOs tend to operate in geographically distinct areas, with Enexis and Liander covering most of the North, Stedin covering most of South Holland, Enexis covering most of the Southeast and DELTA covering much of Zeeland. The Dutch transmission grid is owned and operated by TenneT, which itself is fully government owned and is the only transmission system operator (TSO) in the Netherlands. As of January 2010, TenneT also owns and operates a large portion of the German electricity transmission grid.

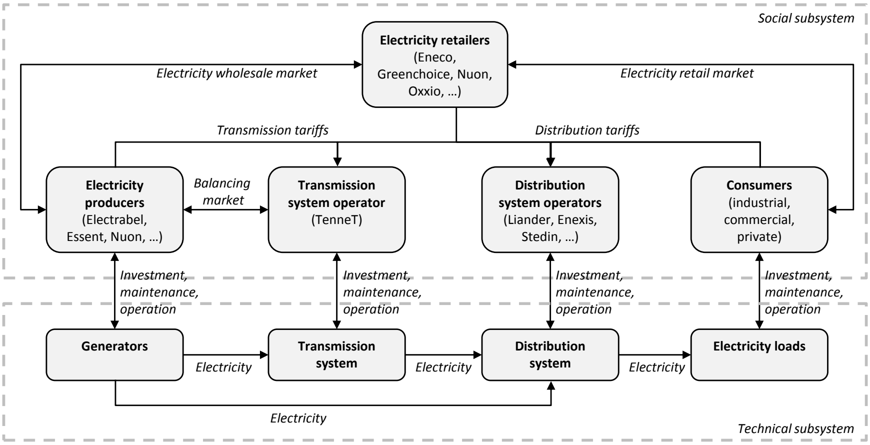


Figure 6.1: Current socio-technical structure of the Dutch electricity infrastructure.

The Dutch electricity market was liberalized in 2004, which has resulted in a separation of ownership between the processes of electricity generation and transport as well as many new market entrants. The operation of the Dutch electricity infrastructure is facilitated by way of several markets, including the electricity retail market, electricity wholesale markets and balancing markets. Wholesale trading in electricity in the Netherlands occurs via several mechanisms, including bilateral contracts, over-the-counter (OTC) contracts and spot market exchanges. Bilateral contracts entail direct contracts between producers and retailers, whereas OTC contracts involve the trading of standardized quantities of electricity via brokers. Spot exchanges of electricity take place within the APX day-ahead and intra-day markets, and futures trading takes place within the power derivatives exchange ENDEX.

The electricity balancing market is intended to ensure that supply and demand of electricity are in constant balance. Each day, the Dutch TSO compiles an "energy programme" which summarizes the electricity transactions planned for the next day. Differences between the energy programme and actual measured volumes constitute a system imbalance. In order to resolve such imbalances, the TSO dispatches *balancing power* – positive volumes in case of shortage and negative volumes in case of surplus.

Balancing power dispatched by the TSO falls into three categories – reserve power, regulating power and emergency power. *Reserve power* comes in the form of spinning reserve – capacity that can may be immediately activated (or deactivated) to restore a power imbalance. Control of primary reserve power is enabled by automated devices on large-scale production equipment (greater than 5 MW) and is used to automatically resolve short-term imbalances (TenneT, 2013). Secondary and tertiary balancing are used to resolve successively longer-term imbalances. *Regulating power* takes the form of production (or consumption) capacity offered directly by market actors to the TSO in real time. *Emergency power* is a last resort form of balancing power, called upon by the TSO in order to restore system balance when insufficient regulating and reserve capacity is available (TenneT, 2013a). Emergency power is normally provided by dedicated generators and/or load curtailments, or by neighboring TSOs.

## Proposed adaptations

The Dutch electricity infrastructure is already well protected in numerous ways from extreme weather events. Many lines of the transmission system, and nearly all lines of the distribution system are underground. Moreover, many of the largest thermal generators are located in coastal areas, and several inland generators are equipped with cooling towers. Despite these and other existing measures, the Dutch electricity infrastructure remains vulnerable to certain types of extreme weather events. In this chapter, we assess the effectiveness of two types of adaptation measures – enhanced flood protections at key transmission substations and a demand-side management mechanism. The paragraphs below describe these proposed measures in more detail.

Primary (electricity-carrying) components of substations in the Dutch transmission system are generally protected to an on-site water depth of 2.5 meters[1] (Wester, 2013). While in many instances this degree of protection may suffice to preserve substation functionality under the full range of possible flood scenarios, in other instances it may not. One possible form of adaptation involves the outfitting of substations located in flood prone areas with enhanced flood defenses. Measures may include, for instance, the construction of dikes to surround vulnerable substations, the elevation of sensitive equipment above anticipated peak water levels or the repositioning of substations to higher ground. Regardless of the exact mechanism, the essential effect of such measures is to raise the critical water level – the on-site depth above which primary equipment may be affected. The first set of proposed adaptations addressed in this chapter involve the implementation of such measures for substations vulnerable to high water levels.

As noted above, electricity demand in the Netherlands varies in a generally predictable way both seasonally and daily, peaking in the winter and in the afternoon/evening and dipping in the summer and during the night. In the case of critical generation shortages that threaten the ability of the system to supply for this demand, the TSO has several measures at his disposal. These include, for instance, the contracting of emergency power and load shedding. Another measure not currently widely employed in the Netherlands is that of *demand-side management*, which encompasses a range of incentive mechanisms to encourage specific modifications in demand patterns. These measures may take many forms, such as time-of-use pricing, demand bidding and direct load control. As described in chapter 4, such mechanisms have been successfully deployed on a small scale in several places around the globe. In this chapter, we explore the effectiveness of various demand-side management measures for enhancing the heat wave resilience of the Dutch electricity infrastructure.

[1] Secondary components, including those necessary for servicing and control purposes, are generally protected only to a height of one meter.

## 6.3 Technique – structural vulnerability analysis

The model described in this chapter employs the technique of *structural vulnerability analysis*, a technique that assesses how the successive removal of nodes/edges from a network affects its performance. Structural vulnerability analysis has been widely employed in the study of power systems, for instance to study the effects of random failures vs. targeted attacks on system performance (Albert et al., 2004; Chen et al., 2009; Holmgren, 2006; Rosas-Casals et al., 2007; Wang and Rong, 2009). Our implementation of this technique builds on the modeling approach described in chapter 5.

Ideally, a technique for studying the resilience of an infrastructure to extreme weather events should account for: (1) the full range of possible extreme event scenarios, (2) the effects of each scenario on the performance/functionality of each infrastructure component and (3) the consequences of these component-level effects on the performance of the infrastructure as a whole. Accounting for all of these aspects adequately, however, entails an enormous if not insurmountable degree of complexity. In the case of floods, for instance, there exists a nearly infinite range of possible event scenarios, ranging from coastal dike breaches to riverine overflow to heavy rainfall, each of which may occur at numerous geographical locations. Moreover, each of these scenarios may entail a different set of impacts on infrastructure components, depending on the topographical contours of the area and the severity of the event.

In order to manage the complexity of our modeling task, we choose in this chapter not to represent extreme weather events directly, but rather in terms of their consequences on the performance of infrastructure components. A flood scenario, for instance, is represented in terms of its effects on particular substations, and a heat wave scenario is represented in terms of its effects on specific generators. This approach (described in detail below) allows us to sidestep the complexities associated with explicitly representing extreme weather events, while allowing us to focus on the infrastructure-related aspects that are core to this investigation.

While we do not represent extreme weather events directly, we do represent the variable sensitivity of different infrastructure components to extreme weather events. This is reflected in terms of the components that are allowed to fail and the order in which they do so. Components that are more vulnerable to flooding – located in flood-prone areas and lacking sufficient defenses – for instance, will fail before those that are less vulnerable. And components that are not vulnerable at all will not fail at all. In this manner, we seek to identify the *range* of consequences that may be engendered by various types of extreme weather events. By performing similar analyses for different infrastructure configurations – reflecting different adaptation measures – we seek to explore the relative benefits of different adaptations.

## 6.4 Model design

The developed model is divided into two submodels. The first submodel focuses on assessing the effectiveness of improved flood protection measures at electrical substations to enhance the infrastructure's flood resilience. The second submodel focuses on assessing the effectiveness of a demand-side management mechanism to enhance the infrastructure's heat wave resilience.

Each of the developed submodels involves exposing the modeled infrastructure to extreme events of successively increasing magnitude. The magnitude of an extreme event is defined as the number of infrastructure components disabled by the event. With each successive increase in extreme event magnitude, the properties and/or composition of the infrastructure is changed, and the respective submodel evaluates the performance of the changed infrastructure. As with the model introduced in chapter 5, this evaluation takes the form of a power flow calculation which determines the power flow magnitudes across the lines of the infrastructure and the quantity of power delivered to each distribution grid. If the power flow across any line is determined to exceed 1.2 times its nominal capacity – the assumed maximum allowable flow – the line fails and the power flow calculations are executed again. This process is repeated until no lines are exceeding their allowable flows. At this point, the performance of the network is gauged and recorded.

For each submodel, the process of successively increasing event magnitude and evaluating infrastructure performance is repeated 1000 times. In combination, these iterations are intended to provide a sense of the *range* of infrastructure performance under the tested conditions. The paragraphs below further detail the setup of the developed model.

## Representation of the social subsystem

Unlike in the case of the abstract model described in the previous chapter, the model here does not incorporate an explicit representation of the social subsystem in the form of autonomous agents. However, certain aspects of the social subsystem are represented in the procedures of the model, in particular in determining the magnitude and geographical distribution of electricity demand and electricity generation.

The magnitude and geographical distribution of electricity demand are set in accordance with known peak and mean consumption values for the Netherlands for 2010 (the defined base year for the model). Unlike in the model of chapter 5, demand is not assumed to be constant, but rather varies (according to a uniform distribution) between a defined maximum and minimum. This variability is intended to reflect both daily and seasonal variations in electricity demand. Essentially, this amounts to an assumption that aggregate electricity demand (during any one model run) is equally likely to fall anywhere within the known range of maximum and minimum demand levels for 2010.

The magnitude and geographical distribution of generation are set in accordance with the known capacities and geographical locations of large generators (greater than 10 MW) in the Netherlands. Each model run, each of these generators is assigned to produce a random (uniformly distributed) amount of power less than or equal to the known capacity of the generator, such that the sum of demand (plus imports and minus exports) equals the sum of generation. This manner of representing generation dispatch thus accounts for the known capacities of generators, but ignores minimum output constraints of individual generators as well as economic factors which may lead certain generators to be dispatched more or less frequently.

When the integrity of the infrastructure is compromised, redispatching of power plants may occur. More specifically, if one or more active generators fails or is otherwise cut off from the grid, the dispatch pattern is altered such that all remaining generators (including available foreign suppliers) increase their power output in proportion to their available capacity until parity between supply and demand is again reached. This process essentially assumes perfect balancing capability of the TSO within the constraints of available transmission capacity. If insufficient additional capacity is available, load shedding will occur – the power supplied to each customer is reduced in proportion to their demand.

An additional factor accounted for in determining generation dispatch is the possibility for congestion management. In the Dutch power system, congestion management is a role performed by the Dutch TSO involving the strategic upward and downward regulation of generation with the aim of ensuring network integrity. In the model, congestion management is represented in the form of the following two-step algorithm:

1. If a line overload is projected under given demand/supply conditions, a new random generation dispatch pattern and the resulting power flow pattern are calculated.

2. This process of "redispatching" is repeated until a dispatch pattern is found which will not result in line overload, up to a maximum of 100 times (sensitivity analysis shows that further redispatching attempts beyond this value do not significantly affect the results).

This algorithm for representing congestion management ignores the precise process by which congestion management takes place, as well as the economic factors which affect its outcome. In representing this process as a repeated random draw, however, we seek, to some degree, to mimic the outcomes of this process.

Imports and exports from/to the neighboring countries of Germany, Belgium, Great Britain and Norway are incorporated in a manner similar to domestic demand and generation. Using known maximum and minimum export/import values for these countries in 2010 as boundaries for a (uniform) random distribution, we (each run) assign each country a random demand or supply level. These demand/-supply levels are taken into account in the aforementioned procedures for calculating generator (re)dispatch.

## Representation of the technical subsystem

The technical subsystem is represented as a set of interconnected technical components, including 86 generators[2][3], 238 distribution grids[4], 402 transmission lines operating at four different voltage levels, 312 domestic substations[5], 8 foreign substations, 29 transformers and 9 international interconnectors. In combination, these

[2]During the course of a simulation, these generators are aggregated based on their coupled substations.

[3]Distributed generation is also accounted for, based on data concerning the total magnitude of distributed generation in the Netherlands and assumptions about its geographical distribution.

[4]The internal composition of distribution grids is not represented.

[5]Real-world substations spanning multiple voltage levels (e.g. 380/150kV or 220/110kV) are divided into multiple, co-located substations, each operating at a single voltage level and connected to one another via transformers.

components constitute a unified electricity network – an abstract representation of the Dutch electricity infrastructure, including interconnections with neighboring countries. Each of the defined components is assigned a set of key properties, indicated in Table 6.1. The dataset is illustrated in Figure 6.2.

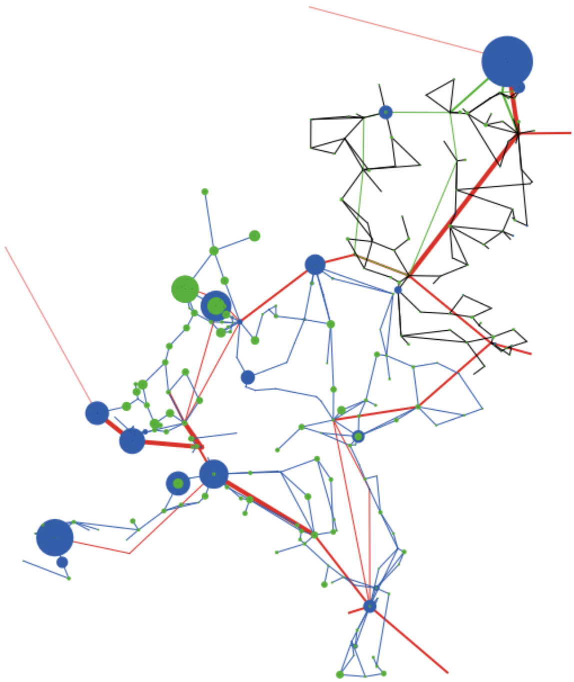

Figure 6.2: Geographically explicit representation of the employed dataset describing the Dutch electricity infrastructure. Blue circles represent (clusters of) generators. Green circles represent distribution grids. Edges represent transmission lines and international interconnectors (red = 380kV+, green = 220kV, blue = 150kV, black = 110kV). The thickness of edges represents the capacity of the respective line. Substations lie at the connection points of transmission lines. The size of generators and distribution grids is determined by the relative magnitude of their generation capacity or peak demand, respectively.

Table 6.1: Key properties of elements represented in the input dataset describing the Dutch electricity infrastructure.

| **Component type** | **Properties** |
|---|---|
| Generators | Generation capacity (maximum real power output), coupled substation, fuel type, cooling method |
| Distribution grids | Peak demand, coupled substation(s) |
| Substations | Voltage level, latitude, longitude |
| Transmission lines and interconnectors | Connected substations, voltage level, nominal capacity, total length, underground length |
| Transformers | Connected substations |

## Representation of extreme weather events

The developed model represents extreme weather events in an indirect manner. Rather than explicitly representing the meteorological circumstances constituting such events, we represent them in terms of their effects on infrastructure components. A flood is represented in terms of the number and locations of substations that fail, and a heat wave is represented in terms of the engendered capacity loss at affected generators. This manner of representing extreme weather events allows us to sidestep the necessity to include detailed representations of possible extreme event scenarios, while allowing us to focus on the infrastructure-related aspects that are core to this investigation. The sections that follow describe our representation of extreme weather events in more detail.

### Floods

Floods are represented in terms of their effects on electrical substations. Each substation is assigned a *flood vulnerability* level based on its geographic location and publicly available flood risk data for that location. Flood risk data for the geographic area of the Netherlands has been obtained from GBO-provincies (2013), and constitutes maximum water depths over the geographic area of the Netherlands. These water depth values have been determined using a variety of (externally developed) flood models which collectively simulate a range of dike breach scenarios across the Netherlands. Substations situated in locations with higher maximum water depths are assumed to have a higher vulnerability level than those in locations with lower depths. It is assumed that substations are protected to water depths up to 2.5 meters. Thus, substations at locations with maximum water depths of less than 2.5 meters are assigned a vulnerability of zero[6]. Substations outside the geographic area of the Netherlands are assumed to have a vulnerability of zero. The locations of vulnerable substations based on this analysis are illustrated in Figure 6.3(a).

A single model run constitutes the successive removal of random substations until all substations with a flood vulnerability greater than zero have failed. Following the failure of each successive substation, the performance of the infrastructure is evaluated as described above. The order in which substations fail during the course of a single run is affected by the substations' relative flood vulnerability, with substations featuring a higher vulnerability more likely to fail before those with a lower vulnerability[7]. It is assumed that substations with a vulnerability value of zero will not fail.

Conceptualized a different way, this manner of representing the effects of floods essentially constitutes successively increasing the flood magnitude (represented as the number of substations failed) until the maximum possible infrastructure effect has been realized (all vulnerable substations have failed). With each successive increase in flood magnitude, the performance of the infrastructure is evaluated. Due to embedded randomness in terms of the order of substations removed (as well as

[6] Due to the resolution of the utilized flood data, it is not possible to distinguish between water depth gradations between 2 meters and 5 meters. We therefore assume that all substations at locations with projected water depths greater than 2 meters are vulnerable.

[7] Technically, this is accomplished using a weighted random sample, with the weights set in accordance with the flood vulnerability values of the substations.

the aforementioned randomness in demand magnitude and generator dispatch), this process of gradually increasing flood magnitude until all vulnerable substations have failed is repeated numerous (1000) times. This provides us with knowledge of infrastructure performance degradation under a large range of possible flood scenarios.

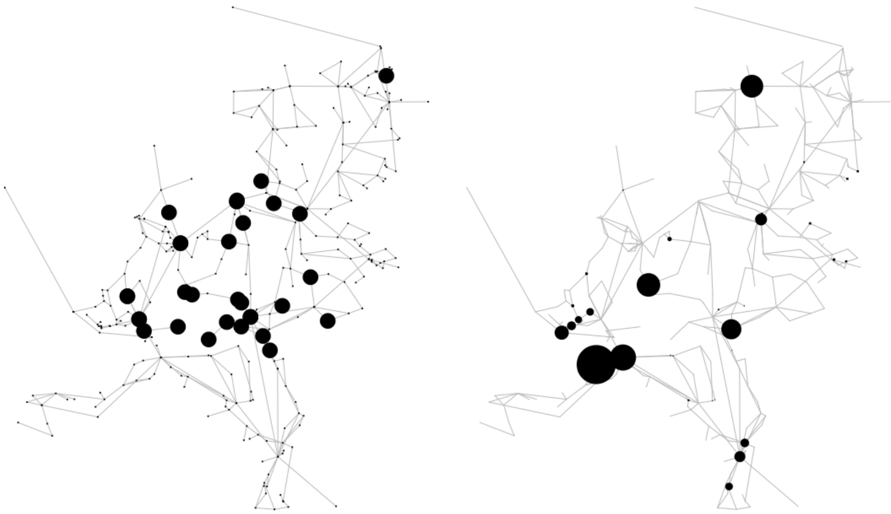

Figure 6.3: Vulnerability of technical components of the Dutch electricity infrastructure. The left pane shows the flood vulnerability of substations in the Netherlands, based on an assumed protection level of 2.5 meters. Large circles indicate substations with projected maximum flood heights exceeding their protection level. Small circles indicate substations with projected maximum flood heights below their protection level. The right pane shows the heat wave vulnerability of generators in the Netherlands. (Groups of) generators are represented by circles, which are sized according to the magnitude of their vulnerable capacity. Larger circles represent (groups of) generators with more vulnerable capacity. Generators are grouped according to the substation to which they are coupled.

### Heat waves

Heat waves are represented in a manner similar to floods, except that they affect generators rather than substations. Each generator is assigned a *heat wave vulnerability* level based on knowledge concerning its location (coastal or inland), the type of generator (thermal or other) and the cooling method (presence of a cooling tower). The vulnerability level for a generator ($V_G$) is calculated as follows.

$$V_G = T_G \times W_G \times C_G$$

where $T_G$ is a binary variable representing whether the generator is a thermal power plant (1 if yes, 0 if no), $W_G$ is a binary variable representing whether the power plant draws from an inland water source (1 if yes, 0 if no), and $C_G$ is a variable representing whether the power plant has a cooling tower (0.5 if yes, 1 if no)[8].

[8] Our choice of 0.5 for the positive value of $A_T$ reflects the claim of Rademaekers et al. (2011) that the temperature sensitivity of an air-cooled nuclear generator is half that of a water-cooled nuclear generator.

Together, these variables provide an estimate of a generator's heat wave vulnerability. The vulnerability values for generators in the Netherlands are illustrated in Figure 6.3(b).

A single model run constitutes the successive reduction of generation capacity in increments of 100 MW from random generators until all vulnerable generation capacity has been eliminated. The vulnerable capacity of a generator is defined as the vulnerability of the generator times its generation capacity. Following each successive reduction in generation capacity, the performance of the infrastructure is evaluated as described above.

In addition to the gradual reduction in available generation capacity, several other known effects of heat waves on infrastructure components are included in the model. First, the capacity of transmission lines is reduced to reflect the effects of extreme temperature conditions. As a basis for adjusting the capacity of transmission lines, we use the *IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors* (IEE, 2007)[9]. Second, we alter peak and mean demand values to reflect summertime conditions[10] and to reflect the effects of temperature. To capture the effect of temperature on demand, we use as a basis the findings of Hekkenberg et al. (2009) that electricity demand in the Netherlands (during summer months) increases on average by 0.5% for every 1°C increase in ambient temperature[11].

Due to the multiple sources of randomness embedded in the model, the process of gradually increasing heat wave magnitude until all vulnerable generation capacity has been eliminated is repeated numerous (1000) times. This provides us with knowledge of infrastructure performance degradation under a large range of possible heat wave scenarios.

## Representation of adaptation measures

For each type of extreme weather event, experimentation with the developed model involves evaluating the effectiveness of a set of adaptation measures. For the case of floods, these tested measures entail the implementation of various degrees of improved flood defenses at vulnerable substations. Improved flood defenses are represented by increasing the protection height of the substation in question to a level equal to the maximum projected water depth at that location – essentially reducing the substation's flood vulnerability to zero. Several degrees of improved flood defense are tested, ranging from the implementation of defenses at 0% of vulnerable substations to the implementation of defenses at 100% of vulnerable substations.

We test two strategies for enhancing substations flood defenses. Under the first strategy, substations are selected for improved flood defenses in order of their *vulnerability* – substations with a higher vulnerability are protected first. Under the second strategy, substations are selected for improved flood defenses in order of their *criticality-adjusted vulnerability* – the product of a substation's vulnerability and its

[9] In implementing the procedure defined in this standard, we assume low-wind conditions, a maximum conductor temperature of 100°C, a line rating temperature of 25°C, a rate of radiated heat loss equivalent to the rate of solar heat gain and an ambient temperature of 33.2°C (the mean peak temperature of heat waves in the Netherlands between 1901 and 2013 (KNMI, 2013))

[10] As a basis for this, we use daily demand values published by TenneT (2013c)

[11] For the purpose of modifying demand, we assume an ambient temperature of 33.2°C

criticality. Criticality is determined by the magnitude of reduction in system performance caused by the failure of a given substation. Substations whose failure, on average, results in a larger drop in system performance, are assigned a higher criticality value[12]. The relative criticality and criticality-adjusted flood vulnerability of substations – as calculated according to this procedure – are illustrated in Figure 6.4. The distribution of these values is illustrated in Figure 6.5. Tables A.1 and A.2 list the names of the substations with the highest calculated criticalities and criticality-adjusted flood vulnerabilities.

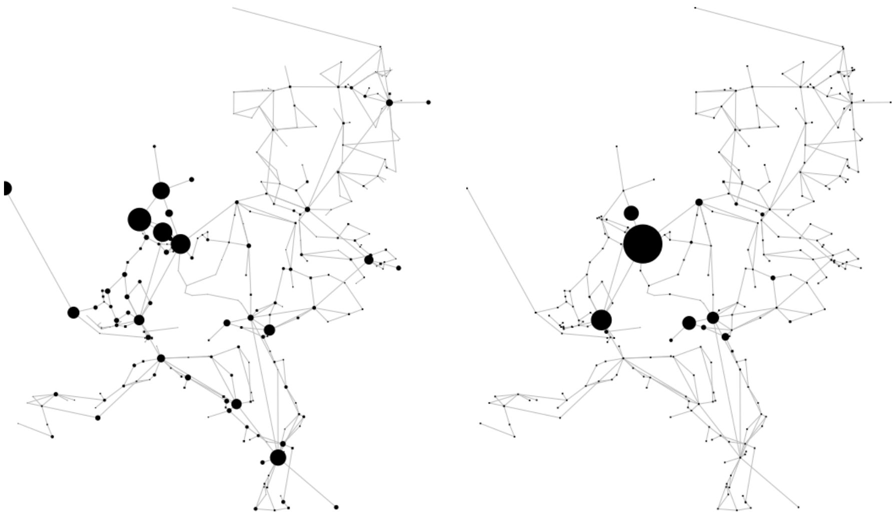

Figure 6.4: Illustration of the Dutch transmission system, with substations sized according to their criticality (left pane) and criticality-adjusted flood vulnerability (right pane).

For the case of heat waves, the tested measures entail the implementation of demand-side management. Demand-side management is represented by a percent-wise reduction in demand, distributed evenly across the distribution grids. The model does not capture the precise mechanism by which this reduction in demand is achieved. Several degrees of demand-side management are tested, ranging from 0% to 25% reduction in demand.

Table 6.2 summarizes the tested adaptation measures.

Table 6.2: Summary of adaptation measures tested in the developed model.

| Measure | Unit | Min | Increment | Max |
|---|---|---|---|---|
| Improved flood defenses (substations protected in order of vulnerability) | % of vulnerable substations protected | 0 | 20 | 100 |
| Improved flood defenses (prioritization of critical substations) | % of vulnerable substations protected | 0 | 20 | 100 |
| Demand-side management | % reduction in demand | 0 | 5 | 25 |

[12]Specifically, the criticality of substations is calculated by successively removing substations in random order, and recording the drop in performance caused by the removal of each successive substation. This procedure is repeated 1000 times, after which the mean drop in system performance resulting from the removal of each individual substation is calculated.

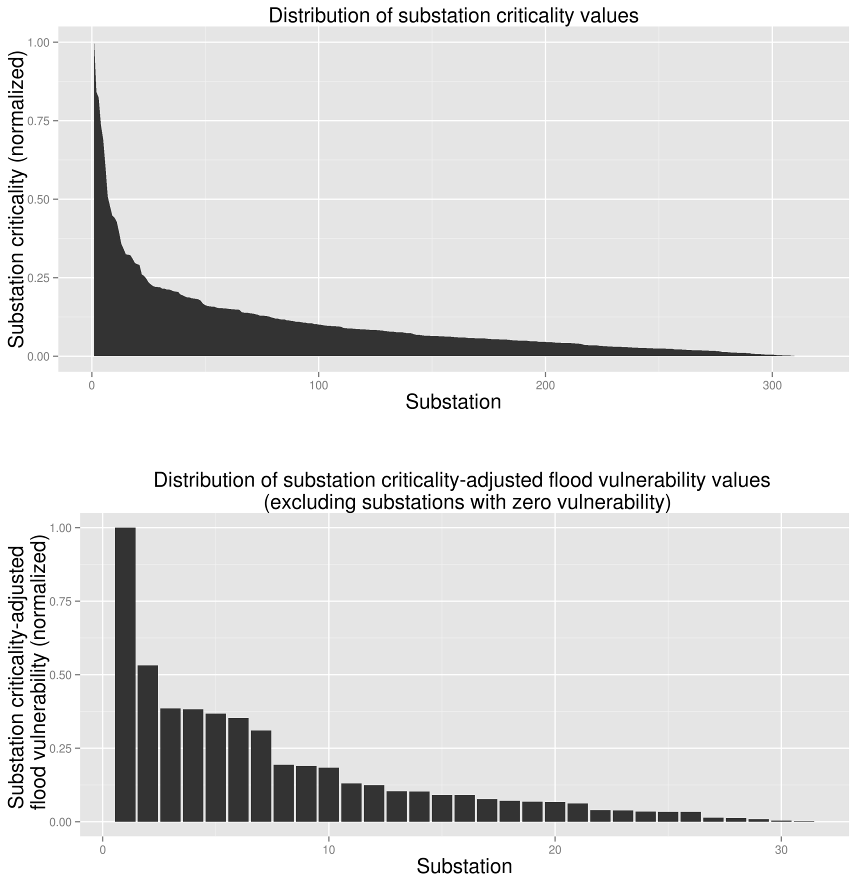


Figure 6.5: Distribution of the criticality (top pane) and criticality-adjusted flood vulnerability (bottom pane) of substations in the Dutch transmission grid. The criticality of a substation is based on the mean drop in system performance caused by the removal of that substation.

## 6.5 Software implementation

The developed model is implemented in MATLAB, and makes use of the MATLAB-based power system simulation package Matpower (Zimmerman et al., 2011). In addition to the Matpower code, the model consists of three Matlab M files. The first of these (*EvaluateNetworkResilience.m*) includes high-level code for setting demand and supply and calculating and plotting the flood and heat-wave resilience of the represented infrastructure, both with and without the aforementioned adaptation measures. During the course of its execution, this file calls the other two supporting M files. The first of these (*LoadNetwork.m*) is responsible for loading, parsing and formatting the input data files, which contain the infrastructure configuration data and component vulnerability values. The second supporting M file (*CalculatePowerFlows.m*) incorporates code for generation redispatch, power flow analysis and cascading failure analysis. As with the model described in chapter 5, the model here employs a DC power flow analysis algorithm.

The model code can be found on the Web at https://github.com/ABollinger/ResilienceAssessmentModel_NLVersion.

## 6.6 Validity of the model

The validity of the developed model has been tested by comparing its results to the results of power flow calculations published in TenneT's *2010–2016 Quality and Capacity Plan* (TenneT, 2009). Specifically, we compare the results of TenneT's power flow calculations under a *no-fault state*[13] with the results of the developed model under a no-fault state. Results are compared on the basis of the transmission line *utilization rate* – the percentage of line capacity used. TenneT (2009) provides the results of power flow calculations under several generation dispatch and import/export scenarios. From these results, we extract the mean, minimum and maximum utilization rates for each of 29 transmission lines (selected based on the availability of sufficient data) and compare them with the mean, minimum and maximum utilization rates of the same 29 lines in the developed model. This procedure provides insight into the degree to which the magnitude and geographical distribution of power transported over the modeled network under normal conditions corresponds with reality.

As shown in Figure 6.6, the results of this analysis suggest that the developed model may generally *underestimate* the magnitude of power flows under a no-fault state. For 83% of the tested lines, the mean utilization rate as calculated based on the model results lies below that calculated based on TenneT's results – with an average magnitude of deviation of about 7%. While the mean utilization rate in the developed model generally lies below that of TenneT's calculations, the model more often manages to capture the *range* of utilization rates observed in TenneT's calculations. For 49% of the tested lines, the range of values produced by the model fully captures the range of values observed in TenneT's data. For most of the lines where this is not the case, the model slightly underestimates the maximum utilization rate, though usually not significantly.

The identified deviations in the results of the developed model with those of TenneT's model(s) may be attributed to several factors – differing demand/supply scenarios, slightly differing assumptions concerning the constitution of the network, and differing calculation methods. The results of our test confirm that there is no order-of-magnitude difference between the results of the developed model and those of TenneT's models. However, they indicate that the developed model generally underestimates the utilization rates of lines, suggesting that the model may somewhat *overestimate* infrastructure resilience. Further research is necessary to confirm this suspicion.

## 6.7 Results and analysis

In this section, we present and analyze the results of the developed model. We begin with an analysis of the infrastructure's flood resilience under different adaptation

[13] A no-fault state corresponds to a state in which all elements of the system are functional

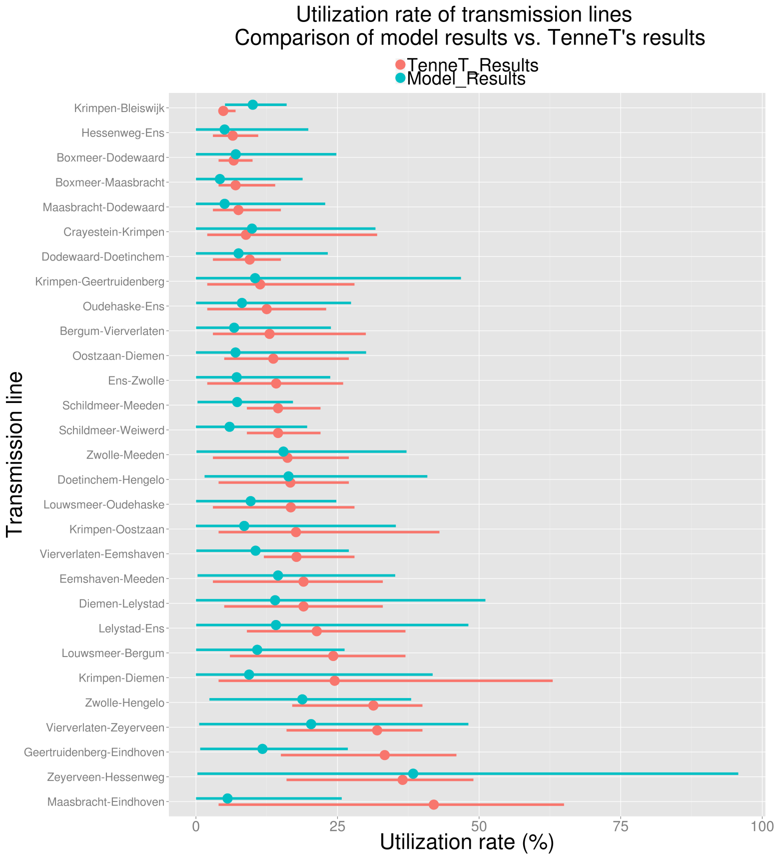


Figure 6.6: Comparison of results of the developed model to the results of TenneT's calculations as published in TenneT (2009). Circles represent the mean utilization rate of the respective transmission lines. The ends of the horizontal lines represent the minimum and maximum utilization rates. The model results generally underestimate the utilization rate of transmission lines under no-fault conditions, but capture the range of observed utilization rates relatively well.

scenarios, followed by an analysis of the infrastructure's heat wave resilience.

## Flood resilience

Figure 6.7 (left pane) illustrates the performance of the defined network exposed to flood events of each possible magnitude, with no adaptation measures in place. The gray lines show the results for each of the 1000 runs of the model. The thicker black line shows the mean performance across these 1000 runs. As expected, these results indicate that the performance of the network (fraction demand served) tends to decrease with increasing event magnitude. As the gray lines illustrate, this drop in performance is anything but smooth. In some cases the failure of a single substation results in a 10%+ drop in performance; in other cases, it results in no performance drop at all.

On average, the performance of the system drops by about 12% with the failure of half of the vulnerable substations and 22% with the failure of all 30. The minimum

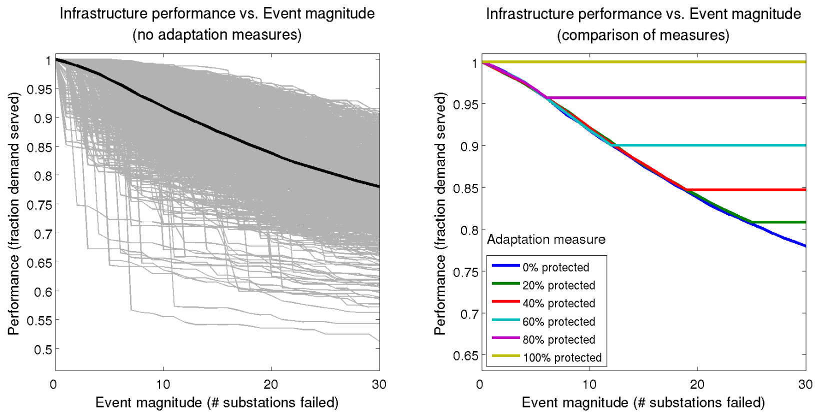


Figure 6.7: Performance of the modeled infrastructure vs. magnitude of the flood event. The left pane illustrates infrastructure performance with no adaptations in place. The right pane compares infrastructure performance with different adaptations implemented. The gray lines in the left pane indicate the results of individual model runs, and the thicker black line shows the mean of these results. The lines in the right pane indicate the mean results across runs for each adaptation scenario. Please be aware of the differing vertical axis scales between the two plots.

performance observed across all runs amounts to approximately 51%, suggesting that a flood *could* feasibly result in a disruption in demand served of approximately 49%. It is also interesting to note that the pattern of performance degradation displays a slightly convex shape, indicating that the performance of the system tends to degrade less rapidly with increasing event magnitude.

Figure 6.7 (right pane) compares the performance of the network across the range of tested adaptation measures, with substations protected in order of their vulnerability. As expected, increasing the percentage of protected substations also tends to increase overall network performance. The general shape and slope of the performance degradation curve is similar regardless of the measure implemented. However, the event magnitude at which performance degradation halts decreases as more substations are protected.

Using the second method for resilience quantification developed in chapter 5 – the *mean fraction demand served across the range of possible extreme event magnitudes* – we can quantify the flood resilience of the infrastructure. The mean resilience of the infrastructure with no adaptation measures in place amounts to a value of approximately 0.88. Across the 1000 runs of the model, the minimum observed value is 0.64 and the maximum is 0.96.

Figure 6.8(a) (left pane) compares the calculated resilience values for each of the six adaptation scenarios, with substations protected in order of their vulnerability. This plot shows that the improvement in resilience is relatively negligible when 20% of vulnerable substations are protected, but increases more clearly thereafter. With 100% of substations projected, a flood resilience of 1 is achieved. It is interesting to note, however, that while the median resilience value generally increases with a greater number of substations protected, low outliers are still observed. Even at a protection level of 80% – where we observe a median resilience of 0.98 – we also observe a single run with a resilience value of 0.71.

Figure 6.8(b) compares the calculated resilience values for each of the six adaptation scenarios, with priority given to protection of *critical substations*. Compared with the previous case, in which substations are protected in order of their vulnerability, we see here larger improvements in resilience with the protection of a smaller fraction of substations. With 20% of vulnerable substations protected, for instance, we see an increase in mean resilience of about 0.07 (or about 7.8%) – compared with a negligible increase in the previous case. In addition to a more rapid rise in mean resilience with an increasing fraction of protected substations, we see a more rapid dissipation of low outliers – with 60% of vulnerable substations protected, we observe a minimum resilience value of 0.93. Moreover, with only 80% of substations protected, the system achieves perfect flood resilience (a value of 1) – compared with 100% in the previous case.

## Heat wave resilience

Figure 6.9 (left pane) illustrates the performance of the defined network exposed to heat wave events of each possible magnitude, with no adaptation measures in place. Gray lines show the results for each of the 1000 runs of the model, and the thicker black line shows the mean performance across these 1000 runs. These results indicate that the performance of the network (fraction demand served) tends to decrease with increasing event magnitude, though the decrease is relatively slight compared with the flood case – the minimum performance value observed across all runs is 0.78. In fact, most of the runs (90%) display essentially no drop in performance at all, even at large event magnitudes.

A closer look at the results reveals that this drop in performance is due to a combination of insufficient generation capacity and insufficient line capacities. In some situations, the gradual disabling of generation capacity eventually creates a situation in which remaining supply is simply insufficient to cover demand, resulting in a drop in infrastructure performance commensurate with this supply deficit. In other cases, the gradual disabling of generation capacity results in a situation in which the distribution of generator dispatch produces power flows in excess of line capacities. This latter situation may be most damaging to the performance of the infrastructure, as it sometimes results in failure cascades which disable additional system components.

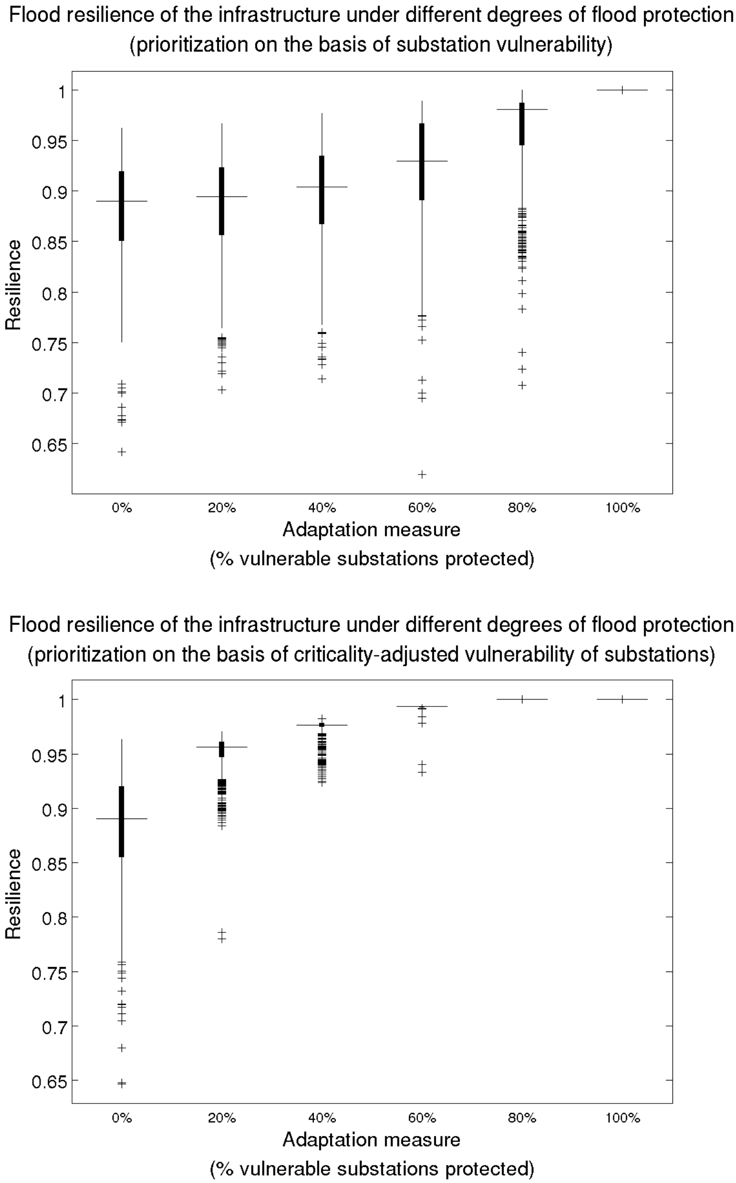


Figure 6.8: Comparison of resilience values obtained under the different flood protection strategies – with substations protected in order of their vulnerability (top pane) and in order of their criticality-adjusted vulnerability (bottom pane). The ends of the dark box indicate the 25th and 75th percentiles; the "whiskers" extending from the boxes include the most extreme data points not considered outliers; outliers are plotted individually as crosses. See chapter 5 for a thorough explanation of the employed metric for resilience.

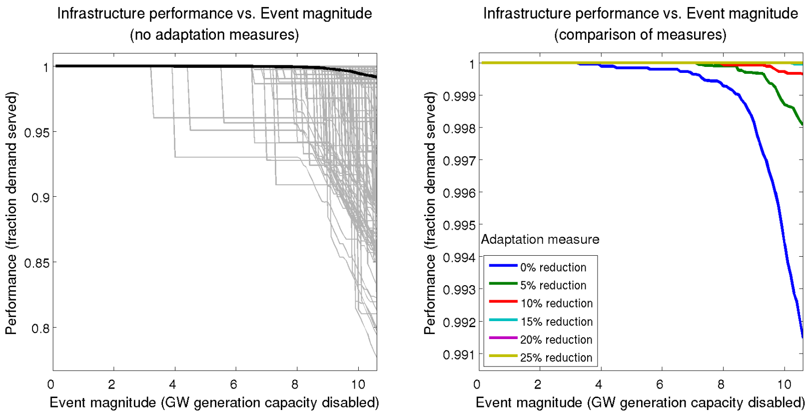


Figure 6.9: Performance of the modeled infrastructure vs. magnitude of the heat wave event. The left pane illustrates infrastructure performance with no adaptations in place. The right pane compares infrastructure performance with different adaptations implemented. Please be aware of the differing vertical axis scales between the two plots.

Figure 6.9 (right pane) compares the performance of the network across the range of tested adaptation measures. As expected, increasing the percentage of demand reduction also tends to increase the mean network performance. However, this effect is only observed up to levels of demand reduction of less than 20%, at which point the performance of the network is no longer affected by heat wave events of any magnitude.

Using the same method of resilience quantification employed in the flood case, the mean heat wave resilience of the infrastructure (with no adaptation measures) amounts to a value of approximately 0.999 – suggesting nearly perfect resilience. Across the 1000 runs of the model, the minimum observed value is 0.94 and the maximum is 1.00. Figure 6.10 compares the calculated resilience values for each of the six adaptation scenarios. This plot indicates that the improvement in resilience observed with increasing fraction of demand reduction is due not to a shift in the median values, but rather to a gradual elimination of low outliers. At 20% demand reduction and above, these low outliers are completely eliminated.

## 6.8 Discussion

The results described above suggest that the modeled infrastructure displays some vulnerability to both flood events and heat wave events, within the range of possible event magnitudes. They also suggest that the infrastructure is relatively less vulnerable to heat wave events than flood events. In the case of heat waves, the maximum possible drop in mean system performance is almost imperceptible. In the case of floods, the maximum drop exceeds 20%. Taken as a whole, these results suggest a highly resilient Dutch infrastructure – an infrastructure that remains largely functional even in the face of highly unlikely large magnitude events.

Most of the tested adaptation measures demonstrate a clear ability to reduce, and in some cases even eliminate, the infrastructure's vulnerability to floods and heat waves. If substations are protected in order of their vulnerability, enhanced flood

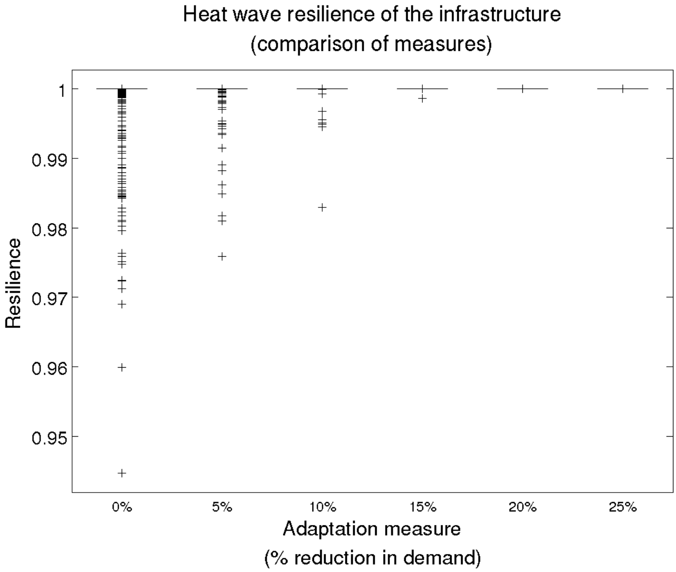


Figure 6.10: Comparison of resilience values obtained across the tested adaptation scenarios. The ends of the dark box (horizontal line in this case) indicate the 25th and 75th percentiles; the "whiskers" extending from the boxes (not visible in this case) include the most extreme data points not considered outliers; outliers are plotted individually as crosses.

protection of vulnerable substations shows increasing returns with a successively increased fraction of protected substations. With protection of 20% of substations, the resilience benefit is negligible. With protection of an additional 20%, we observe a resilience benefit of about 1.7% relative to the base (no adaptation) case. And with protection of an additional 40% of substations, we observe a resilience benefit of 4.6% relative to the base case. This suggests that larger investments in substation flood protection measures may be proportionally more beneficial than small investments.

If we take into account the criticality of substations, the story is different. By prioritizing the protection of more critical substations, we observe larger increases in resilience with less investment – already a 7.8% increase in resilience with 20% of substations protected. In this case, smaller investments in substation flood protection measures are seen to be proportionally more beneficial than large investments – although even relatively large investments generate more resilience benefit than in the previous case.

This result is not unexpected. It is logical that prioritizing the protection of critical substations should be a more efficient strategy than protecting only on the basis of vulnerability. However, this is not always the strategy adopted by transmission system operators, who often prefer to combine investments in flood defenses with major renovations or refurbishments to substations. In other words, prioritization often occurs on the basis of factors unrelated to a substation's criticality, such as its age. This is efficient in a different sense, but not necessarily optimal from flood protection standpoint. The results of our model provide a quantitative basis for comparing these different strategies. The next step, which we stop short of implementing here, is to weigh the costs of implementing these different strategies against the potential costs of lost load and necessary repairs.

The resilience benefit of a demand-side management mechanism for dealing with heat wave events is less substantial than that of flood protections. With a reduction in demand of 5%, we observe a mean resilience benefit of only 0.08%, and with a reduction of 15% a benefit of 0.10% (relative to the base case). This is not necessarily an argument against a demand-side management mechanism – this depends on the cost of such measures relative to the expected cost of inaction (also considering potential co-benefits[14]) – though it indicates that the likely benefit in terms of system performance during heat wave events is likely to be minor.

## 6.9 Limitations of the model

The results presented above must be viewed in light of the assumptions underlying the developed model. First amongst these is the manner in which the flood vulnerability of electrical substations is determined. We have used the maximum flood depth at substation locations as a proxy for flood vulnerability, though other factors clearly play a role in the real world. One key excluded factor is the anticipated flood return time at a given location, determined amongst others by the design specifications of the dike rings within which a substation is situated. Also excluded in this case are the geographical dynamics of flood progression, which may enhance the likelihood that clusters of substations within a given geographic area fail simultaneously. Accounting for these factors may improve the flood vulnerability estimates of transmission substations, and lead to a more accurate assessment of overall system resilience to floods.

A second key limitation of the model results has to do with the exclusion of the flood sensitivities of generators and distribution grid substations from the flood resilience assessment[15]. In light of these exclusions, the flood resilience assessment results should be viewed as an evaluation of transmission infrastructure resilience, rather than an evaluation of the resilience of the infrastructure as a whole. Inclusion of distribution grid elements would likely result in a reduction in the magnitude of identified flood resilience values, given that the protection heights of these substations tend to be significantly lower than those of transmission substations. On the other hand, it is unlikely that disturbances at the distribution level would propagate to the transmission level, meaning that the consequences of individual failures would likely be more limited, and would not affect the stability of the transmission system. Adequately incorporating distribution system elements in national level models is challenging for several reasons, including the large number of components in these networks and a lack of available data concerning component properties and network topologies. One approach to alleviate this involves the use of synthetic distribution networks, as employed by Thacker and Hall (2014).

Third, the model in its current form does not consider possible flood-induced

[14]An argument in favor of demand-side management is also reduced necessity for investments in peaking plants and/or grid capacity.

[15]The model indirectly captures the flood sensitivity of generators in terms of the sensitivity of the substations to which they are connected. However, these substations are not always co-located with the respective generators, which means that the sensitivity of the generators themselves are not always adequately represented.

changes in demand. In many circumstances, floods may be accompanied by the evacuation of inhabitants from affected areas, as well as the shuttering of industrial and commercial facilities. All of these factors may contribute to reductions in demand, which may significantly reduce the consequence of flooding in terms of lost load. On the other hand, it is important to keep in mind that transmission substations often serve large geographical areas, much of which may not be affected under a flood scenario that affects one or more of the feeding substations. Moreover, it is important to recognize that elements of the transmission system, unlike those of the distribution system, serve the function of transporting electricity over large distances. For this reason, the failure of one or more transmission substations due to localized flooding may have impacts far beyond the geographic scope of the flood event, also in those areas where demand may be unaffected.

A fourth key limitation of the model in its current form is that the vulnerabilities of individual power plants are currently based on approximations that do not account for the specific hydrological characteristics of different inland water bodies or the distinct sensitivities of different thermal generation technologies to changes in air and water temperature. Initial progress in these respects has been made using cycle-tempo models and historical temperature data for different water bodies in the Netherlands (Karamerou, 2014). This research has not yet been coupled with the model described above, but may be incorporated into future work to facilitate a more accurate quantification of generation vulnerability to heat waves.

Finally, the model in its current form does not quantitatively address how the frequency and magnitude of extreme events may change under different climate scenarios, and how these changes may subsequently affect the frequency and magnitude of infrastructure failures. Nor have we attempted in this study to quantify the probability of different levels of performance under conditions of climate change. These may be useful steps in enabling a comparison of the benefits and costs of various adaptation options, but they are complicated by the difficulty of assigning objective probabilities to many of the underlying variables. A possible alternative to a probabilistic approach is an approach based on *robust decision making* (Lempert et al., 2003), in which the aim is not to identify optimal strategies, but rather strategies that perform "well enough" across a range of possible futures. Application of this approach to the selection of investment strategies in infrastructure networks will be further addressed in chapter 9.

## 6.10 Synthesis

Growing evidence suggests that the frequency and severity of extreme weather events is likely to increase in the coming decades. Given the potential of events such as floods, heat waves, droughts and windstorms to disrupt the functionality of electricity transport systems, it is vital to understand how the Dutch electricity infrastructure may fare under a changing climate, and to identify effective options for supporting its resilience.

In this chapter, we have described the development and results of a model for assessing measures to support electricity infrastructure resilience to extreme weather events. The developed model focuses on two types of extreme weather events with particular relevance to the Dutch situation – floods and heat waves. The results suggest that the modeled infrastructure displays some vulnerability to both flood and heat wave events, but that the infrastructure is relatively less vulnerable to heat waves than floods. Most of the tested adaptation measures demonstrate a clear ability to reduce, and in some cases even eliminate, the infrastructure's vulnerability to floods and heat waves. However, prioritizing the protection of critical substations was shown to significantly enhance the efficiency of substation protection measures.

The immediate policy applicability of these results is limited by certain elements of the model design, especially the manner in which the vulnerabilities of individual substations and generators are determined and the exclusion of the electricity distribution system. We have pointed to several improvements and extensions to the model design that can address these limitations and in doing so enhance the contribution of this work to policy development. Despite these limitations, the present results offer a first indication of the vulnerability of the Dutch electricity infrastructure in the context of climate change, and of the potential of various measures to enhance resilience. Moreover, the employed approach – which accounts for the interconnectedness of infrastructure components as well as key power system characteristics largely absent from previous studies – illuminates new possibilities for future work in this area.

We see several productive directions for future research. While the present study has explored infrastructure performance and dynamics under a wide range of extreme event contingencies, we have neglected to quantitatively address how the frequency and magnitude of extreme events may change under different climate scenarios, and how these changes may subsequently affect the frequency and magnitude of infrastructure failures. This is an essential next step in enabling a comparison of the benefits and costs of various adaptation options. Moreover, the present study has investigated the effects of a handful of hypothetical adaptation measures, but has not considered how the Dutch electricity infrastructure may change more broadly over the coming decades. Given the rapidly changing socio-technical composition of this infrastructures – in particular driven by climate change mitigation concerns – this is a key aspect for consideration.

# Part III

# Case study 2

# Chapter 7

# Growing electricity networks

## 7.1 Introduction

Current demands for more sustainable and resilient electricity infrastructures will entail large-scale technical changes over the coming decades (Department of Energy and Climate Change, 2011; HM Treasury, 2011; NIAC, 2009; Possemiers et al., 2010). These "next generation" infrastructures cannot be designed from scratch, but will *evolve* from the current social landscape – including power producing companies, consumers, transmission and distribution companies and others – and the existing installed physical base – consisting of power plants, power lines, substations and numerous other technical components. Changes will be driven by the actions and interactions of numerous boundedly rational (Simon, 1957) actors working within, and seeking to overcome, the constraints of the current technical configuration.

Effectively guiding and shaping these developments necessitates a deep understanding of both the *social* and the *technical* dimensions of infrastructure development, as well as how they are linked. This can be facilitated through the use of suitable models. In line with this need, a growing body of research has applied a complex adaptive systems (CAS) perspective (Holland, 1992) as a basis for exploring the effectiveness of policies for supporting transitions in electricity generation and consumption (Batten and Grozev, 2006; Chappin, 2011; Chappin and Afman, 2013; Chappin and Dijkema, 2009; Weidlich and Veit, 2008). The bottom-up structure of these models is ideally aligned with the fragmented control typical of today's infrastructure. However, one key aspect has been missing from these models and from this body of research – the *network* that ties generators and consumers together.

An adequate network is essential to a functioning electricity system. Hindrances to its development may inhibit society's ability to realize much needed infrastructure improvements, such as renewable energy technologies and smart grids. In today's infrastructure systems, such hindrances often derive from the social realm. Political controversy, financial constraints, vested company interests, and NIMBY-ism may all play a role. In the Netherlands, this is reflected in current debates about how to 'socialize' the significant costs of connecting new offshore wind farms to the grid. In Germany, it is reflected in recent opposition to the construction of new long-distance power lines, threatening to derail the country's current push towards renewable energy (Froehlingsdorf, 2011). In seeking to shape the future development of the electricity infrastructure, we must understand how these social factors may drive and/or hinder the development of the technical network.

This chapter introduces the second case study of this research. Here, we introduce an abstract model of electricity network growth and evolution in which the *social* and the *technical* dimensions are explicitly linked. The purpose of the model is to explore the consequences of various developments within the social subsystem on the properties of the emergent technical network. The model employs a CAS perspective, capturing the development of the electricity grid as a consequence of the actions and interactions of a set of agents with one another and with their environment. The decision rules of these agents are modeled after the decision processes of corresponding real-world actors – power producers and a grid operator – and reflect the boundedly rational nature of these actors. In combination, these rules drive the development of the network and allow it to adapt to changes in its environment.

According to the requirements delineated at the end of chapter 2, the model developed in this chapter must: (1) entail representation of the electricity infrastructure as a *socio-technical system*; (2) entail representation of the electricity infrastructure as a *complex system*, whose complexity is manifested in both the interconnectedness of its technical components and in the interests, knowledge and capabilities of its social components; and (3) entail representation of the electricity infrastructure as an *evolutionary system*, exhibiting processes of variation, selection and heredity.

## 7.2 Modeling the growth and evolution of infrastructure networks

The model introduced in this chapter builds on a rich body of research on modeling the growth and evolution of infrastructure networks. The foundations for research in the area of network growth and evolution lie in the network growth models of Erdos and Renyi (1960), Watts and Strogatz (1998) and Barabasi and Albert (1999), who seek to identify simple rules underlying the growth and evolution of complex networks of different types. Erdos and Renyi (1960) explore the growth of random graphs and the dynamics of connectivity under such growth. Watts and Strogatz (1998) introduce the notion of small-world networks, and demonstrate similarities with various real-world networks, including power grids. And Barabasi and Albert (1999) investigate the growth of scale-free networks and the emergence of power-law distributions as a result of preferential attachment mechanisms. Models like these have demonstrated a capability to generate structures mimicking the topological features of real-world infrastructure networks – for instance, scale-free networks have been used to approximate the topology of real-world power systems (Chassin and Posse, 2005; Nan, 2011). However, the elegant simplicity of these models limits their capacity to effectively capture the messy relationships between social processes and growth patterns in technical infrastructure networks.

One area of research which has sought to capture these types of relationships is that of *self-organized transportation networks*. A seminal work in this field is the *active walker model* (Lam, 1995), in which agents moving across a landscape gradually change the landscape and eventually give rise to a transport network. Subsequent research has built on this general idea. Xie and Levinson (2009) introduce a model of road network growth based on iterative simulation of travel dynamics coupled with distributed investment and disinvestment decisions. Models such as these demonstrate the potential for capturing the bottom-up emergence of technical infrastructure networks and their evolution in a dynamic social environment.

In the area of electricity networks, most research to date dealing with long-term development processes falls into the category of *transmission expansion planning models*. Given a particular topology of the transmission network as a starting point, these models assess different network expansion options in search of one or more (quasi-)optimal transmission plans. The original models in the field of transmission expansion planning (e.g. Kaltenbach et al. (1970)) focused on identifying an optimal set of immediate grid investments. Some more recent models (e.g. da Rocha and Saraiva (2012)) look beyond the immediate future and seek an optimal sequence of investments over a long-term planning horizon. Also with this more recent strand of research, however, the focus lies on identifying an *optimal* set of investments at a *particular* point in time. The models are generally not used to explore the long-term evolution of an infrastructure and do not account for the presence of multiple interacting decision makers. This hinders their ability to adequately capture potential social constraints on infrastructure development.

A more recent strain of research has explored the application of more *bottom-up* approaches to modeling the long-term development of the electricity infrastructure. Much of this research has focused on investigating the dynamics of technology transitions in electricity generation. The objective of such models tends to be the evaluation of GHG mitigation policies such as carbon taxes (Davis et al., 2009) and cap-and-trade schemes (Chappin and Dijkema, 2009; Weidlich and Veit, 2008) in terms of their long-term impacts on the power generation portfolio. These models normally employ agent-based modeling, with the key agents being power producers tasked with making repeated investments in power generation facilities over a timespan of decades. While these models are able to capture the evolution of the electricity generation portfolio as a result of socio-economic influences, they generally ignore the development of the *network* – the web of power lines, substations and other technical components that link production and consumption.

Via the model in this chapter, we seek to bridge the bottom-up approach demonstrated in the network growth models of Erdos and Renyi (1960), Watts and Strogatz (1998) and Barabasi and Albert (1999) with the top-down approach of transmission system expansion planning models. Where transmission expansion planning models assume a largely omniscient planner seeking an *optimal* network configuration at a particular point in time, the model introduced below features a boundedly rational network operator seeking a *sufficient* network under dynamic, multi-actor circumstances. Where network growth models assume the bottom up emergence of network structure, our model features a central planner – the grid operator – who "consciously" designs the network structure, but must do so based on the actions of other agents (power producers[1]) and under conditions of incomplete knowledge about future developments.

[1] In the Netherlands, the transmission system operator is obliged to connect new generation facilities above a certain size to the grid.

## 7.3 System framing - the transmission grid as an evolving socio-technical system

Building on the system framing introduced in chapter 2, we frame the electricity infrastructure here as an evolving, dynamic socio-technical system encompassing the generation, transport and use of electrical energy. When viewed from this perspective, the social and technical subsystems of this infrastructure can be seen as *co-evolving* with one another and in concert with their environment – the advent of electricity infrastructures transformed daily routines, social roles and economic opportunities in much of the world. In turn, this social transformation placed new requirements on and induced function changes within the technical subsystem.

### The technical subsystem

In this case study, we focus on the *transmission grid* – the portion of the power grid responsible for the bulk transfer of electricity from large generators to electrical substations in the vicinity of demand centers. When power systems emerged in the former half of the 20th century, they were separated into islands centered around demand centers, each managed independently and providing for its own demand. These isolated grids were gradually linked to provide backup power and improve stability, and were extended to connect progressively larger and more remote power generation facilities (Schewe, 2009). Today's transmission grids link these formerly disparate networks into unified regional, national and even supra-national power systems.

The key task of the transmission grid lies in providing the links between large generators and distribution grids, which then deliver power directly to most consumers. This task is facilitated by a variety of technical components – power lines, substations and several types of reactive power compensation facilities. Transmission grids can be thought of as being composed of two distinct subsystems, a *high-voltage (HV)* grid, operating at 110kV – 150kV, and an *extra high-voltage (EHV)* grid, operating at 220kV – 380kV. HV grids were the first of these to be constructed – emerging to connect the isolated distribution grids in a country or region. As power systems developed further and large generation facilities (greater than one gigawatt) became commonplace, EHV grids – a more economical means of transporting large quantities of power over large distances – were built to link the largest of the generation and demand centers. Figure 7.1 illustrates the growth of a national transmission grid over time, and the emergence of the HV and EHV subsystems. This process continues – nowadays, many EHV grids are expanding, and some are even being succeeded by so-called *ultra high-voltage (UHV)* grids, usually operating on direct current and at voltages greater than 700kV and capable of transporting enormous amounts of power between distant regions.

The development of the technical infrastructure in many countries has entailed multiple *function changes*. Initially, the HV grid was intended to provide a backup function, serving to balance power between distribution grids and allowing large generators to periodically go off-line for maintenance. Gradually – driven by economies of scale that made large (often distant) generation facilities preferable to smaller-scale local ones – the function of the transmission grid shifted. It became a network

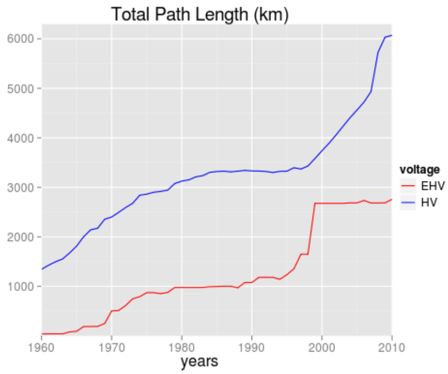

Figure 7.1: The development of the Dutch transmission grid illustrates the consecutive emergence of an HV and an EHV grid (data obtained from Energie-Nederland (2012)).

for transporting bulk power over large distances, from loci of generation to loci of consumption. Nowadays, with growing concerns about sustainability and falling costs of many distributed generation technologies, the balancing function of the grid is again acquiring increased importance. Simultaneously, increasing integration of European national grids means that the transmission grid increasingly serves a balancing function at the international level as well. Each of these function changes has significantly altered the magnitude and nature of power flows between network nodes, driving new investments in technical infrastructure components to maintain reliability and efficiency.

The technical subsystem resides within a spatial environment which may affect its development in myriad ways. Each component of the technical subsystem places certain requirements on its physical surroundings. Thermal generation facilities require ready access to large quantities of water for cooling purposes, and must be located in close proximity to power substations capable of channeling their output to the grid. Wind turbines and solar photovoltaics are ideally situated in locations with high wind volumes and unimpeded solar insolation, respectively, in order to maximize financial returns.

Technical components may also influence their surroundings, in both positive and negative ways. Transmission lines and nuclear power plants pose a radiation risk to their environment, and transmission lines, power plants and substations may affect the perceived aesthetic quality of their surroundings. In practice, these and other such interactions result in significant restrictions in terms of the spatial placement of technical components, which in certain situations may impede the development of the infrastructure (BBC, 2011; Devine-Wright, 2005; Froehlingsdorf, 2011). On the other hand, access to power from the grid opens up significant economic opportunities. The spatial development of the technical subsystem reflects these interactions, as well as changing perceptions concerning their significance.

## The social subsystem

Throughout most of the 20th century, the key tasks of electricity generation, transmission and distribution in most industrialized countries were concentrated within a single organizational entity, a vertically-integrated utility. Processes of economic liberalization in recent decades have induced vertical de-integration and a general shift from centralized to fragmented control of the technical infrastructure (Markard and Truffer, 2006; van Damme, 2005; Vries et al., 2006). In many countries, electricity transmission networks, distribution networks and generation facilities are owned, operated and planned by distinct organization entities – TSOs, DSOs and power producers. This vertical de-integration has introduced new evolutionary pressures on elements of the technical system, changing how they are designed, implemented, operated and maintained.

Power producers,TSOs and DSOs are the key actors directly involved in the planning, construction and maintenance of the technical subsystem. Next to these actors are others who are less directly involved in the management of the technical subsystem, including regulators, electricity retailers and consumers. Regulators are responsible for ensuring transparency and competitiveness, and safeguarding the interests of consumers; consumers, both household and industrial, are the main users of the infrastructure; and retailers broker the sale of electricity between producers and consumers. Together, these actors collectively drive the development of the infrastructure. No single actor has control over the system as a whole – the infrastructure grows and evolves as a consequence of myriad actions and interactions within this ecology of actors.

## Interactions between the social and technical subsystems

Vertical de-integration and accompanying institutional reforms have vastly increased the quantity and diversity of actors and interactions within the social subsystem of the electricity infrastructure. In light of this shift, it has been argued that electricity infrastructures are best viewed as *complex adaptive systems (CAS)* – dynamic networks of interacting agents that evolve, anticipate and exhibit aggregate behavior (Chappin and Dijkema, 2009; Holland, 1992). From this perspective, the power system grows and evolves as a consequence of the decisions and interactions of a set of agents, and in turn affects how these agents make decisions and interact. The overall structure of the socio-technical infrastructure is an emergent outcome of these underlying social processes and technical design parameters, interacting through a coupled fitness landscape (Kauffman and Johnsen, 1991). Changes in the social realm – e.g. the imposition of new sustainability or reliability requirements – affect the relative fitness of different technical (network) configurations. Likewise, changes in the technical configuration of the network may affect the fitness of the social system configuration – e.g. the partnerships, strategies and financial performance of actors.

One of the key links between the social and technical subsystems is the investment decisions of actors – producers invest in power plants, consumers in electricity consuming devices (e.g. computers, light bulbs) or installations (e.g. factories, data centers), and the TSO in power lines, substations and other grid components. The procedures by which these actors make decisions may be highly complex (Chappin et al., 2007). The decisions of power producers to invest in new generating units, for instance, may depend on fuel prices, environmental regulation and/or carbon prices, construction costs, available transmission capacity, technology risk, permitting procedures and other factors (ICF International, 2010). The decisions of a TSO to invest in grid components depend on, amongst others, projections of future supply and demand, security of supply concerns and land-use limitations.

## 7.4 Model design

The question driving the development of this model is the following: *How do developments within the social subsystem of the electricity infrastructure affect the properties of the emergent technical network?* In answering this question, our model must adequately capture: (1) the fragmented social structure surrounding today's electricity infrastructures and relevant constraints on the behavior of actors, (2) important properties of the technical network which affect its capacity to grow and adapt, and (3) key links between the attributes of this social system and the development of the technical network.

The design of the model includes distinct representation of the social and technical subsystems, and interactions between them. The social subsystem is represented by two types of agents, *electricity producers* and a *transmission system operator (TSO)*. These agents have limited knowledge of their environment and limited knowledge of future developments within the system, but are endowed with detailed representation of the key factors and constraints affecting their investment decisions. We exclude the regulator, DSOs, consumers and retailers, as their roles are secondary in light of the model's purpose.

The technical subsystem is represented by a set of *infrastructure components* – generators, power lines, substations, transformers, distribution grids and large loads (large electricity consuming facilities such as factories) – distinct objects which together comprise a "synthetic" infrastructure. In line with the points stated above, these components reside within a spatial environment. Moreover, these components are not completely independent entities – they interact with one another in a way that allows us to capture the function of the infrastructure as a whole, and to detect *changes* in function over time.

Interaction between the social and technical subsystems takes the form of investments and disinvestments on the part of the agents in infrastructure components. Each timestep during the course of a simulation, TSO and producer agents have the option to invest in various types of technical components. Electricity producers invest in generators, and the TSO invests in power lines, substations and transformers. Large loads and distribution grids are added and removed at a constant rate – the factors and actors determining their development are exogenous to the model. As a result of the repeated investment decisions of agents, and the development of large loads and distribution grids, a transmission grid emerges and evolves over time.

In the paragraphs that follow, we elaborate further on three key aspects of the model: the agent behavior, the spatial environment and the software implementation.

### Agent behavior

The growth and evolution of the transmission network in this model is driven by the investment (and disinvestment) decisions of the agents and their responses to changes in the grid. As much research has already been devoted to formalizing the investment decisions of electricity producers (Chappin et al., 2007; Davis et al., 2009; Weidlich and Veit, 2008), we focus here on the decision procedures of the TSO agent.

As stated above, this model sits along a spectrum between the top-down approach of transmission expansion planning models and the purely bottom-up approach of network growth models. The decision procedures of the TSO agent balance these perspectives. On one hand, the TSO agent, like real world TSOs, has certain societal obligations – to link all parties to the grid, to ensure a certain degree of reliability, etc. The TSO agent is required to actively construct a grid in line with these obligations. On the other hand, the TSO agent is powerless in his ability to control the development of electricity supply and demand – generators and loads emerge according to the calculated decisions of electricity producers and consumers. He can only passively respond to the actions of these agents.

The decision rules of the TSO agent can be viewed as constituting an evolutionary algorithm, defining processes of variation, selection and heredity (Kasmire et al., 2011), but not precisely determining the development of the technical infrastructure. *Variation* occurs as investments in new infrastructure components are made and these components become manifested as parts of the technical network. *Selection* occurs as the suitability of the current configuration to meet projected future needs is assessed, and disinvestment decisions are made. *Heredity* occurs as useful components are strengthened (e.g. adding capacity to heavily used lines) or replaced when they reach the end of their lifetime.

The base of the TSO's algorithm is a set of four responsibilities, arrived at in discussion with domain experts and based on a review of relevant literature (Elia Group, 2013; European Parliament, 2009; Knops, 2003; TenneT, 2012b)[2]:

1. The TSO is required to accept all applications for connections to the transmission grid, and must construct connections to the respective component(s).

2. The TSO must ensure that the failure of any one component of the transmission grid will not cause a failure elsewhere (this is referred to as the *n-1* criterion[3]).

3. The TSO must ensure that the transmission grid is capable of supplying power under all demand scenarios, including peak conditions.

4. As required by the regulator, the TSO must execute his responsibilities in the most cost-efficient way possible, choosing the least-cost option that satisfies his obligations at a particular point in time.

In connecting components to the grid (responsibility 1), the TSO seeks the least-cost route (responsibility 4) that allows him to link an isolated component with the existing grid. To find this route, he generates a range of possible routes through the landscape and calculates the cost of each one, taking into account both their length

[2]These rules are approximations and leave out certain important responsibilities of real-world TSOs that are beyond the scope of the model – e.g. resolving faults and disruptions, maintaining the energy balance, managing congestion and supporting the smooth operation of electricity markets.

[3]In practice, the n-1 criterion is often implemented as n-1 "during maintenance", or even n-2, which is intended to ensure the integrity of the system also when one component is decommissioned for maintenance and another fails.

and the land-use values of the landscape they traverse. He then constructs a line following the route with the least overall cost.

In adding redundancies (responsibility 2), the objective of the TSO is to ensure that every component in the transmission grid is accessible via two distinct routes, and that both of these routes have sufficient capacity to accommodate peak flows in the event of a single component failure. To achieve this objective, the TSO creates loop structures by strategically adding new lines between existing substations – he will always seek to maintain a grid with a certain minimum percentage of components embedded in loop structures. This is a rough adaptation of the n-1 criterion that currently guides the construction of redundancies in real-world transmission grids (EIHP, 2007).

To ensure sufficient capacity (responsibilities 2 & 3), the grid operator tries to ensure that each individual component of the grid has capacity commensurate with the power it will be required to transport under peak conditions. The decision procedures of the TSO assume a single peak scenario each year against which these transport requirements can be set. In order to set the appropriate capacity levels, the TSO makes a projection of the grid topology several years into the future, and calculates the power flows over each line in this projected grid under the peak condition. This is accomplished using a power flow analysis submodel. This submodel accepts the current grid topology and peak demand/supply scenario as inputs, and outputs the real power injections to and from each of the lines in the network. If the projected peak power flows over a line exceed its current capacity, the TSO increases the respective line's capacity so that it can accommodate these flows.

Initially, the TSO links all substations using 150kV power lines and substations. If, however, the TSO projects that the power injections to a particular substation will exceed a given threshold, he adds an extra-high-voltage (380kV) substation adjacent to the existing substation, constructs a transformer between them and links the new substation to the nearest 380kV substation. This task falls within the obligation of the TSO to carry out his tasks in a least-cost manner (responsibility 4), since extra-high-voltage components are more economical when larger quantities of power are being transported, especially over large distances.

The TSO has limited resources with which to fulfill his defined responsibilities. Depending on his available financial resources (an exogenous model parameter), the TSO may be more or less capable of fully carrying out his defined tasks. The consequences of a financial shortage are explored in the following section.

Pseudocode for the TSO's decision procedures can be found in Appendix B.

## Spatial environment

By incorporating certain aspects of the spatial environment, we seek to capture key geographical constraints to the development of the grid. A simulation begins with a randomly generated spatial landscape consisting of a set of isolated distribution grids, each centered on a particular *load center* – an urban or industrial area with defined geographic boundaries (see Figure 7.2). The geographical boundaries of these load centers determine the boundaries of the associated distribution grid, and their population distribution affects the values of the parcels of land within them[4]. These land values, in turn, affect the decisions of the TSO in placing grid components and identifying a locally optimal path for a new transmission line. In this way, we seek to mimic the effect of land-use constraints on network investments. In the current version of the model, the properties of load centers, including their spatial boundaries and population distribution, remain constant during the course of a simulation.

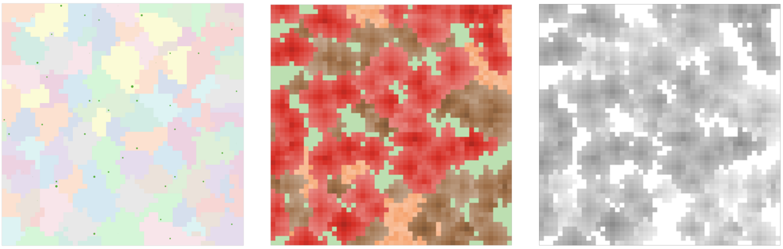

Figure 7.2: An example of a spatial landscape generated at the start of a simulation, including distribution grids (left), load centers (middle), and land values (right). The coloring of cells in the middle pane represents the type of land use: red represents urban areas, brown represents industrial areas, orange represents agricultural areas and green represents nature areas. The shading of cells in the right pane represents land values, with darker areas representing areas of higher land value.

While the spatial boundaries of distribution grids and the land values within them are not time-varying, the power demand of a distribution grid may fluctuate during the course of a simulation. The initial power demand of a distribution grid is a function of the size and land-use characteristics (urban vs. industrial) of the area covered. By default, the power demands of all distribution grids grow at the same user-defined rate during the course of a simulation. However, the growth rates of individual distribution grids can be manually adjusted by the user to mimic geographically disparate development patterns within the landscape.

We initialize the simulation with a random spatial landscape (instead of an abstracted real-world landscape) for several reasons. Most importantly, this setup allows us to explore the consequences of variations in this landscape on the emergent network structure. We address this in more detail below. Moreover, this setup provides a simple starting point which can be easily modified to reflect different scenarios. In the following chapter, this starting point will be adjusted to reflect the current Dutch transmission infrastructure.

## 7.5 Software implementation

In order to adequately represent the dynamics and functionality of the social and technical subsystems, as well as the interactions between them, we employ several pieces of software. The social subsystem is captured in the agent-based modeling platform Netlogo (Wilensky, 2012). The technical subsystem is represented using the MATLAB-based power system simulation package Matpower (Zimmerman et al., 2011). Runtime communication between these pieces of software is enabled by way

[4]The population and land value of a parcel of land are inversely proportional to the distance of the parcel from the geographic midpoint of a load center

of a custom-developed Netlogo extension, the *OctaveConnect* extension (an earlier version of the *MatpowerConnect* extension discussed in chapter 5).

Using and linking these pieces of software allows us to richly represent key processes of both the social and technical subsystems – the decision making processes of actors and transfers of power in the transmission grid. In fulfilling his responsibilities (specifically responsibilities 2 & 3), the TSO agent must forecast the magnitude of electricity flows through the lines of the future transmission grid. Each timestep, the investment decisions of power producers and the TSO (represented in Netlogo) determine a given structure for the technical network. By way of the OctaveConnect extension, this structure is passed to Matpower, which calculates power flows by solving an AC power flow problem using a Newton's Method solver. Once calculated, the power flow values are passed back to Netlogo and incorporated into the decision making procedures of the TSO agent.

Code for the model and the OctaveConnect extension are available online at http://www.openabm.org/model/3822/version/1/view.

## 7.6 Experiments and results

In order to evaluate the developed model with respect to the question stated above, we have carried out three experiments. In the first experiment, we assess the results of several simulations at the default parameter settings, corresponding to a given configuration of the social subsystem. This experiment is intended to provide insight into the consistency of results under controlled conditions. In the second experiment, we explore how changes in the properties of the social subsystem affect the structure of the transmission network that emerges. This experiment is intended to give insight into the relationships between the properties of the social subsystem and those of the emergent technical network. In the third experiment, we assess the consequences of a sudden societal development on the evolution of the network. This experiment is intended to provide us with insight into the dynamic responsiveness of the technical network to changes in the social subsystem.

In addition to these experiments, we perform an analysis to compare the properties of the *generated* electricity networks to those of *real-world* electricity networks. This analysis does not comprise a formal validation of the model, but is intended to provide some insight into its suitability for exploring the development of transmission grids in real-world contexts.

In the first and second experiments, the simulation is run for a period of 75 years, with one timestep equal to one year of simulation time. In the third experiment, the simulation is run for 100 years. The starting point for all simulations is a random landscape consisting of 100 isolated distribution grids. During the course of a simulation, power producers and the TSO agent make repeated decisions to invest and disinvest in technical infrastructure components, the demand of distribution grids grows or shrinks as consumer demand changes, and large loads are added and removed. As a result of these actions, a transmission infrastructure grows and evolves over time. Several key metrics are collected during the course of each simulation (see Table 7.1). These metrics are intended to capture pertinent aspects of the development of the emergent technical network that will allow us to discern relationships between the structure of this network and the social drivers of its development.

Table 7.1: Metrics tracked during the course of experimentation.

| **Metric** | **Description** | **Units** |
|---|---|---|
| *Total path length HV* | Sum of the length of high-voltage lines in the generated network | km |
| *Total path length EHV* | Sum of the length of extra high-voltage lines in the generated network | km |
| *Mean degree* | Average number of power lines connected to substations in the generated network | power lines |
| *Mean capacity of links* | Mean capacity of power lines in the generated network | MW |

## Experiment 1: Emergence of an artificial transmission grid

This section presents the results of several simulation runs at the default parameter settings. The purpose of this experiment is to discern general features of the system's dynamic behavior and to evaluate variability in this behavior under controlled conditions. Figure 7.3(a) illustrates the growth of a transmission infrastructure during the course of a single simulation at the default parameter settings. As this graph shows, two distinct stages in the development of the transmission grid can be identified. The first stage (0 – 20 years) is one of rapid growth, in which a high-voltage (HV) grid emerges to connect the isolated distribution grids and a number of large generators are built, linking directly to the components of the newly-built transmission grid. The limits to growth during this stage are mostly determined by the restricted resources of the TSO. The second stage (20 – 75 years) is one of maturation. During this stage, redundancies are added to the network and the infrastructure gradually grows to accommodate increasing demand and generation capacity – the capacity of lines increases and an extra high-voltage (EHV) grid emerges to connect the largest generation and demand centers.

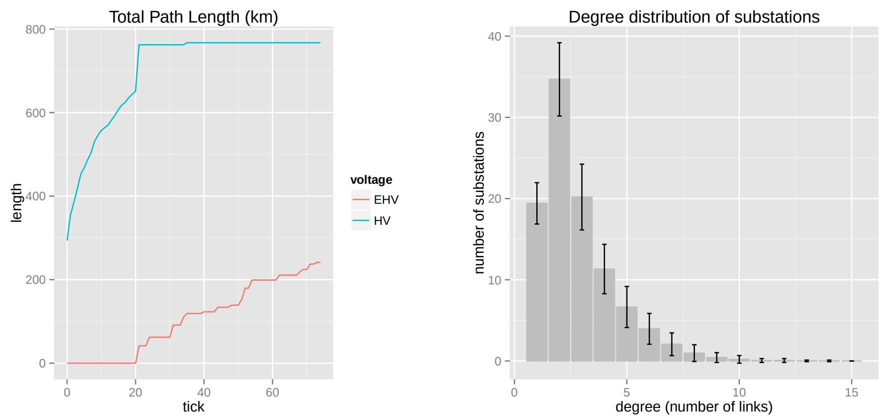


Figure 7.3: Results for the default case. Total path length of the HV and EHV networks during the course of a single simulation at the default parameter settings; and degree distribution of substations in the generated networks, collected over 100 simulation runs at the default parameter settings. Error bars show values within one standard deviation on either side of the mean.

Figure 7.4 shows several examples of an emergent network after 75 years. Each run of the simulation generates a unique network. The differences between these generated networks are partially due to variations in the initial environment – differences in the geographical distribution and relative power demand of distribution grids. However, they are also due to path dependencies in the development of the network, the order in which investments are made. Even under identical initial environments, no two resulting networks will be precisely identical.

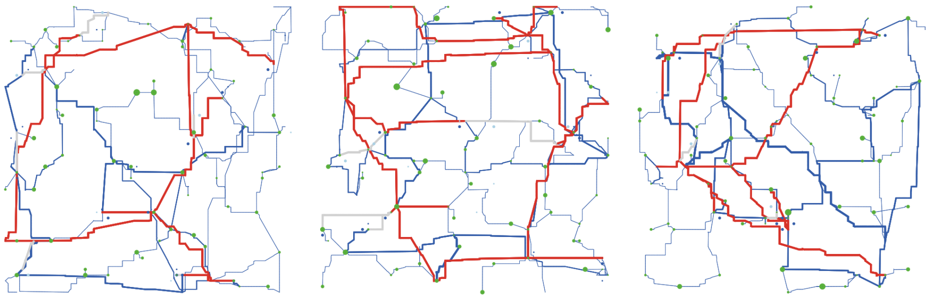

Figure 7.4: Three examples of an emergent network after 75 years. Each run generates a unique network. Red lines represent lines of the 380kV grid and blue lines represent lines of the 150kV grid. Green circles represent distribution grids. The thickness of lines is determined by their relative capacity.

Although a diversity of networks may emerge under identical starting conditions, the properties of these networks turn out to be quite similar. Table 7.2 summarizes the properties of 100 networks generated at the default parameter settings. Indeed, we see only minor variations in metric values, with a coefficient of variation of less than 0.15 in all cases. The same is true of the degree distribution – the distribution of the number of links connected to each substation – illustrated in Figure 7.3(b). The relatively low variability in the values of these metrics under given parameter conditions provides us with a basis against which to assess the consequences of changes in these conditions.

Table 7.2: Summary of metric values collected over 100 simulation runs at the default parameter settings

| **Metric** | **Mean value** | **Coefficient of variation** |
|---|---|---|
| *Total path length HV* | 708.4 | 0.045 |
| *Total path length EHV* | 282.7 | 0.127 |
| *Mean degree* | 2.81 | 0.024 |
| *Mean capacity of links* | 1035.3 | 0.052 |

## Experiment 2: Relationship between societal variables and grid topology

In this experiment, we assess how various changes in the parameter conditions affect the properties of the transmission network that emerges. The purpose of this is to discern relationships between selected properties of the social subsystem and the structure of the emergent technical network. The parameters that are varied have been selected to reflect different scenarios in terms of the features of the social subsystem, including consumer demand, redundancy requirements, and the economic and technological landscape. The parameters that have been varied during the course of experimentation and the ranges over which their respective values have been adjusted are shown in Table 7.3. In each case, the values of all other parameters are left at their default values.

Table 7.3: Parameters varied in the course of experimentation with the model.

| **Parameter** | **Description** | **Units** | **Default value** | **Range** |
|---|---|---|---|---|
| *Looped percentage* | Percentage of substations the grid operator seeks to embed in loop structures | % | 60 | 0 to 100 |
| *Demand growth rate* | The annual growth rate of distribution grid power demand | MW | 1 | -1 to 3 |
| *Distributed generator cost* | The variable cost of a distributed generator (a generator with output capacity less than 60MW) | Euro/ MWh | 100 | 50 to 100 |
| *Maximum annual expenditures* | The maximum allowed annual expenditures of the TSO | Euro | 300,000 | 50,000 to 500,000 |

In all cases, adjusting the value of a particular parameter has a marked effect on the topology of the generated network. As illustrated in Figure 7.5, adjusting the rate of demand growth strongly affects the size of the EHV grid that emerges and the capacity of lines. Higher demand growth results in more generation capacity and more power being transported through the grid. The TSO responds by building higher capacity lines and a larger EHV network. A larger EHV network means that more substations are linked to this network, resulting in a higher mean degree.

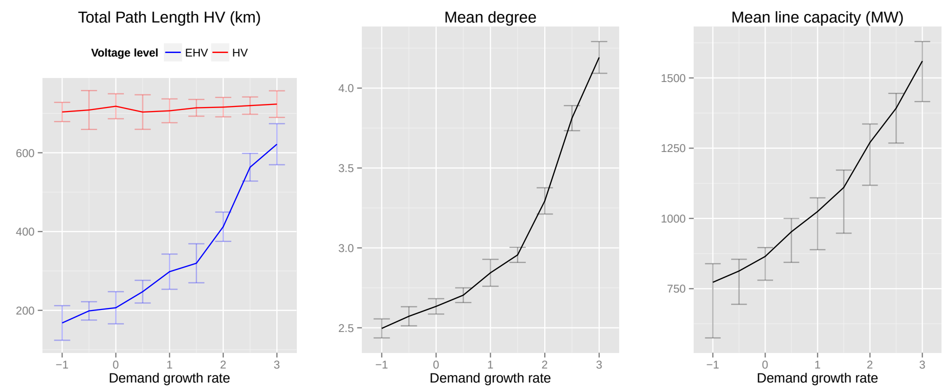


Figure 7.5: Effect of variations in the demand growth rate on the topology of the resulting network.

As illustrated in Figure 7.6, changing the variable cost of distributed generation technologies has several effects on the resulting topology. Because producer agents in the model always invest in the least expensive generation technology, a phase change in the structure of the system occurs when the price of a distributed generator falls below that of a centralized generator. An infrastructure develops in which generators are embedded in distribution grids, rather than being connected directly to the transmission grids. This subsequently lowers demand on the transmission grid, resulting in a network with a lower capacity and a smaller, or even non-existent, EHV grid.

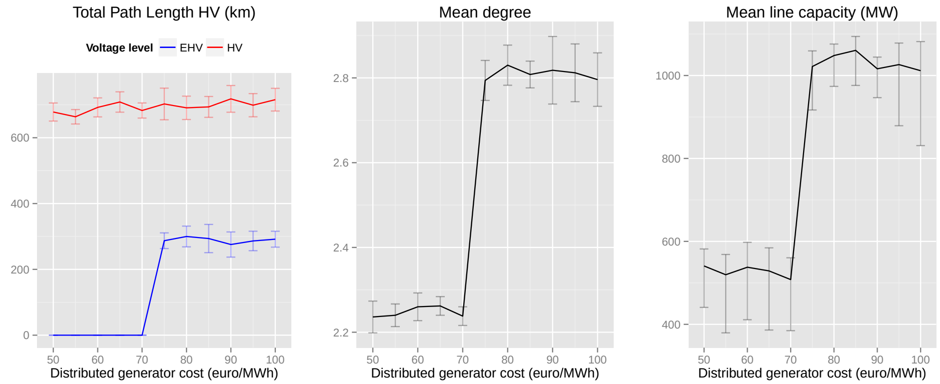


Figure 7.6: Effect of variations in the cost of distributed generation technologies on the topology of the resulting network.

As illustrated in Figure 7.7, adjusting the desired percentage of looped components of the TSO – essentially a societally-determined redundancy requirement – affects certain aspects of the resulting network. A higher looped percentage causes the grid operator to construct more redundant lines in the form of loop structures. The addition of these redundancies means a network with more linkages between components, both in the HV and EHV grids, meaning a greater path length and a higher mean degree. The desired percentage of looped components also has a moderate effect on mean line capacities, with the highest capacities at moderate "looped percentage" levels.

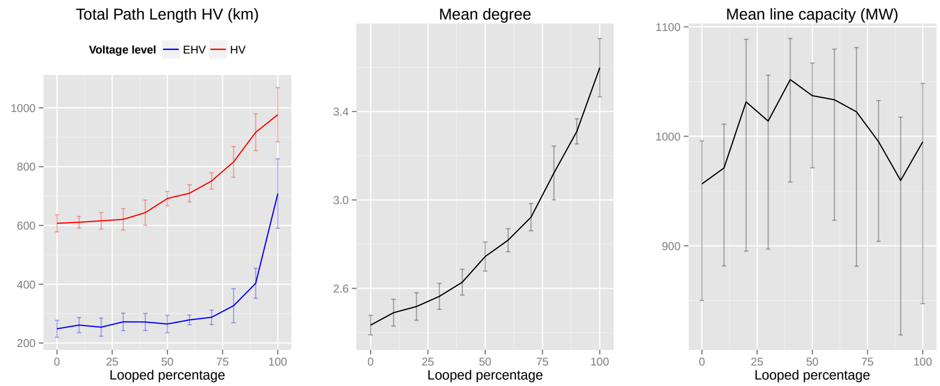


Figure 7.7: Effect of variations in the desired percentage of looped components on the topology of the resulting network.

Finally, Figure 7.8 illustrates the effect of an increasing ceiling on the TSOs expenditures. At a very low ceiling level, the TSO has insufficient funds to construct an EHV grid or add redundancies to the network. At these levels, both the path length and the mean degree are diminished. Once moderate ceiling levels are reached, the TSO's financial resources are no longer an impediment to the development of the network. A higher ceiling does not affect the resulting network topology.

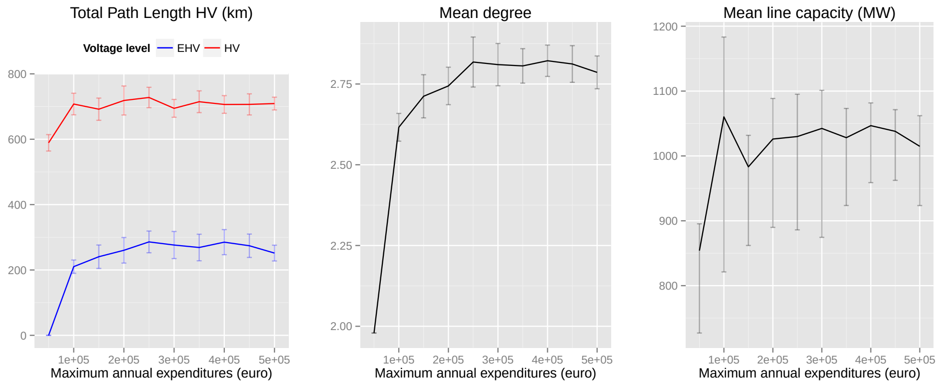


Figure 7.8: Effect of variations in the maximum expenditures of the TSO on the topology of the resulting network.

## Experiment 3: Adaptation of the network to a societal development

In the previous section, we explored the relationships between various changes in parameter conditions – corresponding to different configurations of the social subsystem – and the properties of the emergent network. In this section, we assess the consequences of a sudden societal development on the evolution of the network. We first allow a network to evolve at the default parameter conditions for a period of 50 years, allowing a relatively mature network to develop. At 50 years, we introduce a sudden drop (step change) in the cost of distributed generation technologies – from 100 to 50 euro/MWh – and allow the system to evolve for another 50 years. Via this experiment, we seek to gain insight into the *adaptability* of the infrastructure under changing conditions.

Figure 7.9 compares the values of several metrics collected during the course of 10 simulation runs under these conditions. As these plots illustrate, a sudden drop in the cost of distributed generation technologies has a clear effect on the development of the system, stabilizing the growth of the network – both in terms of path length and capacity – despite continued growth in demand and generation capacity. However, this change notably does not cause a roll-back to the sort of "minimal" grid observed when the cost of distributed generation is low from the start of the simulation (Figure 7.6). This is a result of both the long lifetime of grid components and of the unwillingness of the TSO agent to dismantle costly infrastructure that he has already put in place.

## Analysis of similarities to real-world electricity networks

In this section, we explore the similarities and differences of the modeled system to real-world electricity networks. First, we compare the mean degree of generated

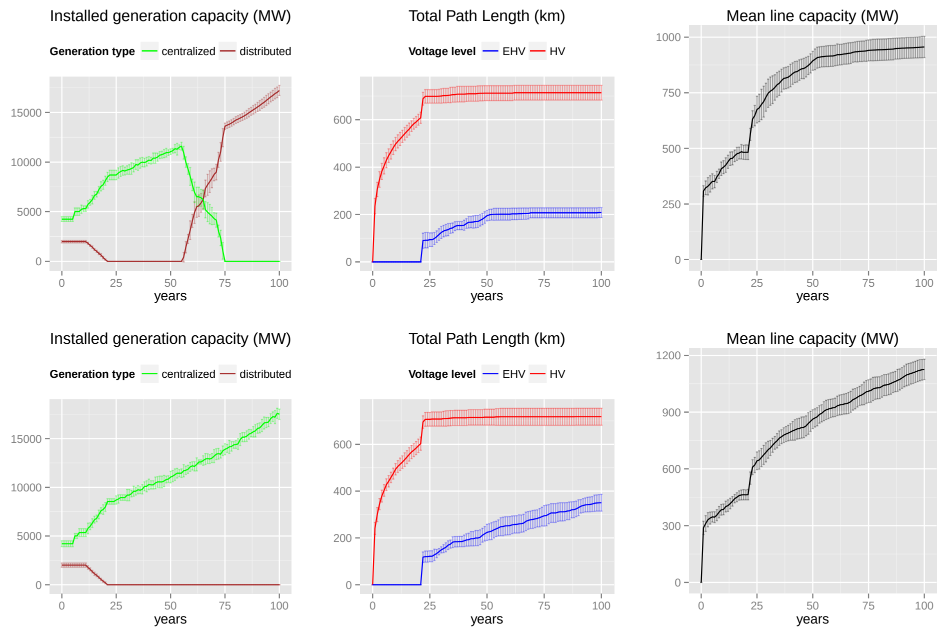


Figure 7.9: Effects of a step change in the cost of distributed generation at 50 years (top plots) vs. no change in the cost of distributed generation (bottom plots). A sudden drop in the cost of distributed generation incites a transition from centralized to distributed generation (top left). This, in turn, reduces net demand (demand less generation capacity) within distribution grids, which reduces load on the transmission grid. This causes the TSO agent to reduce his investments in new EHV lines and in additional capacity for existing lines – resulting in a leveling out of total path length (top middle) and mean line capacity (top right) compared with the control case (bottom plots). Results are averaged over 10 runs. Error bars indicate values within one standard deviation on either side of the mean.

networks with that of 19 European national transmission grids[5]. European transmission grid data for this comparison has been taken from Rosas-Casals (2009). Generated network data for this comparison is based on a full-factorial experiment of 288 model runs using the ranges given in Table 7.3. Results of this comparison are illustrated in Figure 7.10(a). As this plot illustrates, the selected real-world networks have mean degrees ranging from 2.11 to 2.82, with a mean of 2.45. The generated networks encompass a much wider range of mean degrees, with values ranging from 1.98 to 6.36, and a mean of 2.45. Under some combinations of parameter values, the model does indeed produce networks with a mean degree similar to that observed in the selected real-world networks. However, the model also generates networks with mean degrees above and below those observed in the selected real-world networks, implying that the parameter space encompasses social subsystem configurations beyond those observed in the selected European countries. This is exactly the sort of flexibility one expects in a model intended as a basis for exploring the consequences of future changes in the social subsystem.

[5]This includes Belgium, The Netherlands, Germany, Italy, Austria, Romania, Greece, Croatia, Portugal, Poland, Slovak Republic, Bulgaria, Switzerland, Czech Republic, France, Hungary, Bosnia, Spain and Serbia

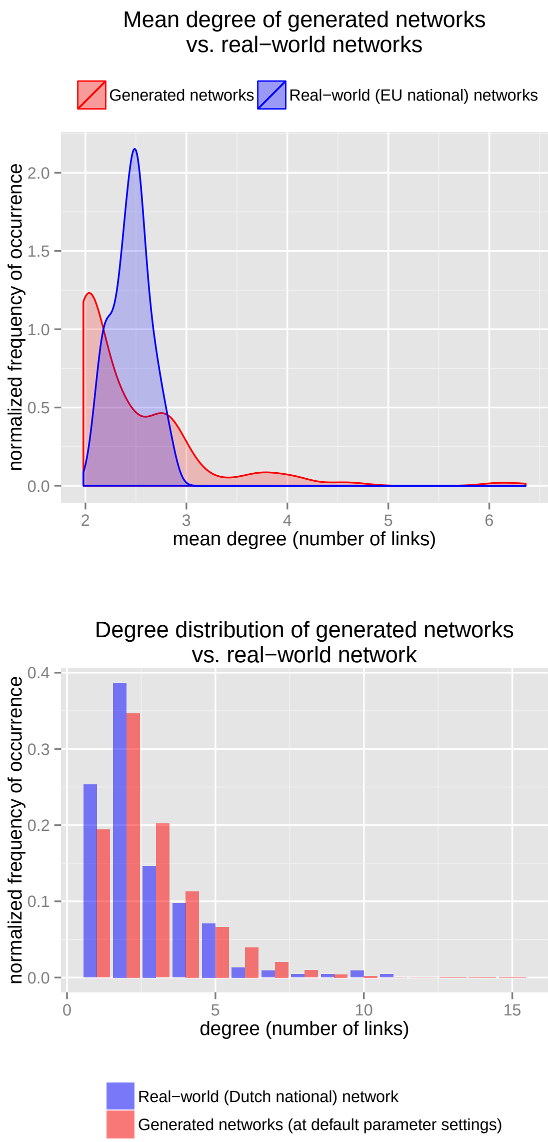


Figure 7.10: Comparison of generated networks with real-world transmission grids. Left pane: Density plots comparing the mean degree of generated networks with the mean degree of 19 national transmission networks in Europe. As illustrated by the plot, the values produced by the model encompass the range of values observed in European transmission networks. Right pane: Comparison of the degree distribution of generated networks at the default settings to that of the transmission network of the Netherlands. The degree distributions generated by the model display a similar pattern to those of the Dutch network.

In Figure 7.10(b), we compare the degree distribution of generated networks with that of the transmission network of the Netherlands. Data pertaining to the Dutch transmission grid has been taken from official documentation of the Dutch transmission system operator (TenneT, 2009). Generated network data for this comparison is based on mean values taken from 100 simulation runs at the default parameter settings (identical to the data used in Figure 7.3(b)). As illustrated in Figure 7.10(b), the Dutch transmission grid and the generated networks demonstrate a similar degree distribution pattern, with both networks showing a peak at a degree of two links per substation, and thereafter a nonlinearly decreasing frequency of occurrence with increasing degree. Relative to the Dutch transmission network, the mean of the generated networks slightly under-represents the frequency of low (one and two) degree substations, and slightly over-represents the frequency of moderate (three to eight) degree substations. While the generated networks do not precisely replicate the degree distribution of the selected real-world network, they produce a very similar pattern, further attesting to the capacity of the model to produce realistic networks.

## 7.7 Model evaluation

In this section, we evaluate the suitability of the developed model with respect to the stated aims of the modeling exercise. Two questions are pertinent:

1. To what degree does the model demonstrate consistent and explainable relationships between the properties of the social subsystem and those of the emergent technical network?

2. To what degree is the model a suitable basis for exploring the development of *real-world* transmission grids under different circumstances?

With respect to the former of these questions, the results from the first experiment illustrate how the delineated decision rules give rise to a network whose properties are relatively stable under the tested parameter conditions, despite significant randomness in the geographical landscape and in the order of investments. This demonstrates the capacity of the model to provide consistent results.

The results from the second and third experiments reveal clear relationships between variables of the social subsystem and the structure of the emergent technical network. The results from the second experiment show that increased electricity demand drives the development of a larger network with more lines and higher capacities; that greater decentralization of production stimulates a smaller network; that increased preference for loop structures promotes a more interconnected network; and that an increased expenditures ceiling only affects network development to a point. The results from the third experiment show limited adaptability of the technical network to changes in the social subsystem. Each of these results is explainable in the sense that it can be attributed to particular features of the represented system. Moreover, they are consistent in the sense that the results do not deviate significantly across model runs under identical parameter conditions. We can thus conclude that the employed approach indeed demonstrates consistent and explainable relationships between the properties of the social subsystem and those of the emergent technical network.

With respect to the latter question, we are interested in how well the approach mimics patterns of development observed in real-world electricity infrastructures. As noted, the results from the first experiment illustrate how the delineated decision rules give rise to a network whose properties are relatively stable despite significant randomness in the geographical landscape. This result is in line with the findings of Rosas-Casals (2009) that many European transmission grids feature similar network properties, even given vastly different geographical contexts. In other words, the consistency of results despite geographical randomness is not a model artefact, but mimics a feature of real-world infrastructures.

The results from the comparison between generated and real-world networks indicate that the model is capable of generating networks with properties similar to those of real-world transmission networks. In particular, the mean degree of generated networks encompasses the range of mean degrees observed in European transmission networks, and the degree distribution at the default settings shows similarity to that of a typical real-world transmission network. These results further testify to the suitability of the employed approach in exploring the development of real-world transmission grids.

While the developed model is able to capture certain social drivers of technical network evolution, it is restricted in its ability to capture feedbacks in the opposite direction – the social subsystem is limited in its ability to adapt alongside the technical; the fitness landscapes are not fully coupled. This misses an important dimension of the real-world system in which the development of the technical system may affect the attitude and behavior, if not the role, of the actors in the social landscape. For instance, decentralization of electricity generation may allow consumers to morph into small-scale producers, who may eventually self-organize to form local electricity markets (Sonnenschein et al., 2012). Research in the social simulation community in areas such as innovation networks (Gilbert et al., 2001) and inter-firm partnership formation (Oezman, 2007) could help to enrich the model's limited representation of dynamics within the social subsystem, and their relationships with technical developments.

## 7.8 Synthesis

Meeting current demands for a more sustainable and resilient electricity system necessitates improved understanding of how these infrastructures may evolve as circumstances change. The model presented in this paper is a robust starting point for such research. By representing the behavior of grid operators alongside power producers, we are able to capture the development of the electricity grid alongside generation and demand. By representing key linkages between the social and technical subsystems of the electricity infrastructure, we are able to explore the consequences of various societal developments on the development of the technical network. And by representing relevant properties of the technical infrastructure, we are able to identify limitations on the system's ability to adapt as circumstances change.

These capabilities endow us with a powerful tool for exploring the future development of real-world electricity networks under different circumstances. Further elaboration and incorporation of reverse feedbacks – impacts of technical developments on social roles and organization – can facilitate the capture of electricity infrastructures as true artificial societies. In the next chapter, we build on the developed model, refining the decision making processes and seeding the model with a detailed representation of the Dutch electricity infrastructure. This allows us to explore the development of the infrastructure under different circumstances, with the aim of understanding how various factors may support or detract from its resilience.

# Chapter 8

# Future development of the Dutch transmission infrastructure and consequences for resilience

## 8.1 Introduction

The development of the electricity infrastructure is influenced by myriad factors unrelated to climate resilience. Foremost amongst these are climate mitigation concerns, manifested in a range of institutional forms. These concerns are not likely to subside any time soon, and as such may significantly affect the infrastructure's development over the coming decades. In light of this key determinant of the infrastructure's future development, a relevant question is the following: *How might a low-carbon transition affect the vulnerability of the Dutch electricity infrastructure to climate change, and how can we harness this transition to support climate resilience?* This is the chief question we seek to answer in this chapter.

This chapter describes the second part of the second case study of this research. In the sections that follow, we describe the development and results of a model exploring future development trajectories of the Dutch electricity infrastructure. The results of this model – which describe possible configurations of the infrastructure in 2050 – are then evaluated with respect to their resilience to extreme weather events. The model described in this chapter builds on the abstract model introduced in chapter 7, but with a more limited scope and several refinements to better reflect the socio-technical composition and characteristics of the Dutch electricity infrastructure. The model described in this chapter also makes use of a slightly modified version of the model introduced in chapter 6 for assessing extreme weather resilience.

The model introduced in this chapter must be seen in the context of several related modeling efforts not described in this book. These related efforts, taking place within the EMLAB-Generation modeling project, deal with the development of agent-based models to explore transitions in electricity generation in Northwest

Europe (De Vries et al., 2013; TU Delft, 2013). The model described in this chapter is complementary to these efforts in that it represents the development of the transmission system *alongside* generation – enabling exploration of the effects of developments in generation on the *resilience* of the infrastructure as an interconnected system.

In particular, the model described in this chapter should be seen as a complement to the model of Paling (2013), which captures the processes underlying the long-term spatial and technological development of the Dutch generation portfolio. The model of Paling (2013) represents key factors contributing to the decisions of power producers in terms of where to site new power plants and which generation technologies to employ, and represents how these factors influence the development of the generation portfolio under different conditions. The model of Paling (2013), however, does not explore the effects of generation developments on the transmission infrastructure, which is the focus of the model described in this chapter. Though we stop short of explicitly linking the results from the model of Paling (2013) with the developed model of transmission development, this may be a fruitful direction for future research.

We continue in the next section with a description of the focal system of this chapter – the Dutch electricity infrastructure – stressing the determinants of transmission system development in the Netherlands. After this, we introduce the modeling technique, model design and software implementation used for the developed model. Next, we offer a limited validation of the developed model and present the results of several experiments. Drawing from these results, we conclude with a discussion with respect to the research question above.

## 8.2 System description – determinants of transmission system development in the Netherlands

The purpose of this chapter is to understand the consequences of future development trajectories of the Dutch electricity infrastructure on its resilience to extreme weather events. In order to explore these future development trajectories, we need to understand the processes underlying the infrastructure's evolution. The model developed in this chapter focuses on a particular aspect of this evolution – the evolution of the *transmission system*. In the paragraphs below, we provide an overview of the key determinants of transmission system development in the Netherlands, namely the investment process of the TSO and the key features of the regulatory environment. For a more thorough description of the Dutch electricity infrastructure in terms of its socio-technical composition, we refer the reader to chapter 6.

### Investment process of the TSO

Transmission system investments in the Netherlands are carried out by the transmission system operator (TSO), *TenneT*. TenneT is the manager of electricity transmission grids in the Netherlands with voltage levels of 110 kV and higher[1]. The

[1] As of 2010, TenneT also manages a portion of the German transmission network. In this chapter, we focus exclusively on TenneT's activities within the Netherlands

core tasks of TenneT as manager of these grids include the provision of connection services, transmission services and system services. *Connection services* entail the provision of connections to the transmission grid, the arrangement of maintenance for these connections and the rectification of any faults which may occur (TenneT, 2014a). *Transmission services* refer to the facilitation of transmission of electricity across the national high-voltage grid. This involves managing the grid and creating arrangements with regional and neighboring country grid operators to ensure the smooth transmission of electricity (TenneT, 2014b). *System services* entail services to ensure the safe and efficient transmission of electricity, the resolution of large-scale disruptions and the maintenance and restoration of the balance between electricity generation and consumption (TenneT, 2014c).

In performing these services, TenneT must make investments in different types of grid components, including maintenance and replacement of existing components, capacity expansions and grid extensions. In determining necessary investments, TenneT follows an *asset management* model, which entails assembling investment plans based on asset needs (Okhuijsen, 2013). In implementing an asset management model, TenneT follows a *risk-based* investment strategy, beginning with the identification of grid constraints from load flow calculations, failure investigations and asset health data (Okhuijsen, 2013).

In this context, TenneT's decision process with regard to investments may be conceptualized as a four-step process (Okhuijsen, 2013). First, grid constraints are assessed using an *asset risk analysis*. This analysis takes into account aspects including safety, quality of supply, financial considerations, reputation, customers, environment and compliance. Second, each risk is categorized according to the severity of its effect and its frequency. For risks exceeding a particular threshold, mitigating measures are recorded in the portfolio. Third, the portfolio is analyzed and optimized in terms of risk, performance and cost. Finally, an annual investment plan is created, which includes a selection of investment projects to start and projects to defer.

## Regulatory environment

While TenneT is ultimately responsible for expanding and maintaining the Dutch transmission grid, its investment decisions are affected by a range of other actors and institutions. One of the key challenges faced by TenneT in planning investments is the uncertainty associated with developments in electricity supply. Since the liberalization of the Dutch electricity sector, transmission investments and generation investments are undertaken by organizationally distinct actors with incomplete knowledge of one another's strategic plans. Given that the planning and construction time of large generators is generally much shorter than that of transmission lines, TenneT must plan grid investments under conditions of incomplete knowledge as to when and where these facilities may be built by electricity production companies. This challenge is further compounded by the generally long lifetimes of transmission grid assets – a transmission substation typically lasts 40-50 years – meaning that current grid investments may have to deal with a vastly different technological and geographical distribution of generation during the course of their lifetime.

TenneT's investment decisions are also affected by several laws and regulatory actors. The 1998 *Elektriciteitswet* (Electricity Act) established TenneT as the Dutch TSO and the *Nederlandse Mededingingsautoriteit* (Netherlands Competition Authority), or NMa, as the energy regulator. The NMa is responsible for approving the large investment proposals of TenneT, since these investments can significantly affect TenneT's tariffs. In addition to approving large investments, the NMa requires TenneT to regularly (every 2 years) submit a *Quality and Capacity Plan*, which provides an official account of developments in the Dutch electricity market and necessary actions for maintaining a high-quality and reliable transmission system (TenneT, 2009). In particular, the *Quality and Capacity Plan* describes the results of calculations – load flow calculations, short-circuit calculations and stability calculations – over a seven year time horizon in order to determine to what degree anticipated power transmission needs can be realized with the present grid (TenneT, 2009).

Next to the requirements and decisions of the NMa, TenneT's investment decisions are affected by spatial planning processes. In particular, the Ministry of Economic Affairs drafts (at irregular intervals) a *Structuurschema Elektriciteitsvoorziening* (Electricity Supply Structure Plan), the most recent of which – the *Derde Structuurschema Elektriciteitsvoorziening*, or SEVIII (Tweede Kamer, 2009) – was released in 2009. This document details allocated spaces and corridors for transmission lines and large-scale electricity production facilities in the Netherlands for the coming years. The SEVIII allocates 35 corridors for high-voltage lines and 38 locations for large power production facilities (Tweede Kamer, 2009).

A final key regulatory document affecting TenneT's investment decisions is the *Netcode* (Grid code), which contains conditions for the conduct of grid administrators with respect to grid operation, design and performance (Nederlandse Mededingingsautoriteit, 2014). With respect to the design of the grid, the Grid Code consists of three key criteria (TenneT, 2009):

**Criterion A:** "A fully operational grid must be capable of secure transmission of such input and output as the connected parties require, even if one network element fails."

**Criterion B:** "In the event of any circuit, transformer, production unit, or bulk user being unavailable due to maintenance, such input and output as the connected parties require must be achievable even if one network element fails. Here, only loads occurring during the maintenance period as a result of input or output have to be taken into account."

**Criterion C:** "In the event of failure of any circuit, transformer, any two production units, or any bulk user, it must be possible, even during peak load, to return the system to a condition where the n-1 criterion is satisfied by redistributing production or by other measures agreed in advance."

## Compliance in practice

Compliance with the regulatory environment is a core element of TenneT's asset management model, and thus a key determinant of investment needs. In practice, compliance with the Grid Code means that TenneT designs the Dutch 220 and 380kV grids according to an *n-2* criterion, meaning that these grids must remain fully functional in case of the simultaneous failure/maintenance of any two components, assuming high load (winter) conditions (TenneT, 2013d). The 110 and 150kV grids are designed according to an *n-1 under maintenance* criterion, meaning that they must remain fully functional in case of the failure of any one component under high load conditions, and failure/maintenance of any two components under low load (summer) conditions (TenneT, 2013d). In testing the compliance of the grid with respect to these criteria, TenneT performs n-1 and n-2 contingency analyses under various scenarios in terms of generation dispatch, imports/exports and the future development of supply (TenneT, 2013d).

Because the planning and development time for transmission investments often exceeds the seven year time horizon of TenneT's Quality and Capacity Plans, TenneT's planning procedures also involve longer term forecasts of market development. The most recent of these longer term forecasts is solidified in TenneT's *Vision2030* document (Tennet, 2011), which describes several possible scenarios for the development of the Dutch electricity market to 2030 and consequences in terms of transmission requirements. The result of this document is an overall concept for the transmission grid of 2030, which is based around a single strong 380kV ring complemented by direct connections between production locations and this ring or to load centers (Tennet, 2011).

## 8.3 Technique – hybrid modeling

The model described in this chapter employs a hybrid technique of agent-based modeling, contingency analysis and structural vulnerability analysis. *Agent-based modeling* is used to capture the investment decisions of the TSO, and to generate an evolving technical network. *Contingency analysis* is used to represent a particular aspect of the TSO's decision process, namely its efforts to develop a system with a particular level of security. *Structural vulnerability analysis* is used to assess the resilience of generated configurations of the technical subsystem.

It is important to point out that the agent-based portion of the developed model is only agent-based insofar as investment decisions are encapsulated within defined agents. The interactions between these agents are uni-directional – the TSO responds to investments by power producers, but not vice versa. Moreover, the investment decisions of power producers are determined by exogenously defined scenarios, rather than interactions with other agents or complex "cognitive" processes. In this sense, the agent-based portion of the model is less an agent-based model *as such* than an "agent-encapsulated" algorithm, with this algorithm describing the TSO's investment process. The reason for encapsulating this algorithm within the context of an agent is to allow for extending and linking this model with other agent-based models, in particular the work of Paling (2013).

## 8.4 Model design

In this section, we will describe the design of the developed model. As noted above, the model employs a hybrid technique of agent-based modeling, contingency analysis and structural vulnerability analysis. As such, the design of the model may be conceptualized in terms of three submodels – an agent-based submodel, a contingency analysis submodel and a structural vulnerability analysis submodel. The relations between these submodels are illustrated in Figure 8.1. In the sections that follow, each of these submodels is described in some detail. At the end of this section, we describe in more detail the data inputs to the model.

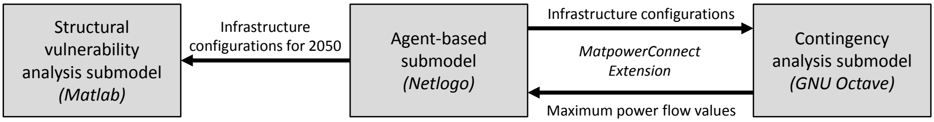


Figure 8.1: Relations between the employed submodels and software packages.

## The agent-based submodel

The agent-based submodel represents the decision processes of the TSO and power producers with respect to investments in technical infrastructure components. The input to the agent-based submodel is a dataset describing a base year (2010) configuration of the Dutch electricity infrastructure. The output is a set of datasets describing possible 2050 configurations of the infrastructure. As with the model described in the previous chapter, the TSO agent is chiefly responsible for investing in components of the transmission network, specifically substations, transformers and transmission lines. Power producers are responsible for investing in electricity generation capacity.

As noted above, the investment decisions of power producers in this model are determined by exogenously defined scenarios, rather than – as in the model of the previous chapter – by decision processes internal to the agents themselves. The reason for defining power producers as agents at all is to allow for future extension of the model in the form of replacing the defined scenarios with internal decision processes that better reflect the distinct motivations and bounded rationalities of these actors. The tested generation development scenarios are listed in Table 8.1. The purpose of these scenarios is not to comprehensively represent the possible development trajectories of generation in the Netherlands, but rather to capture a set of *qualitatively different* development trajectories which may lead to very different developments in the transmission infrastructure.

All generation development scenarios include a gradual (5% per year) reduction in large-scale centralized capacity at locations not specified for further development in the SEVIII document. This reduction in production capacity, as well as increases in demand, are compensated in different ways in the different scenarios. In the centralized scenario, they are compensated by growth in large-scale fossil fuel-based production facilities in the locations specified by the SEVIII document. Centralized production increases annually by an amount equal to the sum of the annual demand increase and the newly obsolescent production capacity at non-SEVIII locations. In the distributed scenario, they are compensated by growth in distributed generation; in the offshore wind scenario by growth in offshore wind; and in the import scenario by growth in imports. The export scenario is similar to the centralized scenario except that import demand in Germany, Belgium and the UK increases by 1% per year, rather than remaining constant, as it does in the previous scenarios.

Table 8.1: Generation development scenarios implemented in the agent-based submodel

| **Scenario** | **Description** |
|---|---|
| Centralized | Generation development dominated by growth in large-scale, fossil fuel-based production facilities. Gradual shift of generation capacity towards the SEVIII allocated production sites. |
| Distributed | Generation development dominated by growth in small-scale, distributed technologies. Gradual reduction in existing centralized, fossil fuel-based capacity. Growth in distributed generation is equally distributed amongst the distribution grids. |
| Offshore wind | Generation development dominated by growth in offshore wind. Gradual reduction in existing centralized, fossil fuel-based capacity. Growth in offshore wind is equally distributed amongst locations offshore of Maasvlakte, Beverwijk, Eemshaven and Borssele. |
| Import | Gradual reduction in existing centralized, fossil fuel-based capacity (1% per year), compensated by a gradual increase in imports from neighboring countries. Increase in imports is equally divided amongst the foreign interconnectors. |
| Export | Generation development dominated by growth in large-scale, fossil fuel-based production facilities. Gradual shift of generation capacity towards the SEVIII allocated production sites. 1% per year growth in import demand in Germany, Belgium and the UK. |

In addition to the generation development scenarios described in Table 8.1, the model also includes several scenarios in terms of domestic *demand development*. Development of demand in the model is determined by a parameter defining the percentage growth in demand of distribution grids in the Netherlands. Three demand development scenarios are tested, corresponding to a 0% annual growth in demand, a 1.5% annual growth in demand and a 3% annual growth in demand. In each of these scenarios, the rate of demand growth (in percentage terms) is equally distributed across the distribution grids. In experimenting with the model, we perform runs across the multi-dimensional scenario space framed by the generation development and demand development scenarios. That is, the model is run at each possible combination of generation development and demand development scenarios.

The manner of representing the development of electricity generation and demand in the agent-based submodel neglects several key aspects. Foremost amongst these is that the defined scenarios capture only a few select points within the range of possible future developments. While we have deliberately selected scenarios that are qualitatively distinct from one another, the limited number of the selected scenarios means that we inevitably miss a vast space of possible futures. A second feature of the model important to remark upon is the continuous nature of supply growth in the generation development scenarios. In reality, the growth of generation entails investments in discrete generation units, which may be very large. In other words, growth in supply tends to be considerably more irregular and discontinuous than represented in the model. Given that the dynamics of supply growth inevitably also affect the dynamics of growth in electricity transmission capacity, this assumption inevitably affects the model results – though we anticipate these effects to be minimal.

### Decision procedures of the TSO agent

The investment decisions of the TSO agent consist of two distinct procedures – one procedure describing the decision process for *new line* investments and one procedure describing the decision process for capacity expansions of *existing lines*. The decision process for new line investments simply involves the TSO constructing predefined new lines at predefined times, in line with known/anticipated projects in the Netherlands. These projects and their anticipated completion times, as implemented in the model, are listed in Table 8.2 and pictured in Figure 8.2. Projects not currently in planning or under consideration are currently excluded from the model.

Table 8.2: Ongoing and anticipated projects for the construction of new transmission lines in the Netherlands

| **Project name** | **Project description** | **Anticipated completion** |
|---|---|---|
| Randstad-Zuidring | 380kV connection in the south Randstad area, extending from the Westerlee substation to the Bleiswijk substation, also spanning the Wateringen substation (TenneT, 2014d) | 2013 |
| Doetinchem-Wesel | 380kV international connection from the Doetinchem substation in the east of the Netherlands to Wesel in Germany (TenneT, 2014a) | 2016 |
| COBRA-Cable | Subsea HVDC international connection from Eemshaven in the Netherlands to the Danish coast (Energinet.dk, 2013) | 2017 |
| Randstad-Noordring | 380kV connection in the north Randstad area, extending from the Bleiswijk substation to the Beverwijk substation (TenneT, 2014c) | 2018 |
| Zuidwest-380 | 380kV connection in the southwest of the Netherlands, extending from Borssele to Tilburg (TenneT, 2014d) | 2018 |
| Noordwest-380 | 380kV connection in the north of the Netherlands, extending from the Eemshaven substation to the Ens substation (TenneT, 2014b) | 2020 |
| Diemen-Dodewaard-380 | Possible 380kV connection through the center of the Netherlands, extending from Diemen in the West to Dodewaard in the East, and passing through Utrecht (Tennet, 2011) | 2030 |

The TSO's decision process for investing in *capacity expansions* is structured around ensuring continuous compliance with the Dutch *Grid Code*. The decision process of the TSO represents (in abstracted form) the procedure by which TenneT identifies necessary investments to ensure the continued alignment of its grids with these criteria. Each timestep, the TSO agent carries out a set of five different n-2 contingency analyses over the 220 and 380kV grids, each corresponding to a different scenario in terms of generation dispatch and export/import. These scenarios are listed in Table 8.3, and are loosely based on those used in TenneT's 2010 *Quality and Capacity Plan* (TenneT, 2009)[2]. The aim of these scenarios is to capture the range of possible power flow magnitudes to which the elements of the technical system may be subjected. In addition to carrying out these analyses over the 220 and 380kV grids, the TSO agent also carries out a single n-1 contingency analysis over each of the 110 and 150kV grids. In the case of all of these analyses, the

[2]It is important to note that these scenarios play a different role than the generation and demand development scenarios discussed above. The generation and demand development scenarios determine how the TSO's socio-technical environment develops, whereas the dispatch/import/export scenarios described here are a part of the TSO agent's investment decision processes.

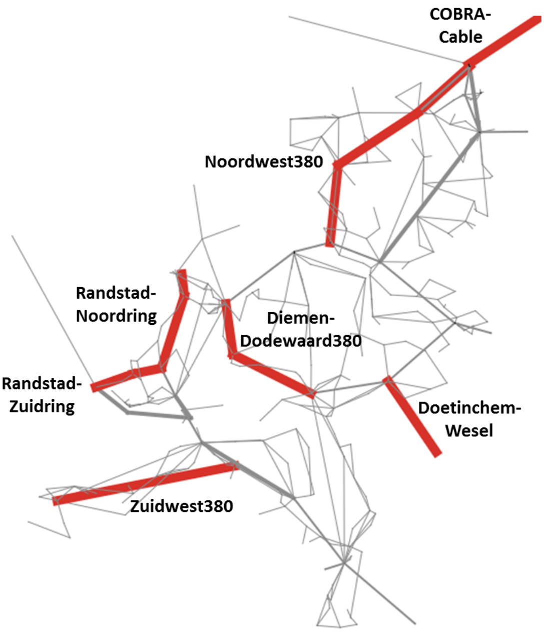


Figure 8.2: Representation of the Dutch transmission network, with planned/anticipated new transmission lines are highlighted in red.

magnitude of demand is set in line with high load (winter) conditions.

Table 8.3: Scenarios for generation dispatch and import/export used by the TSO agent in performing contingency analyses. These scenarios are loosely based on the scenarios used in TenneT's 2010 *Quality and Capacity Plan* (TenneT, 2009).

| **Scenario** | **Description** |
|---|---|
| ExportBasic | Relatively high level of domestic production; high exports to Germany, Belgium and the UK |
| ExportNorth | High domestic production in the northern part of the Netherlands; high exports to Germany, Belgium and the UK |
| ExportWind | High domestic production by onshore and offshore wind; high exports to Germany and Belgium |
| ExportSouthwest | High domestic production in the southwest part of the Netherlands; high exports to Germany, Belgium and the UK |
| ExportWest | High domestic production in the west part of the Netherlands; high exports to Germany and Belgium |
| Import | Relatively low level of domestic production; high imports from Germany, Belgium and Norway |

The contingency analysis calculations are carried out by the contingency analysis submodel, which is described in more detail below. Each timestep, the results of this model – which constitute maximum anticipated power flows over each line of the transmission system – are passed back to the agent-based submodel and used by the TSO agent as a basis for making capacity investments. For each line whose maximum anticipated power flow exceeds its current capacity by more than 10%, the

TSO agent will undertake a capacity expansion project. It is assumed that a capacity upgrade occurs immediately. This assumption essentially implies that the the TSO's decision process for investing in capacity expansions entails *perfect knowledge* on the part of the TSO with respect to generation and demand developments. This is admittedly a questionable assumption in light of the large role of uncertainties in generation development in TenneT's planning procedures. However, given that the effects of these uncertainties are not the primary focus of this model, we have chosen to exclude them here.

The setup of this procedure makes a number of key simplifications with respect to TenneT's stated procedures for determining necessary investments with respect to the Grid Code, with different consequences for the validity of the results. In particular, capacity expansions in the model refer only to expansions of *transmission line* capacity. Capacity expansions for other types of components, such as transformers and busbars, are not considered. In analyzing the infrastructure's resilience, this means that we ignore potential capacity constraints associated with these components, suggesting that we may miss certain failure mechanisms and overestimate system resilience. Additionally, the developed model only executes an *n-1* contingency analysis (under high load conditions) for the 110 and 150kV grids, whereas TenneT also tests these grids using an n-2 contingency analysis under low load (summer) conditions. This may mean that the developed model, under certain circumstances, underestimates the magnitude of capacity expansions. Finally, the TSO agent in the developed model will *always* make a capacity investment when the procedure identifies a shortage – essentially excluding the latter part of TenneT's investment procedure in which identified risks are categorized and investments optimized (and possibly deferred). This may mean that the model overestimates the magnitude of capacity expansions under certain circumstances.

## The contingency analysis submodel

As mentioned above, the purpose of the contingency analysis submodel is to carry out n-1 and n-2 contingency analyses over a given electricity network. These electricity networks are instantiated within the agent-based submodel and passed to the contingency analysis submodel, which then calculates the maximum power flows through each line of the given network across the range of tested contingencies. This list of maximum power flows is then passed back to the agent-based submodel, and – as described above – incorporated into the decision procedures of the TSO agent.

The contingency analysis submodel essentially consists of two procedures, an n-1 analysis and an n-2 analysis. The n-1 analysis involves iteratively removing each circuit of the network and calculating the resulting power flows through each line of the system. The n-2 analysis involves iteratively removing each possible *pair* of circuits in the network and calculating the resulting power flows through each line. The n-2 analysis in particular involves a significant amount of computation. For instance, a network with 100 links of 2 circuits each requires (200 X 199 = ) 39,800 iterations. However, the computational load is reduced by the fact that the removal of many circuits will not result in any change in power flows[3]. For both the n-1

[3] It is assumed that the removal of a single circuit from a line with two circuits, or the removal of two circuits from a line with three circuits, will not affect power flows.

and n-2 analyses, power flow calculations take the form of a DC power flow analysis, which – as discussed in chapter 5 – is faster and more robust but sometimes less accurate than an AC analysis.

A key simplification of the contingency analysis submodel described here, compared with the contingency analyses carried out by TenneT, is that our submodel only tests contingencies relating to the failure/maintenance of *circuits*. TenneT's analyses take into account the failure/maintenance of further system elements, such as busbar systems, transformers and production units (TenneT, 2009).

### The structural vulnerability analysis submodel

The structural vulnerability analysis (SVA) submodel takes as input the network configurations developed within the agent-based submodel, and evaluates these networks in terms of their resilience to extreme weather events – in particular floods and heat waves. The SVA submodel is essentially identical to the model introduced in chapter 6, and involves exposing an electricity network to extreme events of successively increasing magnitude. With each successive increase in extreme event magnitude, the properties and/or composition of the infrastructure is changed and the infrastructure's performance is evaluated. This evaluation takes the form of a power flow calculation which determines the power flow magnitudes across the lines of the infrastructure and the quantity of power delivered to each distribution grid. For a more detailed description of this model, we refer the reader to chapter 6.

There are two important differences between the SVA submodel and the model introduced in chapter 6. First, the inputs to the SVA submodel are representations of possible configurations of the Dutch electricity infrastructure in 2050, rather than representations of the current configuration of the infrastructure. Second, the SVA submodel only evaluates resilience of the network in the absence of any adaptation measures. The potential effects of flood protections and demand-side management are not considered.

### Input data

The input to this model is a dataset describing the base year (2010) configuration of the Dutch electricity infrastructure, as well as a dataset describing anticipated transmission investments to 2050. The first of these datasets is identical to that used as input to the model in chapter 6 (illustrated in Figure 8.3). The second reflects TenneT's planned and anticipated projects, as listed in Table 8.2 and illustrated in Figure 8.2.

## 8.5 Software implementation

The model has been implemented in a combination of software packages. The agent-based submodel is implemented in the agent-based modeling platform *Netlogo* (Wilensky, 2012). The contingency analysis submodel is implemented as a Matlab M file and runs in the numerical computation software *GNU Octave*. It makes use of the power system simulation package Matpower (Zimmerman et al.,


Figure 8.3: Representation of the Dutch transmission network, based on the model's input dataset. 380kV and 220kV (EHV) lines are colored in red and green, respectively. 150kV and 110kV (HV) lines are colored in gray. Major substations are labeled for reference.

2011). Runtime communication with Netlogo is enabled using a modified version of the *MatpowerConnect* extension (see chapter 5 for a description of this software). The structural vulnerability analysis submodel is implemented in *Matlab* as a set of three Matlab M files. The reader is referred to chapter 6 for a more thorough description of the software implementation of this submodel. Figure 8.1 illustrates the relations amongst the employed submodels and software packages. The computer code for all submodels can be downloaded from GitHub at `https://github.com/ABollinger/NetworkEvolutionModel_NLVersion`.

## 8.6 Validity of the model

In this section, we perform a limited assessment of the validity of the developed model by comparing the results from the first timestep of the model with the results of an analysis published in TenneT's 2010 *Quality and Capacity Plan* (TenneT, 2009). The TenneT data used in this comparison comprise the results of an analysis of the 2010 state of the Dutch transmission grid against Criterion B of the Dutch *Grid Code* (see above for a description of this criterion). For a full description of the setup of TenneT's analysis, we refer the reader to TenneT (2009). We compare the results of TenneT's analysis with the results of the developed model on the basis of *capacity exceedance* – that is, by comparing the discrete lines which in both cases are identified to exceed their nominal capacity under the tested range of generation/demand scenarios[4]. This comparison is intended to provide some insight into the degree to which the outcomes of the TSO agent's decision procedures correspond with those of TenneT's procedures.

In total, 34 transmission lines in the developed model were found to experience maximum anticipated loads exceeding their starting capacities. All other 362 lines were found to experience maximum anticipated loads below their starting capacities. These numbers are drawn from the results of the agent-based and contingency analysis submodels at the end of the first timestep of the simulation, and as such represent the results under a range of possible generation dispatch and import/export scenarios. A listing of the lines found to experience loads exceeding their capacities is provided in Table C.1 in the appendix, together with plots of the maximum anticipated loads across each line (Figure C.1 in the appendix).

The Venn diagram in Figure 8.4 summarizes the results of the comparison between Tennet's data and the results of the developed model. Of the lines experiencing maximum anticipated loads in exceedance of their transmission capacity, 8 were set with artificial capacities in the input data (due to missing data). An additional 11 were also found in one or more of the scenarios of TenneT's 2010 *Quality and Capacity Plan* (TenneT, 2009) to experience maximum anticipated loads in exceedance of their capacity. This leaves 15 lines that were found in the decision procedure of the TSO agent to experience maximum anticipated loads exceeding their transmission capacities, but which were not found to be doing so in TenneT's own procedures. TenneT's procedures identified a total of 68 lines anticipated to exceed their capacities, only 11 of which were found to be doing so in the results of the developed model. This leaves 57 lines that were found in TenneT's results to experience maximum anticipated loads exceeding their transmission capacities, but which were not found to be doing so in the results of the developed model. This suggests a misalignment in the results of (15 + 57 =) 72 lines, out of a total of 396 lines – a misalignment of 18%.

The identified misalignment between TenneT's data and the results of the developed model may likely be attributed to differences in the composition and properties of the network utilized by TenneT in its analysis, as well as aforementioned differences between the contingency analysis procedure used in the model with that used by TenneT. The relatively low misalignment between the outcomes of the TSO agent's decision procedure and TenneT's decision procedures testifies to the validity of the developed model. It is important to mention, however, that we did not fully analyze the discrepancies between these datasets - additional data would be necessary for this. We also excluded from consideration the possible effects of other aspects of TenneT's investment decision procedure, including e.g. risks unrelated to Grid Code compliance.

Further assessment of the model's validity is provided in the Discussion section below, where we qualitatively compare the results of the developed model with published projections of the development of the Dutch transmission infrastructure.

[4] Nominal capacity values in the developed model are obtained from TenneT (2009)

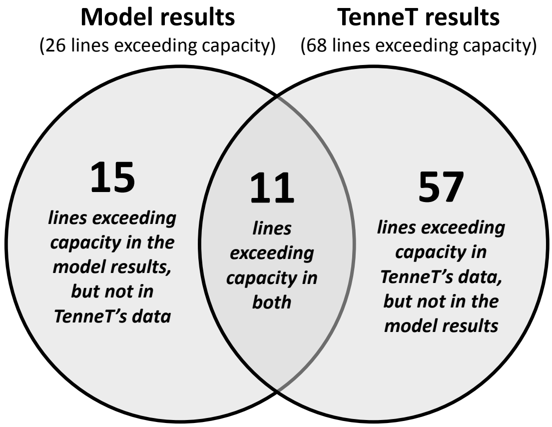


Figure 8.4: Summary of the comparison between TenneT's data and the model results. Lines set using artificial capacities have been excluded from the model results.

## 8.7 Results and analysis

In this section, we present and analyze the results of the developed model. The results presented in this section represent the outcomes of 15 runs of the developed model, one run at each distinct combination of generation development scenarios and demand development scenarios. Because there are no sources of randomness in the agent-based submodel and the contingency analysis submodel, we only perform a single model run at each point in the scenario space. Randomness in the SVA submodel is accounted for via multiple (1000) runs of that particular submodel. In the paragraphs that follow, we first discuss the results in terms of the generated evolutionary trajectories of the infrastructure. After this, we discuss the implications of these different evolutionary trajectories in terms of the infrastructure's flood and heat wave resilience.

### Evolutionary trajectories of the infrastructure

Each distinct combination of generation development and demand development scenarios produces a unique set of demands on the transmission network, which change over time. As a result of this unique set of demands, the transmission system develops differently under different conditions. Figures 8.5 and 8.6 illustrate the development of cumulative transmission capacity under the different scenarios for the extra high-voltage (EHV) and high-voltage (HV) networks, respectively. As these plots illustrate, by far the largest increases in overall transmission capacity in the EHV grid may be observed in the import scenario, followed (for the cases of 1.5% demand growth and 3% demand growth) by the offshore wind scenario. The large growth rates under the import scenario may likely be attributed to the additional capacity necessary to transport power from neighboring countries to demand centers in the Netherlands.

Under demand growth rates of 1.5% and 3%, the smallest growth in EHV transmission capacity occurs in the centralized and distributed generation scenarios. This is logical, as a centralized scenario means that the structure of flows remains largely unchanged relative to the current situation, meaning that large capacity investments are unnecessary. While the distributed generation scenario may entail a different structure of flows, it also reduces the need for massive EHV capacity, as more electricity is produced within the subgrids themselves. In all scenarios, we see a rapid growth in EHV capacity during the first 10 years of the simulation, and in most cases a reduced rate after that. This large growth at the beginning of the simulation may be attributed to the number of new line projects that are completed before 2020, as described in Table 8.2.

For the HV grid, we also see large increases in overall transmission capacity under the import scenario, but these increases are not as different in comparison with the other scenarios as for the EHV case. Interestingly, however, for the HV grid, we see by far the smallest growth in transmission capacity in the distributed generation scenario – about half the level of growth observed in the other generation development scenarios. This can likely be explained by the fact that – with more generation occurring within distribution grids themselves – less capacity is needed to transport power from the connection points of the EHV/HV grids to the distribution grids.

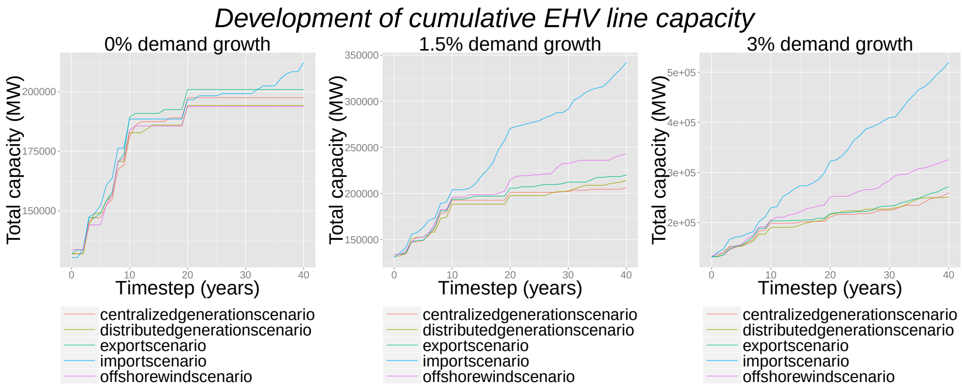


Figure 8.5: Results of the model: development of cumulative transmission capacity in the extra high-voltage (EHV) grid between 2010 and 2050 under the different tested scenarios. Cumulative transmission capacity is defined as the sum of transmission capacity of all lines in the transmission grid. It does not account for the relative length of the lines.

### Centralized generation scenario

In order to better understand the reasons underlying these observed patterns, we now take a closer look at the geographical distribution of capacity changes. Figure 8.7 illustrates the results for the centralized generation scenario – which entails generation development dominated by growth in large-scale, fossil fuel-based production facilities, together with a shift of generation towards the SEVIII locations. Similar maps for the HV network can be found in Appendix C.2. As illustrated in Figure 8.7, we observe in the centralized generation scenario a relatively high rate of capacity growth in the west of the Netherlands. This is particularly true in the 380kV corri-

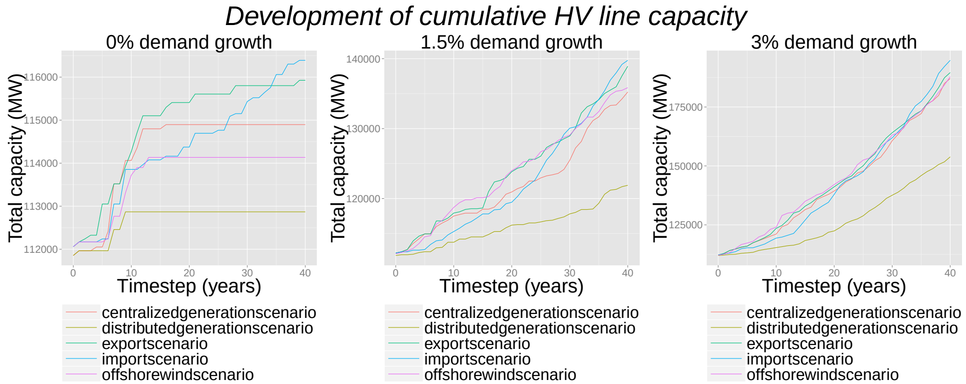


Figure 8.6: Results of the model: development of cumulative transmission capacity in the high-voltage (HV) grid between 2010 and 2050 under the different tested scenarios.

dor extending between the Ens and Geertruidenberg substations. These patterns of growth align with a need to transport electricity from the coastal production centers of Maasvlakte, Borssele, and Diemen/Lelystad – where centralized generation facilities are located – to the demand centers, particularly in the Randstad region.

As can be expected, we observe more capacity growth under higher rates of demand growth. At 3% demand growth, we observe significant growth in capacity in the northern and central parts of the Netherlands, in addition to that in the west. In this case, especially high rates of growth occur in the 380kV corridor between Eemshaven and Zwolle, likely corresponding to large increases in generation in the Eemshaven port area, which have to be transported to the Randstad.

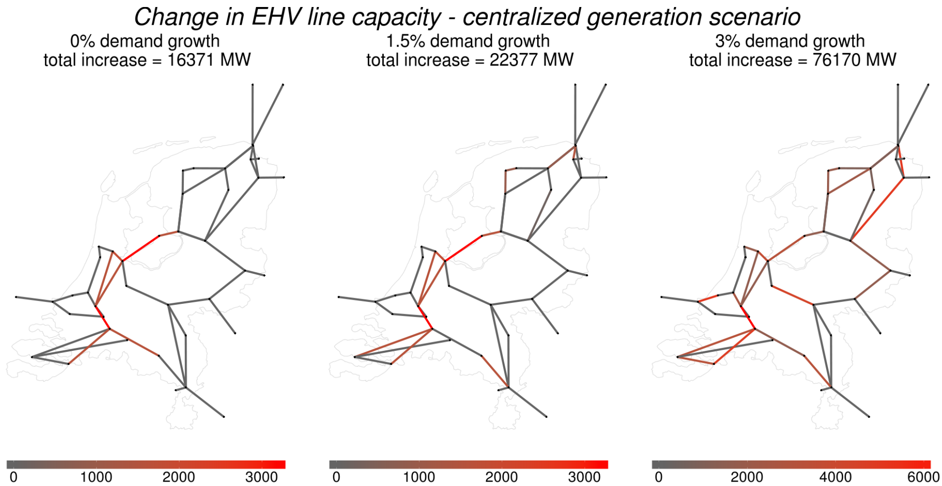


Figure 8.7: Development of transmission capacity in the extra high-voltage (EHV) grid under the centralized generation scenario, according to the model results. Line colors indicate the relative growth in transmission capacity (in MW) between 2011 and 2050. The first year of the simulation is excluded so as to eliminate distortion of the results due to missing line capacity data in the model inputs.

### Distributed generation scenario

Figure 8.8 illustrates the results for the distributed generation scenario – entailing a situation in which generation development is dominated by growth in small-scale, distributed generation technologies. The geographical distribution of EHV capacity growth in this scenario is quite similar to the centralized generation case, with significant capacity growth along the Ens-Geertruidenberg corridor under all demand growth rates. The magnitude of capacity growth in the distributed generation scenario is also on the same order of magnitude of that observed in the centralized generation scenario – 13GW at 0% demand growth and 68GW at 3% demand growth.

The similarity between the outcomes of the distributed and centralized generation scenarios is interesting and somewhat curious, as it suggests that a future based around small-scale distributed generation may have similar implications for the TSO as a future based around large-scale centralized generation. This may be attributed to the fact that, in the model, growth in distributed generation is (assumed to be) spread evenly across the country, while demand is still concentrated in the Randstad region. Thus, even though much of demand is being satisfied by small-scale generation facilities embedded within the distribution grids, the distance that electricity must travel to reach customers remains quite large. As in the centralized generation scenario, this necessitates the realization of additional transmission capacity to transport power from the North and East to the Randstad region. If the geographical distribution of distributed generation was better matched with the geographical distribution of demand, this would not be the case.

Despite the apparent similarities to between the distributed and centralized generation scenarios, it is important to point out some key differences. First, capacity growth in the distributed generation scenario is, for the most part, somewhat lower than in the centralized generation scenario. Second, we observe less capacity growth in the Eemshaven-Meeden corridor and in the Geertruidenberg-Borssele/Zandvliet. The latter of these differences may be attributed to the reduced significance of coastal production centers relative to the centralized generation scenario.

Figure 8.9 illustrates the results for the offshore wind scenario – in which development is dominated by growth in offshore wind, complemented with a gradual reduction in existing centralized, fossil fuel-based capacity. We see some important differences here to the previous scenarios. Especially in the 1.5% and 3% demand scenarios, we observe greater development of EHV capacity in the east-west direction relative to the previous cases. This is particularly evident in the corridors between Maasvlakte and Bleiswijk/Krimpen, between Borssele and Geertruidenberg, between Eindhoven and Maasbracht, and between Utrecht and Dodewaard. In the 3% demand growth scenario, we also see significant capacity growth in the north-south 380kV corridor between Eemshaven and Zwolle. These corridors of capacity growth are consistent with needs to transport larger amounts of power between the assumed offshore connection points of Borssele, Maasvlakte, Beverwijk and Eemshaven, and the demand centers of the Netherlands.

In terms of overall magnitude, the offshore wind scenario produces significantly more EHV capacity growth than the centralized and distributed generation scenarios. In fact, cumulative capacity growth in the 3% demand scenario is nearly *double* that of the previous scenarios. Interestingly, however, this is not the case for the

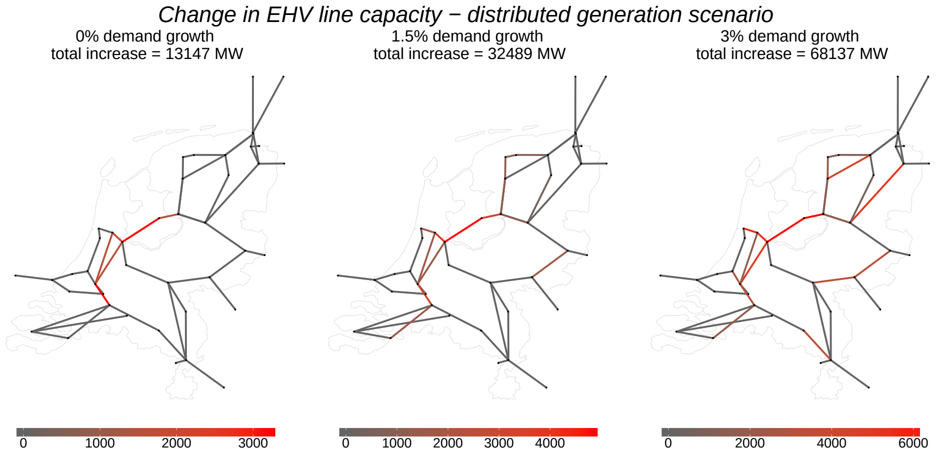


Figure 8.8: Development of transmission capacity in the extra high-voltage (EHV) grid under the distributed generation scenario.

0% demand growth case, under which the magnitude of capacity development is actually *less* than that in the previous cases. These differences may be attributed to the altered pattern of power flows engendered by the offshore wind scenario. When the wind is blowing, large magnitudes of electricity must be transported from the coastal production centers of Borssele, Maasvlakte, Beverwijk and Eemshaven – even more so than in the centralized generation scenario. This is most evident in the 3% demand growth case. It is less evident in the 0% demand growth case, where growth in offshore wind capacity is smaller.

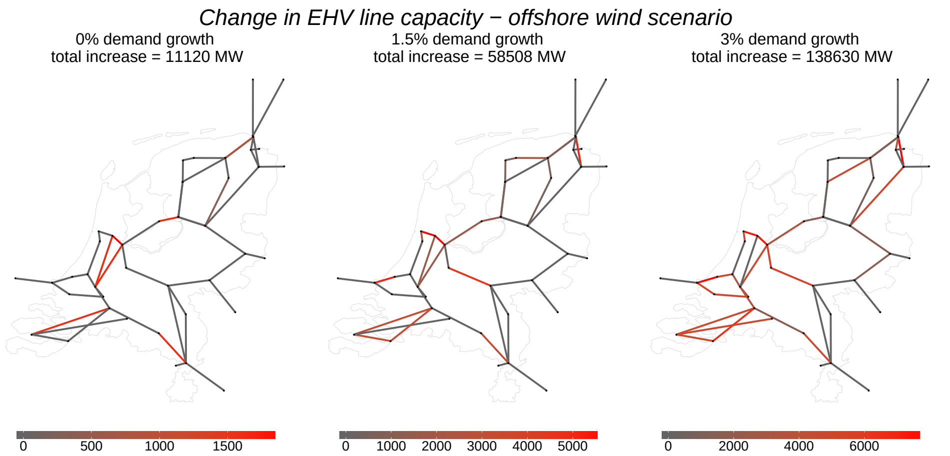


Figure 8.9: Development of transmission capacity in the extra high-voltage (EHV) grid under the offshore wind scenario.

### Import scenario

Figure 8.10 illustrates the results for the import scenario – which corresponds to a gradual reduction in existing centralized, fossil fuel-based capacity compensated by a gradual increase in imports from neighboring countries. The most distinctive feature in the results of this scenario is the overall magnitude of capacity growth – well more than double (and almost triple) that of the offshore wind scenario.

In terms of the geographical distribution of capacity growth, the results of the import scenario exhibit some similarities to those of the centralized generation scenario – relatively large capacity increases in the 380kV corridor between Ens and Geertruidenberg, and between between Eemshaven and Zwolle/Ens. Though the magnitude of growth along these corridors is considerably larger. Under conditions of 1.5% and 3% demand growth, the similarities to the centralized generation scenario are less evident. These conditions produce large EHV capacity increases in the *east* of the country, particularly in the north-south corridor extending between Hengelo and Maasbracht.

All of these developments are consistent with a need – unique to this scenario – to transport large amounts of power from Norway and Denmark in the North, Germany in the East and Belgium in the South, to the demand centers of the Netherlands. This produces a markedly different regime of power flows relative to the centralized generation scenario, with significantly larger power flows emanating from the east, south and north of the country and extending towards the Randstad region.

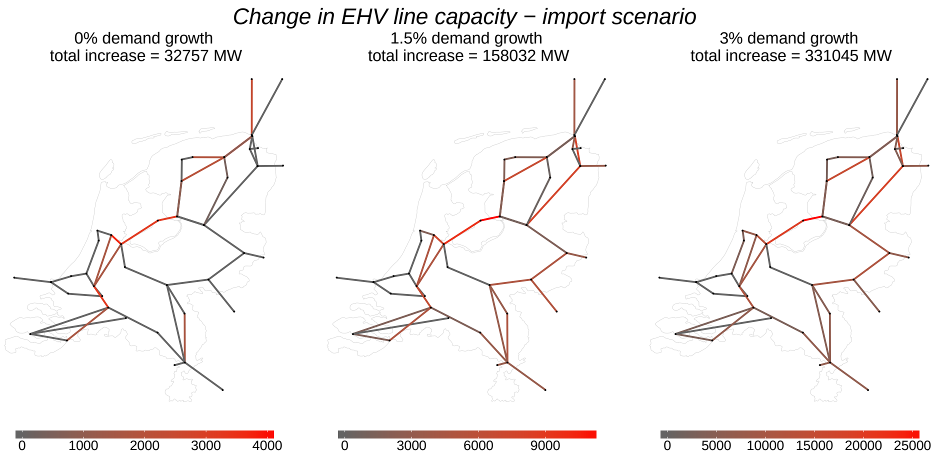


Figure 8.10: Development of transmission capacity in the extra high-voltage (EHV) grid under the import scenario.

### Export scenario

Figure 8.11 illustrates the results for the export scenario – in which generation development is dominated by growth in large-scale, fossil fuel-based production facilities complemented by growth in import demand by Germany, Belgium and the UK. In terms of the geographical distribution of capacity growth, the results of the export scenario are nearly identical to those of the centralized generation scenario, with relatively large capacity increases along the 380kV corridor between Ens and Geertruidenberg, and between Borssele and Geertruidenberg. These similarities make sense insofar as the export scenario entails increases in centralized generation capacity at locations identical to those in the centralized generation scenario.

A key difference between the export scenario and the centralized generation scenario, however, is the somewhat larger overall magnitude of capacity growth in the export scenario. This may be attributed to additional capacity requirements for transporting power to neighboring countries.

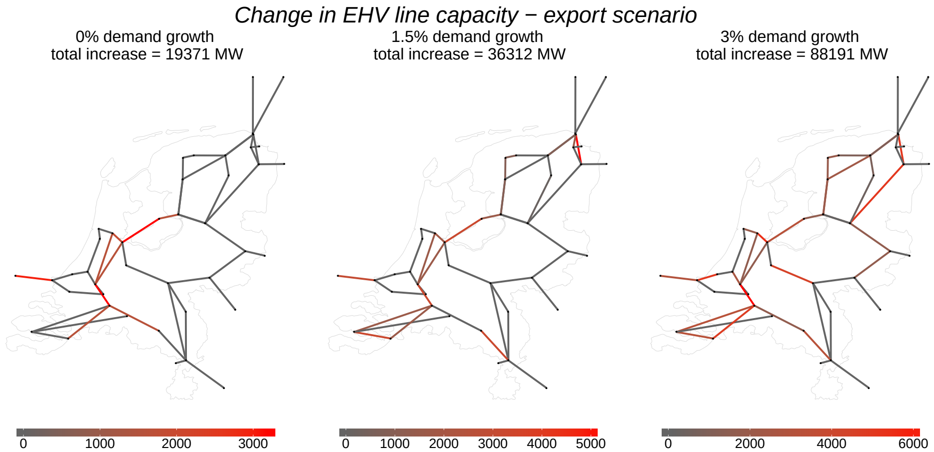


Figure 8.11: Development of transmission capacity in the extra high-voltage (EHV) grid under the export scenario.

## Flood resilience

To what degree do the different development trajectories of the Dutch electricity infrastructure affect its resilience to flood and heat wave events? Using the same set of procedures to evaluate infrastructure resilience as employed in chapter 6, we now present the results of an assessment of the flood and heatwave resilience of the generated infrastructure configurations. These infrastructure configurations represent the end states of the different evolutionary trajectories discussed above – that is, they represent possible configurations of the infrastructure in 2050.

Figure 8.12 illustrates the flood resilience of the infrastructure for each of the tested scenarios. Each horizontal bar/box in this plot represents the range of resilience values observed under a given scenario. As in chapter 6, resilience is defined here as the mean value of infrastructure performance values observed across all possible event magnitudes, with infrastructure performance defined in terms of the *fraction of demand served*. The values in Figure 8.12 are based on 1000 runs of the SVA submodel at each of the 16 different scenarios. The baseline scenario here refers to the current (2010) state of the network.

The results in Figure 8.12 suggest that flood resilience deteriorates significantly with increasing rates of demand growth, a result which holds across all of the generation development scenarios. This pattern may be attributed to two factors. First, further analysis of the model results shows that higher demand growth rates correspond to higher utilization rates of transmission lines – on average by about 4.7% per percentage point increase in demand growth. In other words, greater demand growth means less buffer capacity in the transmission system, meaning that line overloads and cascading failures occur more readily, reducing resilience. Second, higher rates of demand growth may mean that the failure of several key substations can cut supply to a larger proportion of demand. If absolute growth in demand were distributed evenly across the system, this would likely not be the case. However, it is assumed in the agent-based submodel that demand growth occurs disproportionately in areas with already high levels of demand[5] – such as the Randstad area – meaning that the failure of a single substation in this area has a (proportionally) larger effect.

The results in Figure 8.12 also suggest that different generation development scenarios have different consequences for the infrastructure's flood resilience. The centralized generation scenario, offshore wind scenario and export scenario exhibit relatively equivalent levels of resilience. The performance of the distributed generation scenario produces the highest levels of resilience, with a mean resilience value of 0.94 at 0% demand growth, and still a relatively high value of 0.88 at 3% demand growth. The high performance under this scenario can be explained by the greater availability of electricity within the distribution grids themselves, which means that even under conditions in which a large number of substations may have failed, the vast majority of customers retain access to power.

The import scenario performs considerably more poorly than the others, with a maximum mean resilience value of 0.89 (under 0% demand growth) and a minimum mean value of 0.59 (under 3% demand growth). A closer look at the results reveals that this may be attributed to a combination of (1) a relative dearth of available generation capacity in this scenario, and (2) the large distance that electricity must be transported from foreign sources to domestic demand centers. Under conditions of 0% demand growth, we see that generation capacity is adequate to meet demand under normal (no flood) conditions, but that the system is quite brittle – the failure of a few substations significantly reduces system performance. The situations of 1.5% and 3% demand growth also demonstrate this same brittleness, but are additionally affected by the fact that the system is unable to cover all demand, even under normal circumstances.

[5] More precisely, it is assumed that the demand of each distribution grid increases by a fixed percentage each year

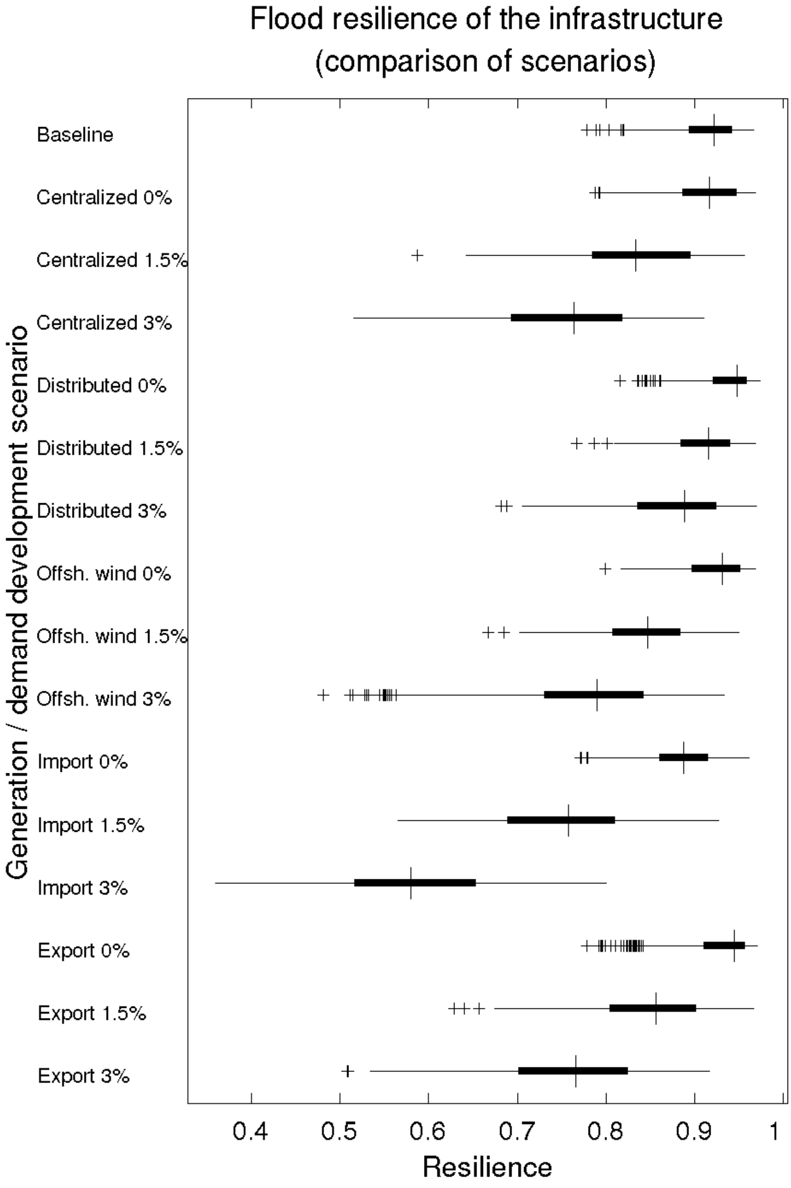


Figure 8.12: Results of the model: comparison of flood resilience values obtained across the tested generation and demand development scenarios. Percentages refer to demand growth rates. The ends of the dark box (horizontal line in this case) indicate the 25th and 75th percentiles; the "whiskers" extending from the boxes include the most extreme data points not considered outliers; outliers are plotted individually as crosses.

### Heat wave resilience

Figure 8.13 illustrates the heat wave resilience of the infrastructure for each of the tested scenarios. As in the flood case, we observe generally lower levels of resilience under higher rates of demand growth. The negative correlation between demand growth and resilience may be partially explained by the higher average utilization rates of transmission lines under high rates of demand growth. An additional relevant factor in this case is an apparent higher ratio under high demand growth scenarios of average electricity demand to generation capacity. In other words, high demand growth means that there is a proportional (but not necessarily absolute) dearth of excess generation capacity[6]. The consequence of this is that, under higher rates of demand growth, a heat wave that disables e.g. 20% of domestic generation may have a larger negative effect on system performance.

Like the flood case, we see in the heat wave case considerable similarity in the means and ranges of resilience values under the centralized generation scenario and the export scenario. Also similar to the flood case, the distributed generation scenario exhibits relatively high levels of resilience, with a means of 1.00 and 0.99 under 0% demand growth and 3% demand growth, respectively. The generally high level of resilience observed under the distributed generation scenario may be attributed largely to the fact that the availability and output capacities of distributed generators are assumed to be unaffected by extreme temperatures.

Counterintuitively, in the case of the distributed generation scenario, we observe higher levels of heat wave resilience under a moderate rate of demand growth (1.5%) than under low (0%) or high (3%) rates of demand growth. Additional simulation runs confirm that this is a robust result and not a statistical artifact. This result may be attributed to the presence of a smaller proportion of heat wave sensitive generation capacity in the system relative to the low demand growth case, in which distributed generation capacity grows less rapidly. Under a high rate of demand growth, the system experiences even more rapid growth in distributed generation than in the moderate growth case. However, in this case, the resilience benefits of distributed generation are outweighed by the detrimental effects of higher transmission line utilization rates.

Interestingly, the offshore wind scenario also performs extremely well, superior even to the distributed generation scenario under 0% demand growth. The reason for this is that offshore wind generators, like distributed generators, are assumed to be unaffected by extreme temperatures. Under 3% growth conditions, however, the offshore wind scenario exhibits a “fat tail” in the direction of low resilience, leading to a minimum observed resilience value of 0.51 – amongst the lowest observed across all scenarios. This fat tail may be attributed to situations in which offshore wind power is insufficient to cover demand, meaning that the system is heavily reliant on fossil generation and imports, both of which may be significantly affected by extreme temperatures.

As in the flood resilience case, the import scenario performs quite poorly. This may be attributed largely to an assumed sensitivity of imports to extreme temperatures. This is not an unthinkable situation, as fossil fuel imports from Germany,

[6] The model results show a 4.0% increase in the ratio of electricity demand to generation capacity per percentage point increase in demand growth.

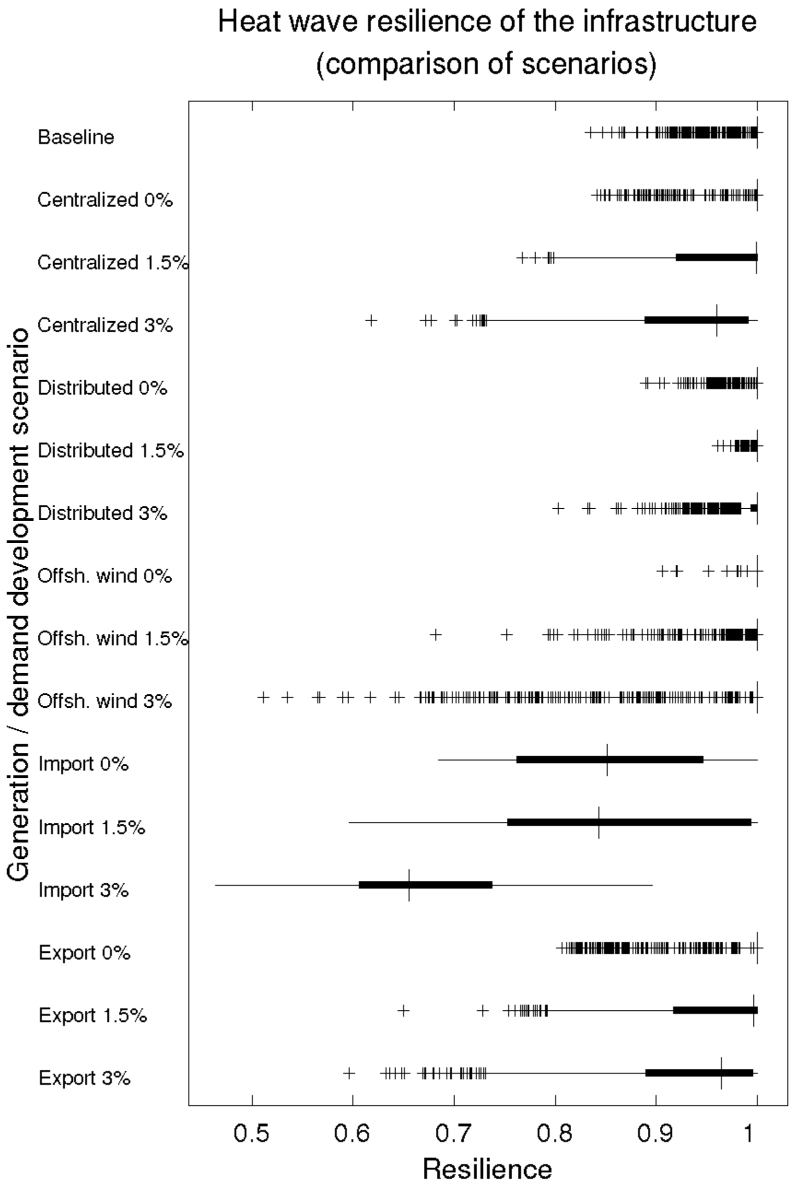


Figure 8.13: Results of the model: comparison of heat wave resilience values obtained across the tested generation and demand development scenarios. Percentages refer to demand growth rates.

nuclear imports from France and hydro imports from Norway may be reduced or cut off entirely under extreme temperature conditions. The existence of large solar capacity in neighboring countries (e.g. Germany) may render this assumption less applicable, though this has not been accounted for in the model.

## 8.8 Discussion

The results described in the previous section highlight several interesting patterns in the possible development trajectories of the Dutch electricity transmission infrastructure, and in the consequences of these trajectories for the infrastructure's extreme weather resilience. In terms of the infrastructure's future development, the model points towards likely significant increases in transmission capacity to 2050. These increases are most acute in an import scenario, which entails large increases in EHV capacity in the East, West and North of the Netherlands. An offshore wind scenario also entails significant EHV capacity investments to accommodate the altered power flow patterns associated with transporting large amounts of power from offshore North Sea locations. Interestingly, scenarios based around centralized and distributed generation result in similar development patterns in the EHV grid, characterized most markedly by relatively high capacity growth in the east of the country and by relatively low overall capacity growth in comparison to the other generation development scenarios.

Via the developed model, we have examined a handful of possible generation and demand development scenarios. While these scenarios do not capture the full range of possible development trajectories of the system, they provide some insight into the potential long-term consequences of future supply and demand developments in terms of network capacity requirements. In particular, the current transmission grid is geared to handle specific power flow patterns characteristic of the installed generation and load base. Fittingly, the results suggest that certain generation development trajectories may entail significantly *altered* patterns of power flow, and thus may require large transmission investments to accommodate these flows. While we have not explored it in this chapter, altered geographical patterns of demand growth would likely have the same effect.

For further insight into the validity of the model, we can compare the results of the agent-based submodel with developments as foreseen in TenneT's *Vision2030* document (Tennet, 2011). In this document, TenneT uses four scenarios as a basis for evaluating transmission needs in the Netherlands to 2030. While it is difficult to quantitatively compare the results of these scenarios with the scenarios used in this study, a qualitative camparison can be made. In particular, TenneT's scenarios foresee possible necessary increases in capacity from Borssele. Maasvlakte, Ijmuiden and Eemshaven to the central 380kV ring, depending on the scenario. They also foresee possible necessary capacity increases within the central 380kV ring, particularly between Diemen and Ens, and between Krimpen and Geertruidenberg.

Each of the capacity increases foreseen in TenneT's *Vision 2030* are also apparent in the results of the developed model, depending on the scenario. This testifies to the validity of our model. However, some important differences are visible. For instance, none of TenneT's scenarios foresee a need for significant additional capacity in the North-South corridor between Diemen and Krimpen, whereas this occurs quite frequently in the results of our model. Likewise, none of TenneT's scenarios identify a capacity shortage in the East of the country, whereas this is an important feature of our import scenario. Such differences between our results and those of TenneT are not unexpected, given the many differences between the scenarios of TenneT's analysis and our scenarios, as well as the differing timeframes of the analyses. Uncovering the reasons for these differences would require a more in-depth investigation into TenneT's scenarios and analyses, which we will not attempt here.

The developed model illustrates not only that different generation and demand development scenarios may result in very different transmission investment patterns, but also, in turn, that these transmission investment patterns (and demand/supply developments) may have certain consequences for the *extreme weather resilience* of the infrastructure. In particular, our results suggest that a future infrastructure based around distributed generation may be highly resilient to both floods and heat waves. A scenario in which the Netherlands is highly dependent on imports, on the other hand, performs very poorly in terms of resilience. A future based around offshore wind may offer significant benefit in terms of heat wave resilience, though this benefit depends on the availability of wind resources during times of extreme heat, which may be limited. Additionally, the results indicate a clear negative correlation between the growth rate of demand and the infrastructure's resilience to floods and heat waves. In particular, high rates of demand growth may reduce existing buffer capacity in transmission and generation, making the infrastructure more prone to systemic breakdown.

Taken together, these findings suggest a path towards an electricity infrastructure that is both climate resilient and sustainable. In particular, low levels of demand growth and enhanced utilization of small-scale renewables-based technologies (e.g. solar photovoltaics) can offer benefits in both of these respects. Solar photovoltaics, in particular, present the advantage that their output often peaks at times when production by traditional thermal generation technologies may be limited due to extreme heat. Despite the advantages of small-scale renewables such as solar and wind, it is important to keep in mind the intermittent nature of their output. Even with widespread deployment of small-scale renewables, more stable (and quickly deployable) forms of generation – such as natural gas-fired plants – are essential. In theory, the intermittency of renewables could also be compensated by imports from neighboring countries. However, the results of the developed model suggest that heavy reliance on imports may reduce the network's resilience insofar as it requires electricity being transported large distances, and from areas which themselves may be stressed under extreme conditions.

The results presented in this chapter must be seen within the context of the assumptions underlying them. The tested scenarios represent only a small portion of the possible development trajectories of the infrastructure, both in terms of the development of generation and that of demand. Moreover, we have ignored currently unforeseen developments in the structure of the Dutch transmission grid. Such investments are highly probable, particularly in the case of interconnectors with neighboring countries as the Netherlands becomes more integrated into a unified European network. Greater integration of the Dutch system into a pan-European network will likely also introduce significant transit flows into the system – flows *between* foreign countries, but passing through the Netherlands. These would create additional unforeseen stresses on the Dutch network, which are not accounted for in the model. Assumptions about the availability and role of imports may also distort the results, particularly in terms of the infrastructure's resilience. More specifically, the SVA submodel assumes that imports are sensitive to extreme heat, but given the increasing role of renewables in neighboring countries – e.g. solar PV in Germany and offshore wind in Germany, Denmark and the UK – this assumption may not hold.

## 8.9 Synthesis

In the introduction to this chapter, we posed the following research question: *How might a low-carbon transition affect the vulnerability of the Dutch electricity infrastructure to climate change, and how can we harness this transition to support climate resilience?* As the results above have demonstrated, a low-carbon transition may have significant effects on the infrastructure's vulnerability to extreme weather events. A transition towards distributed sources of generation could yield significant benefits in terms of resilience. A transition towards offshore wind may yield benefits, but may also increase vulnerability, particularly in cases of high demand growth. And a transition that entails increased reliance on imported electricity could have a detrimental effect on resilience. Taken together, the results of this chapter suggest that if we wish to harness a low-carbon transition to enhance resilience, this may best be accomplished by focusing on reducing the growth of electricity demand and supporting the development of distributed sources of generation. In this chapter, we stop short of exploring precisely *how* such developments may be better supported – much research already has been and continues to be dedicated to this.

The model introduced in this chapter is novel not only in terms of the insights it provides, but also in itself. In particular, the model offers a novel combination of tools and techniques for studying the consequences of long-term infrastructure developments in terms of resilience. We hope that this model may serve as a solid starting point for others seeking to address similar questions, also in other geographical contexts.

# Part IV

# Case study 3

# Chapter 9

# Resilience in multi-infrastructure systems

## Exploration of the effects of interdependencies on infrastructure resilience

## 9.1 Introduction

Hurricane Sandy, which struck the Northeast coast of the United States on 29 October, 2012, was the second costliest Atlantic hurricane in history and the largest Atlantic hurricane ever to occur (NOAA, 2012). The infrastructure impacts of Hurricane Sandy were immense – 8.7 million customers lost power; 25% of customers lost mobile, landline, Internet and cable television service; New York City's subway services were completely shut down; and multiple oil and gas refineries/pipelines were disabled (Comes and van de Walle, 2014). These impacts were not only a direct consequence of meteorological conditions. They were also a result of the *(inter)dependencies* between infrastructures, which allowed failures to cascade from one infrastructure to another – e.g. from the electricity infrastructure to the gas and oil infrastructures, and from the gas and oil infrastructures to the road infrastructure (Comes and van de Walle, 2014) – as well as beyond the geographical scope of the hurricane itself.

Infrastructure interdependencies may play a role in the case of smaller scale events as well. One example of this is offered by an incident which occurred on August 7th, 2008, in Rotterdam, the Netherlands, in which a lightning strike to the electricity infrastructure ended up affecting the road transport, rail transport and inland shipping infrastructures. As is not unusual in the Netherlands, this particular day featured heavy rainfall (45 mm in a five-hour period) complemented by multiple lightning strikes. One of these lightning strikes hit electrical circuitry near the Botlek Tunnel and subsequently cut power to a set of pumps that are normally used to drain excess water from the tunnel. Due to the failing of these pumps and the heavy rainfall, the water level in the tunnel rose to a height of one meter in some areas. This resulted in the closing of the Botlek tunnel and subsequent traffic jams on the A15 highway extending 15 km in both directions, as well as spill-back effects in the form of increased traffic on the A4, N57, A29, A16 and other routes (Rosmuller et al., 2011). The incident also resulted in extra travel time for travelers who shifted to other transport modes, as well as the diversion of inland ships from the Botlek Bridge. A rough estimate sets the economic cost of the incident at approximately 367,500 euros (Rosmuller et al., 2011).

This chapter describes the third case study of this research. The purpose of this case study is to assess the effects of *infrastructure interdependencies* – critical links between different types of infrastructures – on infrastructure resilience. The chapter is divided into three parts:

1. The first part of the chapter provides a brief overview of existing research dealing with infrastructure interdependencies, and particularly their role in affecting resilience.

2. The second part of the chapter describes the method and results of a study of the consequences of infrastructure interdependencies on the flood resilience of a multi-infrastructure system in the North Rotterdam area of the Netherlands. The aim of this study is to discern the effects of a given flood scenario in terms of possible *secondary* infrastructure vulnerabilities – vulnerabilities of infrastructure components due to their dependence on the electricity infrastructure.

3. The third part of the chapter describes the design, implementation and results of a model exploring the effects of interdependencies with other infrastructures on the resilience of a hypothetical electricity infrastructure. This model deals with the very real issue that many interdependencies may be unknown to an infrastructure operator, and assesses different strategies for dealing with this source of uncertainty.

## 9.2 Literature summary – infrastructure interdependency modeling

Infrastructures may feature many different types of interdependencies. A common classification scheme distinguishes between four different interdependency types: physical interdependencies, cyber interdependencies, geographic interdependencies and logical interdependencies (Rinaldi, 2004; Tai et al., 2013).

**Physical interdependencies** refer to situations in which the state of one infrastructure depends on the material output(s) of another.

**Cyber interdependencies** refer to situations in the which the state of an infrastructure depends on information transmitted through another infrastructure.

**Geographic interdependencies** refer to situations in which multiple infrastructures may be simultaneously affected by an environmental event due to their physical proximity to one another.

**Logical interdependencies** refer to situations in which the state of an infrastructure is dependent on another due to policy, legal or regulatory factors.

This final class of interdependencies may also be divided into *procedural* and *societal* interdependencies – the former referring to formal procedures that link infrastructures and the latter referring to societal factors such as public opinion, fear and culture (Tai et al., 2013)

It is also useful to distinguish between first, second, third and higher order effects caused by infrastructure interdependencies (Little, 2003). A first order effect refers an effect induced when a direct disturbance leaps from one infrastructure to another – for instance when a flood induced power disturbance cuts power to an oil refinery. A second order effect refers to an effect induced when this first order effect leaps to yet another infrastructure – for instance when an oil refinery power outage leads to reduced petrol availability at filling stations, subsequently disrupting the transport infrastructure. These multi-order effects may not only cause a disruption to spread between infrastructures, but may also act to magnify disturbances within a single infrastructure as failures traverse feedback loops in the multi-infrastructure network. Moreover, due to time lags and economic linkages, multi-order effects may extend far into the future and far beyond the geographic bounds of the original event.

Due to the many (inter)dependencies between different types of infrastructures and the potential for disruptions to cascade between infrastructures, it is of limited use to assess the resilience of different infrastructures independently. It can often be more useful to view infrastructures as *multi-infrastructure systems* – interacting networks of infrastructure components featuring various (types of) dependencies. Due both to the socio-technical complexity of these systems and the impracticality of experimenting with massive infrastructure failures in the real world, modeling and simulation can play an important role in helping to untangle the potential consequences of disruptions in multi-infrastructure systems.

Recognizing this need, the modeling and simulation community has responded with a growing number of studies in recent years. Figure 9.1 shows the number of papers published between 2001 and 2013 featuring the words "infrastructure interdependency" and "model(ing)", which increased during this period from 3 to 127. Ouyang (2014) differentiates between four different approaches within this body of work: empirical approaches, agent-based approaches, system dynamics approaches and network-based approaches. *Empirical approaches* analyze interdependencies based on historical data and/or expert experience. The above-referenced study by Comes and van de Walle (2014) – which assesses the role of infrastructure interdependencies based on compiled failure data from Hurricane Sandy – offers an example of this class of approaches. *Agent-based approaches* represent the technical components and/or social actors associated with interdependent infrastructures as interacting agents in a model, and explore the emergent effects of these interactions. An example in this category is offered by North (2001), who describes an integrated model of power and gas markets, with a focus on the organizational interdependencies between these markets and the effects of fundamental market transformations in straining these interdependencies. *System dynamics approaches* represent interdependent infrastructures as systems of stocks, flows and informational relations, which explicitly delineate the feedbacks in the system. An example of this approach is described in Conrad et al. (2002), who assess the effects of interdependent infrastructures on emergency service response for the case of a California earthquake.

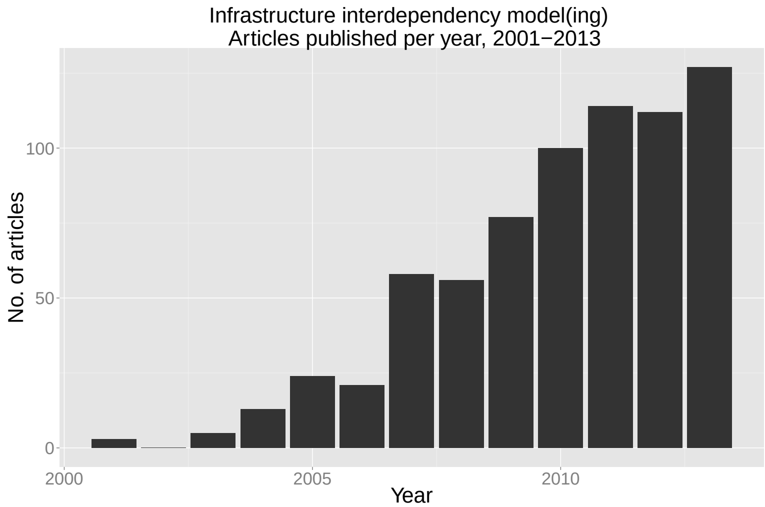


Figure 9.1: Number of articles published per year featuring the words "infrastructure interdepdendency" and "model(ing)". Results are based on a search of the titles, abstracts and keywords of articles in the Scopus database (Elsevier, 2014).

The final category of modeling approaches – *network-based approaches* – is perhaps the most frequently applied for assessing the resilience of multi-infrastructure systems. In the case of network-based approaches, infrastructure components are represented as nodes and the links or interdependencies between them as edges. An example of this type of analysis is introduced in Lam et al. (2013), who use a systematic set of experiments to identify critical nodes in a generic multi-infrastructure network based on the giant component size. Another example is offered by Buldyrev et al. (2010), who compare failure patterns in isolated versus interdependent networks, showing that interdependent networks are relatively sensitive to random failure, with the random removal of a small fraction of nodes producing an iterative cascade of failures across interdependent networks.

Ouyang (2014) furthermore distinguishes between two categories of methods within the body of network-based studies: topology-based methods and flow-based methods. *Topology-based methods* represent interdependent infrastructures based only on their network topologies and feature discrete states for each component. *Flow-based methods* account for the actual flows of goods through the network, sometimes taking into account the differing flow dynamics of various types of commodities. An example of this latter category is offered by Gil and McCalley (2011), who describe a model including three energy production and transportation subsystems – electricity, natural gas and coal – and featuring a multiperiod network flow model which captures bulk energy flows through a network and represents the effects of large-scale disruptions.

In the sections that follow, we introduce two models exploring the effects of interdependencies on infrastructure resilience. The first of these models is a data-driven model exploring the effects of infrastructure dependencies in the case of a given flood scenario in the North Rotterdam area of the Netherlands. This model utilizes a *network-based approach* and a *topology-based method*, representing network functionality in terms of the discrete states of its components. The second model is an abstract (data-free) model, which utilizes a *flow-based method* for representing the functioning of the electricity network. As opposed to the first model, which uses existing data as a starting point for assessing vulnerability, the second model uses a *lack* of data as a starting point – exploring strategies for enhancing resilience under conditions of incomplete knowledge of possible interdependencies.

## 9.3 Analysis of the flood vulnerability of a multi-infrastructure system in North Rotterdam

This section presents the results of an analysis of the flood vulnerability of a multi-infrastructure system in the North Rotterdam area of the Netherlands. This analysis was carried out in the context of a multi-stakeholder project assessing the potential infrastructure consequences of a dike breach-induced flood in this area. The project included experts in hydrological modeling, traffic modeling and power system modeling from several Dutch research institutes and universities, as well as stakeholders from the municipality of Rotterdam and several of the regional infrastructure operators. The analysis described here focuses specifically on the electricity infrastructure and its local links with the road, rail and sewage infrastructures. Other infrastructures – e.g. drinking water, ICT – were excluded due to a lack of necessary data and/or stakeholders. A key partner in the implementation of this analysis was *Stedin*, the operator of the electricity distribution grid in the North Rotterdam area.

Figure 9.2 shows a map of the geographical area of North Rotterdam, marked with the boundaries of the defined study area. The study area contains a number of important infrastructure assets, including: the Rotterdam-Hague Airport, a railroad line of the Randstadt Rail network, a line of the NS rail network, a portion of the A13 and A20 highways, sewage pipes and pumps, a drinking water infrastructure, power cables and substations operating at four different voltage levels (0.4 kV, 10 kV, 25 kV and 50 kV), gas pipelines and others. The study area is bounded on several sides by canals, including the Rotterdamse Schie and the Delftse Schie in the West, the Noorderkanaal in the South and the Rotte Canal in the Southeast. Most of the study area lies well below sea level, in some cases up to nine meters below. The canals around the study area sit at higher elevations, and are bounded on both sides by dikes, which (under normal conditions) prevent water from flowing into the study area.

The starting point for the analysis described here is a set of hypothetical dike breach scenarios. The dike breach locations used for this study are illustrated in Figure 9.2, and will heareafter be referred to as *Schie-Noord* (location 1), *Schie-Zuid* (location 2) and *Rotte* (location 3). These locations were selected by the stakeholders due to their use in a previous flood study, where possible dike breach locations were agreed with the city of Rotterdam and the Water Board of Schieland and the Krimpenerwaard (Nelen en Schuurmans, 2012). Dike breaches such as these are very rare in the Netherlands, though risks may be highest during periods of extreme rain or, ironically, during extreme drought. Peat dikes, in particular, require moisture to

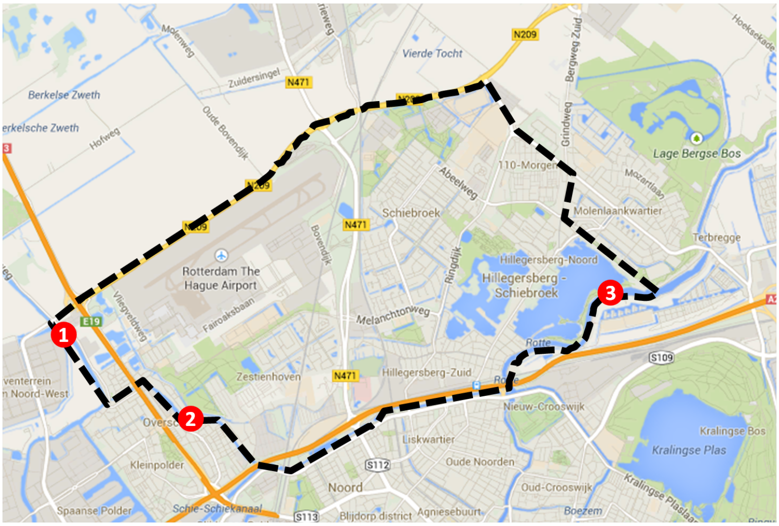

Figure 9.2: Map of the North Rotterdam area, including the dike breach locations (red circles) and the boundaries of the study area (dotted black line).

maintain their shape and firmness, and so may be susceptible to drought-induced failure[1]. The analysis described here does not make any assumptions concerning the specific reasons for the dike breaches at the aforementioned locations.

Based on the knowledge needs of Stedin and other stakeholders, our analysis seeks to address the following questions:

1. Which substations of the electricity infrastructure may be vulnerable in the case of a dike breach at Schie-Noord, Schie-Zuid and Rotte? How many customers could be affected in each of these dike breach scenarios?

2. Which assets of the sewage, road and rail infrastructures may be vulnerable in the case of a Schie-Noord dike breach, due to their dependency on the electricity infrastructure?

3. What measures could enhance the flood resilience of the multi-infrastructure system in North Rotterdam?

## Methodology and model design

The analysis was carried out in four steps. The first step involved compiling an inventory of electrical substations in the study area, including the geographic locations and flood protections of each. The second step involved assessing the flood vulnerability of these substations, based on their geographic location in relation to anticipated water levels under the aforementioned flood scenarios *and* on their dependencies with other (potentially vulnerable) electrical substations. The third step involved assessing *secondary* vulnerabilities – vulnerabilities of sewage, road and rail

[1] A 2003 dike breach in the Dutch village of Wilnis illustrates the potential for drought-induced dike failure.

infrastructure assets due to their dependence on the electricity infrastructure. The final step involved the identification of possible resilience-enhancing measures.

Each of these steps was carried out in consultation with the involved stakeholders, particularly Stedin. Stakeholder input was collected during the course of three workshops, to which all stakeholders and researchers in the project were invited. Between these workshops, additional meetings with representatives from Stedin were held in order to better discern their relevant knowledge needs and to obtain necessary data.

The developed model consists of a network representation of the electricity infrastructure in the study area, as well as the dependent assets of other infrastructures. Key data inputs to the model include: (1) the geographic locations and flood protection heights of electrical substations in the study area; (2) the geographic locations of sewage, road and rail infrastructure assets in the study area; and (3) time-varying water depth projections for each of the aforementioned dike breach scenarios. This data was obtained from Stedin and from other researchers involved in the project.

The developed model entails a number of assumptions. In particular, data concerning the precise linkages between the 10/0.4 kV and 25/10 kV electrical substations, and between the 10/0.4 kV substations and the assets of the sewage and road infrastructures, was not available. It is thus assumed that all 10/0.4 kV substations are directly linked to the nearest (geographically) 25/10 kV substations, and that all sewage and road infrastructure assets are linked to the nearest 10/0.4 kV substations. The former of these assumptions ignores the structural characteristics of low-voltage electricity networks, which are normally arranged in radial or ring structures. By representing all 10/0.4 kV substations as directly linked with the nearest 25/10 kV substations, we ignore some of the dependencies between 10/0.4 kV substations. In other words, we ignore the possibility that the failure of one 10/0.4 kV substation may result in the failure of another (linked) 10/0.4 kV substation. Due to this assumption, our results may slightly under-represent the vulnerability of 10/0.4 kV substations.

An additional assumption is made with regard to the precise flood protection heights of electrical substations. In particular, the protections heights of all substations are assumed to align with the following norms:

- 50/25 kV substations are protected to a height of one meter above the on-site elevation,

- 25/10 kV substations are protected to a height of 0.5 meter above the on-site elevation,

- 10/0.4 kV substations are protected to a height of 0.25 meter above the on-site elevation.

While these norms are generally valid, the precise protection heights of substations may vary in reality, depending on site-specific variables.

The analysis was carried out using the statistical software R. Maps were generated using R and visualized using Google Earth.

## Results – vulnerability of electrical substations

The vulnerability of electrical substations in the study area is assessed in two steps. The first step entails an assessment of the vulnerability of the higher voltage (50/25 kV) substations in the vicinity of the study area, for each of the aforementioned dike breach scenarios. The second step focuses on the lower voltage (25/10 kV and 10/0.4 kV) substations in the study area. In the first step, we assess not only the vulnerabilities of electrical substations, but also the number of customers potentially affected under each dike breach scenario. This allows us to discern which dike breach scenario poses the greatest risk of service disruption in the study area. In the second step, we assess the vulnerabilities of lower voltage substations for the dike breach scenario determined in the first step to pose the greatest risk. In both the first and second steps, water depths correspond to a situation at 120 hours (5 days) after the initial dike breach.

For each of the dike breach scenarios assessed in the first step, a best case and a worst case situation are examined in order to capture the range of possible outcomes. A *best case* situation assumes that a 50/25 kV substation will only be shut down if the substation itself is flooded above its protection level (1 meter). A *worst case* situation assumes that a 50/25 kV substation will be shut down if any piece of land within the geographical area covered by the substation's respective subgrid is flooded above 0.25 meter (the assumed protection height of low-voltage substations). The use of best and worst case situations is intended to capture the range of uncertainty associated with precisely when the infrastructure operator may choose to shut down a given subgrid. The actual consequences of given dike breach scenario can be assumed to lie somewhere between those of the best and worst case situations.

The results of the step 1 analysis are summarized in Table 9.1. In the case of a Schie-Noord or Schie-Zuid dike breach, it was found that the Rotterdam-Hague Airport substation could experience water levels exceeding its protection height – meaning that the Airport and other connected facilities could lose power, even under a best case situation. Under a worst case situation, a Schie-Noord dike breach poses the greatest risk, threatening power supply to more than 30 thousand customers (plus the Airport), as opposed to approximately 21 thousand customers in the case of a Schie-Zuid or Rotte dike breach. In the case of a Rotte dike breach, none of the 50/25 kV substations are directly affected – meaning that under a best case situation, no customers would lose power.

Table 9.1: Summary of the results of a vulnerability analysis of 50/25 kV substations in the study area. A best case situation assumes that a 50/25 kV substation will only be shut down if the substation itself is flooded above its protection level (1 m). A worst case situation assumes that a 50/25 kV substation will be shut down if any piece of land within the geographical area covered by the substation's respective subgrid is flooded above 0.25 m.

| **Dike breach location** | **Situation** | **No. of vulnerable customers** |
|---|---|---|
| Schie-Noord | best case | 0 + Rotterdam Airport |
| Schie-Noord | worst case | 30,652 + Rotterdam Airport |
| Schie-Zuid | best case | 0 + Rotterdam Airport |
| Schie-Zuid | worst case | 21,287 + Rotterdam Airport |
| Rotte | best case | 0 |
| Rotte | worst case | 21,287 |

The second step in assessing the vulnerability of electrical substations in the study area focuses on the 25/10 kV and 10/0.4 kV substations, and is carried out exclusively for a Schie-Noord dike breach scenario. Results are illustrated in Figure 9.3. In total, 42 25/10 kV substations and 85 10/0.4 kV substations were found to be vulnerable. These results account for both on-site water levels, as well as the dependencies of substations on their feeding substations. Most of the vulnerable 25/10 kV substations lie in the western portion of the study area, while most of the vulnerable 10/0.4 kV substations lie in the eastern portion of the study area.

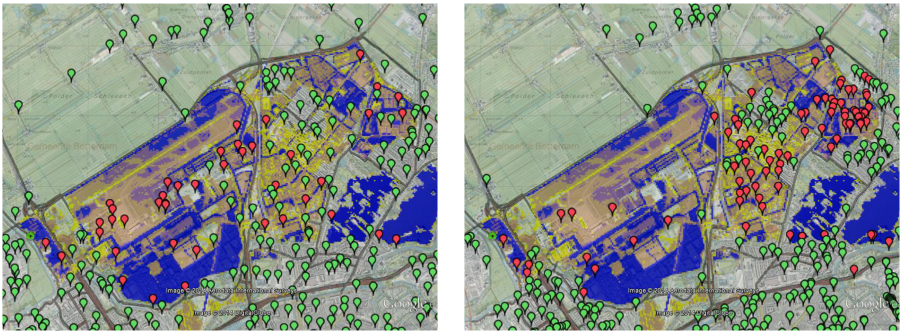

Figure 9.3: Maps illustrating the vulnerability of 25/10 kV substations (left pane) and 10/0.4 kV substations (right pane) in the study area. Balloon icons colored in red indicate vulnerable substations. Balloon icons colored in green indicate substations that are not vulnerable.

## Results – vulnerability of sewage, road and rail assets

Based on the results of the vulnerability analysis of 25/10 kV and 10/0.4 kV substations, we now perform an analysis of *second order vulnerabilities* – vulnerabilities of sewage, road and rail assets due to their dependence on the electricity infrastructure. This analysis is carried out exclusively for the case of a Schie-Noord dike breach scenario, and again assumes water depths corresponding to 120 hours after the initial breach.

The results of this analysis are illustrated in Figure 9.4. As these maps illustrate, a significant portion (approximately 23%) of sewer pumps in the study region were found to be vulnerable. Additionally, six traffic signals in the western corner of the study area were found to be vulnerable[2]. These traffic signals lie at the intersection of the A13 highway and the N209 road, suggesting that this may be a problematic intersection in the case of a Schie-Noord dike breach. Neither of the two rail substations in the vicinity of the study area were found to be vulnerable. The potential vulnerability of other rail assets in the study area is not assessed.

Currently, most of the 25/10 kV and 10/0.4 kV substations in the study area need to be shut down *manually* – that is, in the case of a dike breach, Stedin's technicians would need to physically access vulnerable substations. This could pose a problem if these substations are inaccessible due to high water levels on surrounding roads or on the site of the substations itself. With this in mind, we carried out

[2] It should be noted that the traffic signal data used for this study is incomplete. Namely, it does not include traffic lights on local roads, particularly in the eastern portion of the study area.

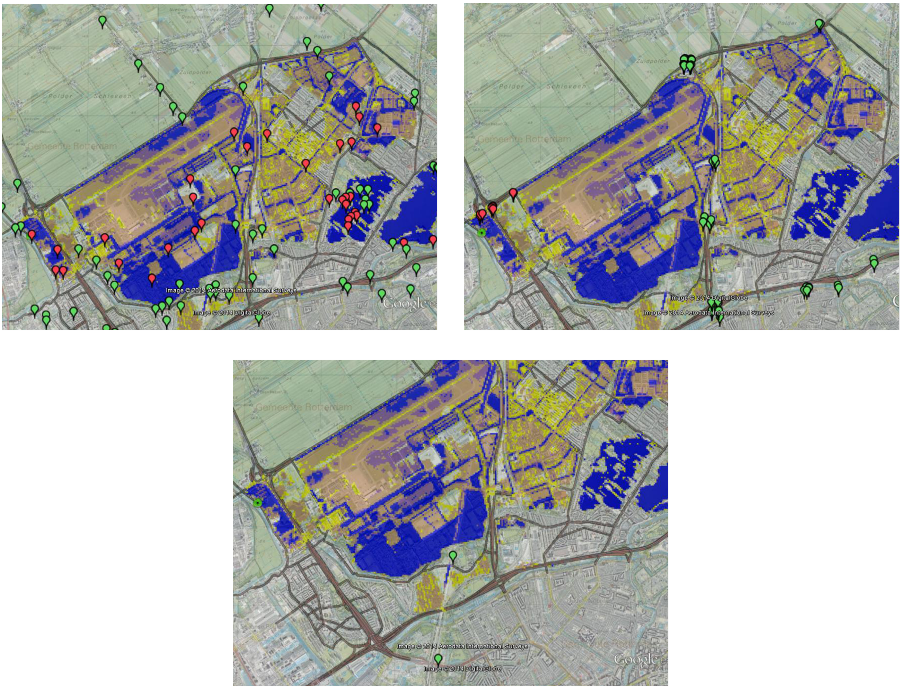

Figure 9.4: Maps illustrating the vulnerability of sewage (top left pane), road (top right pane) and rail (bottom pane) assets in the study area. Balloon icons colored in red indicate vulnerable assets. Balloon icons colored in green indicate assets that are not vulnerable.

a preliminary analysis of possible substation accessibility issues. The results of this analysis are illustrated in Figure 9.5, and show that a significant portion of both the 25/10 kV and 10/0.4 kV substations may be inaccessible. Most of these accessibility issues may be attributed to high on-site water levels, as opposed to high water levels on the surrounding roads[3]. It should be stressed, however, that these results are only preliminary. They do not account fully for the structure of the road network nor the possibility for earlier (before 120 hours) shutdown of vulnerable substations. Further analysis would be necessary to arrive at conclusive results concerning possible accessibility issues.

In this study, we have limited our analysis to the confines of the geographical area outlined in Figure 9.2. However, this does not necessarily mean that infrastructure disturbances induced by a dike breach at the selected locations would necessarily be limited to the defined study area. The failure of certain substations within the study area could result in a loss of power to adjacent areas as well. However, given that the study area itself does not contain any major components of the electricity infrastructure (e.g. large power plants or components of the electricity transmission infrastructure), effects on electricity infrastructure components beyond the immediately adjacent areas are unlikely. The same cannot necessarily be said for the

[3] For the purposes of this analysis, it is assumed that roads are passable to utility vehicles at water depths of up to 0.5 meter, and that substations with on-site water levels greater than 0.5 meter are inaccessible to utility technicians.

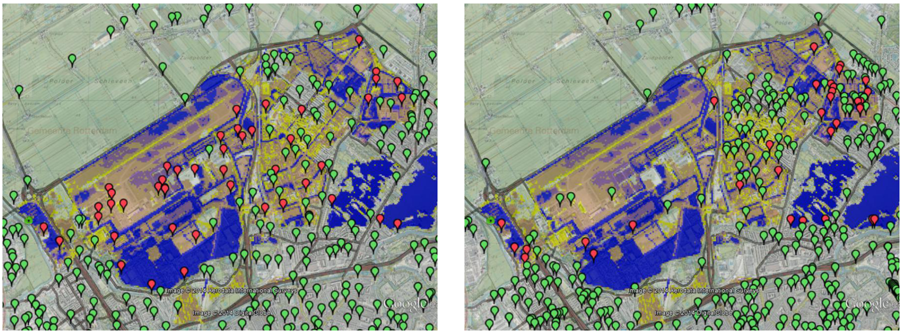

Figure 9.5: Maps illustrating potential accessibility issues associated with 25/10 kV substations (left pane) and 10/0.4 kV substations (right pane) in the study area. Balloon icons colored in red indicate potentially inaccessible substations.

road infrastructure, given that the study area includes portions of the A13 and A20 highways.

## Possible adaptation measures and recommendations for future study

Based on the results of this analysis, we can conclude that a number of electrical substations in the study area may be vulnerable in the case of a dike breach at Schie-Noord, Schie-Zuid or Rotte. Amongst these three dike breach scenarios, a Schie-Noord dike breach poses the greatest risk, potentially resulting in loss of power to more than 30,000 customers, including the Rotterdam-Hague Airport. An extended Schie-Noord dike breach (lasting five or more days) also has the potential to result in the failure of multiple sewage and road infrastructure components, due to their dependencies on the electricity infrastructure. A Schie-Noord dike breach may also pose an issue in terms of possibilities for the manual shutdown of certain 25/10 kV and 10/0.4 kV substations in the study area, though further analysis is necessary to determine the degree of this problem.

Various measures may help to address these vulnerabilities (see Table 9.2). One possibility would be to physically elevate electrical substations. This is feasible in the case of newly constructed substations, and indeed has been implemented in some cases. However, it is more challenging in the case of existing substations, as it would require lengthening the cables feeding these substations, a process which is expensive and can potentially introduce additional vulnerabilities. In the short-term this is thus an unrealistic measure, but, in the longer term, something to be considered.

Another possible measure would be the use of portable generators to provide power to flood-affected areas. This is a feasible solution, and has been implemented by distribution grid operators in the Netherlands for other types of disasters (NRC, 2012). However, it is a solution which can only be implemented once flood waters have sufficiently receded, and cannot ultimately prevent flood-induced damage to infrastructure components. With respect to possible substation accessibility issues, one possibility is to enable the remote shutdown of substations. Already, this has

Table 9.2: Possible adaptation measures to address infrastructure vulnerabilities in the North Rotterdam study area.

| **Measure** | **Target** |
|---|---|
| Physically elevate electrical substations | Electrical substations |
| Remote shutdown of substations | Electrical substations |
| Use of portable generators | Electricity distribution grid |
| Use of portable sewer pumps | Sewage infrastrastructure |
| Backup power for traffic signals | Traffic signals |

been implemented by Stedin for the 50/25 kV substations, and is in the process of being implemented for the 25/10 kV substations. Like the use of portable generators, these measures would not prevent power failures in the case of a dike breach, but could reduce the damage to these components, enabling quicker recovery.

In terms of protecting sewage and road infrastructure assets, a possible measure may be to permit the failure of the feeding electrical substations, but provide backup services for the infrastructure assets. In the case of the road infrastructure, this could entail the provision of backup power to traffic signals. In the case of the sewage infrastructure, it could entail the use of portable sewer pumps that could be brought into a flood-affected area. Both of these are feasible solutions, and have been implemented elsewhere. The matrix boards used on Dutch highways are already furnished with emergency backup power, which can last up to 24 hours (Snelder, 2014). Moreover, solar powered traffic signals are already used in certain parts of the world (Ray, 2012), and solar panels could also be used as a backup source of power for traffic signals.

The analysis presented in this section has provided an initial overview of possible infrastructure vulnerabilities in the case of a dike breach in the North Rotterdam area. However, several important questions remain to be addressed. Foremost amongst these is the degree to which the Rotterdam-Hague Airport may be vulnerable, particularly in the case of a Schie-Noord dike breach. Our analysis suggests that a Schie-Noord dike breach may cause the 50/25 kV substation feeding the Airport to experience water levels exceeding its protection height. While it is known that the Airport possesses an emergency generation facility, it is not clear to what degree this facility itself may be affected in the case of such an event.

A second aspect worthy of further investigation is the precise manner in which a North Rotterdam dike breach may unfold. The current analysis has focused largely on a static situation at 120 hours after an initial dike breach. This neglects the important question of *how much time* actors such as Stedin may have to react in order to prevent or reduce service failures or physical infrastructure damage.

## 9.4 Enhancing infrastructure resilience under conditions of incomplete knowledge of interdependencies – an abstract model

A key challenge in seeking to enhance the resilience of multi-infrastructure systems in practice relates to the fact that many of the interdependencies between infrastructures may be unknown to the actors responsible for operating and safeguarding these infrastructures (Robert and Morabito, 2010). Part of this challenge may be attributed to the organizationally fragmented nature of multi-infrastructure systems – electricity networks, natural gas networks, roads, railways, ICT systems and other infrastructures are normally owned and operated by organizationally distinct actors, which limits the control and knowledge of individual actors (De Bruijne and van Eten, 2007). In the aftermath of Hurricane Sandy, for instance, one of the main recommended actions was greater effort to "identify interdependencies between the electricity and oil and gas sectors to educate stakeholders and decision makers" (U.S. DOE, 2013). In the case of the analysis described in the previous section, experts and stakeholders representing multiple infrastructure domains were actively involved, but knowledge of the interdependencies between these networks was still incomplete, and certain infrastructure networks (ICT, air transport, etc.) were altogether excluded from the study.

Actions by infrastructure operators to identify and catalog infrastructure interdependencies can be an important step to enhancing resilience. However, complete knowledge of infrastructure interdependencies is an elusive goal, as interdependencies are inherently "dynamic and situational" (U.S. DOE, 2013). Infrastructures are constantly changing and co-evolving (Nikolic, 2009), meaning that new interdependencies may continuously arise. Moreover, precisely what constitutes an interdependency may depend on the situation. For instance, the proximity constituting a geographic interdependency may depend on the nature of the threat. These realities limit our capacity to develop accurate models of multi-infrastructure systems, thus restricting our ability to effectively foster resilient infrastructures.

How can we support infrastructure resilience lacking precise knowledge of infrastructure interdependencies? One possible approach to addressing this question is proposed by Barker and Haimes (2009), who introduce a dynamic inoperability input-output model to evaluate the effects of uncertainties associated with infrastructure interdependencies in the case of a disruptive event. Barker and Haimes (2009) use this model to identify *critical* elements in the multi-infrastructure system – "those infrastructure sectors that are most sensitive to economic perturbations due to their inherent interdependencies with other critical sectors". Another possible approach is proposed by Tai et al. (2013), who suggests that, rather than seeking to determine the effects of possible failures in a network, we should solve the inverse problem – to identify those networks that may result in "the most extreme disruptions" (Tai et al., 2013). These networks may then be used to identify scenarios in the real world that could potentially lead to the realization of such disruptions (Tai et al., 2013).

The model described here uses a different approach. We begin by conceptualizing the situation of a boundedly rational infrastructure operator, in this case the operator of an electricity infrastructure. Like Tai et al. (2013), we assume that this operator lacks complete knowledge of the interdependencies between his infrastructures and other infrastructures. Additionally, we assume that the operator faces significant uncertainty concerning the severity and frequency of future disruptive events to which his infrastructure may be exposed. Given the massive uncertainties surrounding looming threats such as climate change and (cyber-)terrorism, this is a very real source of uncertainty for today's infrastructure operators.

How should an infrastructure operator ideally invest to ensure a resilient network in the face of these uncertainties? In addressing this question, we draw from Lempert et al. (2003), who suggest that, in dealing with such situations, decision makers should not seek optimal strategies but rather *robust* strategies – "strategies that perform 'well enough' by meeting or exceeding selected criteria across a broad range of plausible futures". With this in mind, we place our hypothetical infrastructure operator in a simulated environment consisting of a (known) electricity network and an (unknown) interdependent second network, both of which may be subjected to a range of disturbances. We assign the operator four possible strategies for enhancing the resilience of his network, and examine how these strategies perform under different conditions.

## Model design

The starting point for the model is a network representation of a generic electricity infrastructure (infrastructure A). The setup of infrastructure A is based on the IEEE 118 bus power system test case (Christie, 1993b), which represents an archetypal electricity transmission infrastructure. Infrastructure A includes three types of nodes – representing electrical substations, power generation facilities and power consuming facilities, or loads – and one type of link – representing power lines or electrical transformers. Infrastructure A is augmented with links to a second infrastructure network of a different unspecified type (infrastructure B). Infrastructure B could be conceptualized to represent a road infrastructure, natural gas infrastructure, IT infrastructure, etc. Infrastructure B is composed of a set of randomly connected nodes and edges, and features only a single type of node and a single type of edge.

Infrastructures A and B feature a number of common links in the form of *interdependencies*. For the sake of simplicity, we assume that all of these interdependencies are bi-directional – that is, each represents a dependency of infrastructure A on infrastructure B and vice versa. Infrastructures A and B are illustrated in Figure 9.6.

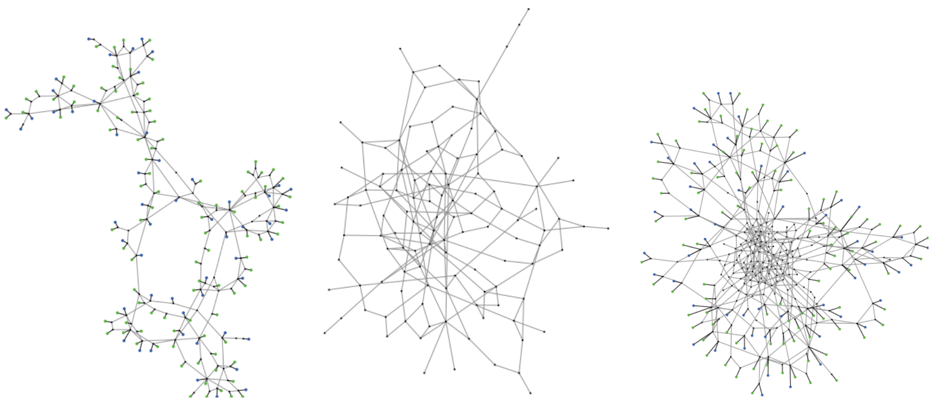

Figure 9.6: Visualization of the modeled infrastructure networks, including infrastructure A (left pane), infrastructure B (center pane) and the combined infrastructure network with interdependencies (right pane).

Each run of the simulation consists of 100 timesteps, each representing a timespan of one year. Every timestep during the course of a simulation, we introduce a set of failures, which correspond to the disabling of a set of links in the multi-infrastructure network. It is assumed that all of the failures within a given year occur simultaneously – that is, each year a single set of concurrent failures occur. These failures may affect links of infrastructure A or infrastructure B, or the interdependencies between them. The number of failures occurring each timestep is randomly determined according to a power law size-frequency distribution. Approximate power law size-frequency distributions are typical of many types of natural disasters (Barton and Nishenko, 2013). Precisely which links are affected by a failure is randomly determined, and all links are returned to working order at the start of the next timestep.

The failure of a single link may affect not only that link, but may also result in a cascade of failures through the multi-infrastructure network. Failure cascades through the electricity network (infrastructure A) are determined by an iterative power flow algorithm. Following a set of initial failures, the algorithm calculates anticipated power flows through the network. If the calculated power flow across any line exceeds its capacity, the line is assumed to fail due to overload. This results in an altered distribution of power flows, which may cause additional lines to fail. This process is repeated until no more power lines are overloaded. Failure cascades in infrastructure B are determined in a simpler manner – if a link fails, it is assumed that there is a 10% chance that each of its neighboring links will fail during that timestep.

Via *interdependency links*, failure cascades may cross over from infrastructure A to infrastructure B, and vice versa. Each time a failure cascades from one infrastructure to the other, it induces (a) failure(s) in the latter. This may eventually cause the failure to cascade (via another route) back to the first infrastructure, and so on. In this manner, we represent not only the propagation of failures within a particular infrastructure, but also the potential for first, second, third and higher order interdependency effects.

The model is implemented in the agent-based modeling platform Netlogo (Wilensky, 2012), and makes use of the MATLAB-based power system simulation package Matpower (Zimmerman et al., 2011). Runtime communication between these pieces of software is enabled by way of the *MatpowerConnect* extension (see Chapter 5). This extension takes as input the properties and configuration of a power system instantiated in Netlogo and provides as output data about real power flows under the specified conditions. The model also makes use of Netlogo's *Rserve* extension, which allows for runtime communication between Netlogo and the statistical computing software R. This extension makes use of R's *gPdtest* package (Estrada and Alva, 2012) for generating pseudo random numbers from a generalized Pareto distribution. These numbers are used in the model for the purpose of determining the magnitude of disruptions in line with a generalized Pareto distribution. The model code can be found on the Web here: `https://github.com/ABollinger/InterdependentInfrastructuresModel`

## Representation of investment strategies

The hypothetical operator of infrastructure A seeks to ensure the infrastructure's resilience in the face of (unknown) future failures. However, the operator's task is complicated by several factors. First, he does not know exactly *how severe* future failure scenarios may be, so he does not know precisely how robust his network must be to withstand these failures. Second, the operator does not know *where or how many* interdependencies exist between his infrastructure (infrastructure A) and infrastructure B. Third, the operator has no control over and limited knowledge of infrastructure B – that is, he cannot influence the design of that network nor can he predict possible failures within it.

The operator of infrastructure A is given a set of four possible strategies to enhance the resilience of his electricity network. The first two of these strategies are adaptive, meaning that the operator adapts his investments as conditions develop. The third strategy is pre-emptive, meaning that the operator makes a single large investment at the start of the simulation. The strategies are as follows:

1. **Focus on the critical links:** Each time a link of the electricity infrastructure fails due to capacity overload, the operator increases the link's capacity by an amount equivalent to the magnitude of the overload.

2. **Focus on the interdependencies:** Each time an unknown interdependency is revealed (due to the failure of an interdependency link), the operator constructs a redundant interdependency link, essentially obviating the possibility for future failure of that link.

3. **Pre-emptively increase capacities:** The operator increases the capacity of all power lines by 50% at the start of the simulation.

4. **Combination:** Combination of strategies 1 and 2.

In addition to these four strategies, we include a null strategy (strategy 0), corresponding to no action on the part of the infrastructure operator. Each investment made by the infrastructure operator is assumed to entail a certain cost. The cost of one additional redundant interdependency link or power line is assumed to be *1 monetary unit*. The cost of one unit of additional power line capacity is assumed to be *1 monetary unit, divided by the mean capacity of power lines in the system.* In other words, the cost of constructing one redundant interdependency link is equivalent to the cost of doubling the capacity of the average link in infrastructure A.

## Experiments

We have carried out a set of 60 experiments with the developed model. The purpose of these experiments is to identify *robust* strategies for enhancing infrastructure resilience – strategies that perform sufficiently well across a range of possible futures. The performance of the different strategies is evaluated using two metrics – resilience and cost. *Resilience* is defined as the mean performance of infrastructure A across all timesteps of all simulations employing that particular strategy, with performance quantified in terms of the *fraction of demand served* – the mean fraction of power received by customers vs. that which was demanded[4]. *Cost* is defined as the sum of all expenditures of the infrastructure operator in making upgrades to his network, again averaged across all simulations employing the respective strategy.

In the course of experimentation, we vary the values of three key parameters: (1) the strategy employed by the infrastructure operator, (2) the number of interdependencies between the electricity infrastructure and the second infrastructure, and (3) the severity of failure scenarios (expressed in terms of the scale parameter of the Generalized Pareto Distribution used to generate the failure magnitudes). The range of values tested for each of these parameters is listed in Table 9.3. In order to control for the multiple sources of randomness in the model, we repeat each of these experiments 45 times.

Table 9.3: Names and tested value ranges/increments of the parameters varied during experimentation with the developed model.

| **Parameter name** | **Range** | **Increment** |
|---|---|---|
| Operator strategy | 0 – 4 | 1 |
| Number of interdependencies | 25 – 100 | 25 |
| Severity of failure scenarios | 5 – 35 | 15 |

## Results and analysis

Figure 9.7 illustrates key results from the developed model. These plots show the spread of resilience and cost values observed across each of the tested strategies. In terms of resilience, the top performing strategies are strategies 4 and 2, corresponding to mean resilience values of 0.87 and 0.85, respectively. Both of these strategies involve focusing on constructing redundant interdependency links between infrastructure A and B, suggesting that failure cascades between infrastructures A and B play an important role in affecting the performance of infrastructure A. Further analysis of the results indicates that, logically, the larger the number of interdependencies, the more advantageous these strategies prove to be. This may be explained by the magnifying effect of interdependencies, which allow disturbances not only to jump from one infrastructure to another, but back and forth between infrastructures – producing second, third and higher order interdependency effects. Redundant interdependency links effectively mitigate these sorts of dynamics.

It is important to note, however, that – under certain circumstances – a strategy of focusing exclusively on the construction of redundant interdependency links (strategy 2) can still result in relatively low resilience values – as low as 0.65. This may be attributed to the inability of this strategy to mitigate the effects of large-scale failure cascades within infrastructure A, which may periodically occur *regardless* of the fragility of the interdependencies with infrastructure B. A strategy combining the construction of redundant interdependencies with the construction of additional capacity for the critical links of infrastructure A (strategy 4) can help to to eliminate these low values. Specifically, this strategy has the effect of increasing the minimum observed resilience value from 0.65 to 0.71.

[4] A resilience value of 1 thus suggests that all power demand of customers is fully satisfied under all conditions, and a value of zero suggests that no power is received by any customers under any circumstances.

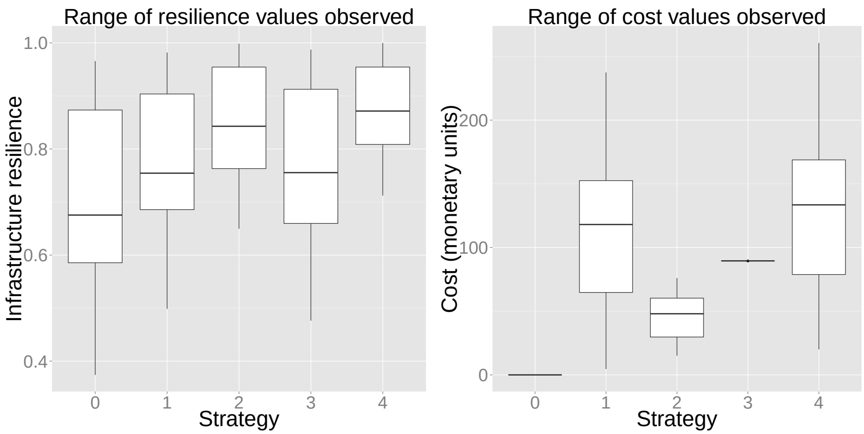


Figure 9.7: Results of the developed model: box plots showing the range of observed resilience values (left pane) and cost values (right pane). The ends of the box indicate the 25th and 75th percentiles; the lines extending from the boxes include the extreme data points not considered outliers.

As illustrated in Figure 9.7, the best performing strategy in terms of cost (excluding strategy 0) is strategy 2, which corresponds to a mean investment of approximately 46 monetary units. On average, strategy 1 is significantly more expensive, featuring a mean investment of approximately 110 units. The explanation for this discrepancy lies in the relative cost of adding capacity to the links of infrastructure A vs. constructing redundant interdependency links. Given the large number of links in infrastructure A (relative to the number of interdependency links) and the magnitude of capacity overshoots, strategy 1 necessitates, under many conditions, massive and costly increases in capacity. Even under conditions in which the system features a large number of interdependency links, the cost of building redundant interdependency links is usually significantly less than the cost of necessary capacity increases in infrastructure A.

However, it is interesting to note that, under certain conditions, strategy 1 can result in *lower* costs than strategy 2 – as low as 4.6 monetary units. These correspond to situations in which the starting capacity of links in infrastructure A is largely sufficient in light of the conditions to which the infrastructure is exposed. A closer look at the results reveals that this occurs only in situations with a very low severity of failure scenarios. Thus, if the infrastructure operator is relatively confident in the limited severity of future failure scenarios, strategy 1 may be a more attractive strategy. In this case, we have have assumed that the operator does not have sufficient information to make such a judgment.

Figure 9.8 illustrates the average infrastructure performance over time for each strategy. As this plot shows, strategies 3 and 4 perform best, on average, at the start of the the simulation, with strategy 2 a close third. This may be explained by the fact that all of these strategies entail some investments at the start of the simulation. Under strategies 2 and 4, these investments take the form of the construction of a handful of redundant interdependency links. Under strategy 3, they take the form of capacity increases in infrastructure A. However, as time proceeds, the performance of the adaptive strategies (strategies 2 and 3) begins to exceed that of strategy 1. Under strategy 2, mean performance rises rapidly at first – permanently exceeding that of strategy 3 after only five years – and gradually levels out as most of the key interdependencies have been located and redundancies constructed. Under strategy 3, infrastructure performance rises more slowly and plateaus after about 50 years.

The variability observed in Figure 9.8 underscores an important part of the story that we have thus far neglected – the relevance of random variations in extreme event magnitudes in affecting the performance of the system. Infrastructure performance may vary drastically from year to year regardless of the strategy taken. The mean standard deviation in infrastructure performance (aggregated by timestep) for each strategy is as follows: 0.34 (strategy 0), 0.31 (strategy 1), 0.28 (strategy 2). 0.32 (strategy 3), 0.26 (strategy 4). While certain strategies – strategies 2 and 4 – are slightly better at mitigating this variability, they cannot eliminate it. Even the top performing strategy (strategy 4) produces performance values as low as zero during the last timestep of the simulation (100 years).

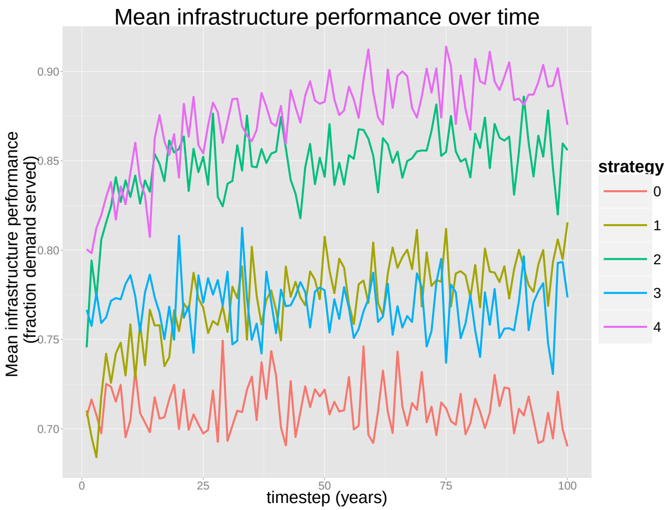


Figure 9.8: Development of mean infrastructure performance over time under each strategy.

Which of the tested strategies is most *robust* depends on the priorities of the infrastructure operator and which values for the different metrics may be considered “good enough”. If the operator prioritizes resilience and prefers minimum resilience values above 0.7, the most robust option would be to follow a strategy combining the construction of redundant interdependencies with the construction of additional capacity for the critical links of infrastructure A (strategy 4). If the operator seeks to minimize his investment costs while still maintaining relatively high resilience values, the most robust option would be to follow strategy 2, and focus exclusively on constructing redundant interdependencies. If the operator seeks certainty in his investment costs (with some degree of added resilience above the baseline case), strategy 3 is the best option, though this comes at a significant penalty in infrastructure resilience relative to strategies 2 and 4.

## Discussion

Uncertainty concerning both the locations/types of infrastructure interdependencies and the severity/frequency of future failure scenarios are very real problems faced by today's infrastructure operators. In this section, we have introduced a model exploring different long-term strategies for an infrastructure operator to invest in light of these uncertainties. We have sought to identify *robust* strategies for supporting infrastructure resilience.

The results from the developed model show that a strategy focusing on the construction of redundant interdependencies may be the most robust option for a financially constrained infrastructure operator. However, each of the tested strategies offers other advantages and disadvantages which have been excluded from the model, but may serve to make these strategies more or less attractive to infrastructure operators functioning within different socio-political contexts. In particular, while strategies 2 and 4 proved advantageous in fostering resilience, these strategies could require cooperation between organizationally distinct actors – different infrastructure operators – featuring different sets of motivations and operating within different institutional regimes. The friction costs and other hurdles associated with such cooperative activities have not been accounted for in this study, and could prove challenging within certain contexts. Strategy 3 presents other difficulties, as it entails a relatively large upfront investment, which may be difficult to justify politically. Strategy 1 requires neither large upfront investments nor cooperation between actors. However, this strategy necessitates massive reactive investments, the sheer size and cost of which may put off regulators and/or customers.

As noted above, an important part of the story here is not just the relative robustness of different strategies, but also the significant degree of annual variability in extreme events. Our analysis showed that the large variability in the magnitude/scope of disturbances translates into significant variability in infrastructure performance – and this regardless of the investment strategy chosen. While the severity of extreme events in the model likely over-represents that observed in the case of most real-world infrastructures, the strong connection between extreme event variability and infrastructure performance offers an important lesson. Namely, it reinforces the relevance of modeling and simulation (M&S) in developing strategies to cope with problems featuring high levels of uncertainty and long timeframes. Strategies based on knee-jerk or purely political responses to unexpectedly disastrous extreme events may result in over-investment, or even under-investment complemented with a false sense of security. It is more advantageous for infrastructure operators to consider the range of future uncertainties – a capability enabled by the use of M&S in combination with exploratory modeling techniques (see chapter 3) – and to identify robust strategies in light of these uncertainties. As our results and the developed model have shown, the combination of these techniques can assist infrastructure operators to identify such strategies and to realize a rational approach in dealing with highly uncertain situations.

It must be kept in mind that the results presented here are specific to the infrastructure configuration tested and rely on a set of assumptions that may not hold in the real world. However, the approach used and the developed model may be useful insofar as they can be tailored to the specific conditions of real-world infrastructure operators faced with a similar dilemma. For instance, the generic network structures used in the current model can be replaced by real-world networks of different types (e.g. ICT, transport, water), and a broader array of (combinations of) investment strategies may be assessed. Specifically, in light of the discussion above, it may be advantageous for infrastructure operators to first identify a set of socio-politically feasible strategies, and then to use the developed model or similar techniques to assess the performance of these strategies.

## 9.5 Synthesis

This chapter has focused on the role of interdependencies in affecting infrastructure resilience. In the first part of the chapter, we provided a summary of literature dealing with (the modeling of) infrastructure interdependencies. This overview revealed growing interest within the scientific community on this topic, and highlighted the increasing use of network-based approaches in studying the consequences of infrastructure interdependencies. The second and third parts of the chapter described a set of models utilizing a network-based approach to explore the effects of infrastructure interdependencies in multi-infrastructure systems.

The first of these models – developed in the context of a participatory multi-stakeholder project – sought to assess the infrastructure consequences of several dike breach scenarios in the North Rotterdam area of the Netherlands. This study identified a number of potentially vulnerable components of the local distribution grid, and, based on this, identified secondary vulnerabilities in the sewage and road infrastructures. In total, 128 electrical substations were identified as vulnerable in the case of a Schie-Noord dike breach, resulting in secondary vulnerabilities affecting at least 6 traffic signals and approximately 23% of sewer pumps within the study area. Based on these results, we identified several suitable adaptation measures – temporary generators and/or sewer pumps, backup electricity for traffic signals and remote shutdown of electrical substations.

Where the first model used existing data as a starting point for assessing vulnerability in a multi-infrastructure system, the second model used a *lack* of data as a starting point – exploring strategies for enhancing resilience under conditions of incomplete knowledge of possible interdependencies. In developing this model, we began by conceptualizing the situation of a hypothetical operator of an electricity infrastructure faced with uncertainty concerning both the interdependencies to which his infrastructure is exposed and the severity of future extreme events. Via experimentation with this model, we identified *robust* strategies for supporting infrastructure resilience in light of these uncertainties. While these results are specific to the infrastructure configuration tested, the developed model offers a template which can be tailored to the specific conditions of real-world infrastructure operators.

As demonstrated in the first part of this chapter, interest within the research community in the consequences of infrastructure interdependencies is increasing. This growing interest reflects a clear trend towards increasing interdependency of our infrastructures. Already, the electricity infrastructure offers essential services to a range of other infrastructures – road, rail, sewage, drinking water, etc – and ICT infrastructures seem to be on a similar trajectory. These interdependencies play a dual role. On one hand – as we have investigated in this chapter – these interdependencies can allow for the propagation of disturbances, leading to potentially massive infrastructure disruptions. On the other hand – and something we have not considered here – interdependencies can help to stabilize an infrastructure in the face of disturbances (Duenas-Osorio et al., 2007). Precisely where the line between these dynamics lies is a question with which we have not explicitly dealt in this chapter. This may be an important area for future research.

By considering the role of infrastructure interdependencies in affecting infrastructure resilience, this case study adds an important dimension to the work presented in the previous case studies. Namely, it addresses the reality that it is increasingly of limited use and validity to deal with electricity infrastructures as independent entities. A key challenge in fostering climate resilient electricity infrastructures has to do with the (overwhelming) complexity of the multi-infrastructure systems within which electricity infrastructures reside. In modeling these systems, we cannot hope to accurately represent the multitude of relationships within them, nor is it clear precisely what degree of system representation is sufficient. The second model presented in this chapter has offered a hint as to how it may be possible to make rational decisions in spite of these limitations, but it is only a starting point. In the next chapter, we deal more broadly with the role of modeling and simulation in the context of infrastructure complexity, which offers additional insights for fostering resilience in multi-infrastructure systems.

# Part V

# Synthesis

# Chapter 10

# Multi-model ecologies

## Facilitating model integration and reuse in the study of infrastructures

This chapter is based on a forthcoming article in the *Journal of Industrial Ecology* titled "Multi-model ecologies – Cultivating model ecosystems in industrial ecology", by L.A. Bollinger, I.Nikolic, C.B. Davis and G.P.J. Dijkema. The first three sections of this chapter, and the last section, have been altered in comparison to this article.

## 10.1 Introduction

Models are simplified representations of the real world. They can exist as neural connections in our minds (mental models), as qualitative sets of relationships on paper (conceptual models) or as logical configurations of electronic gates in a computer (computer models). The case studies described in the previous chapters have involved the development of a number of models – each driven by a specific research question and each featuring a different temporal, geographic or socio-technical scope. In combination, these models are intended to provide broader insight with respect to the issue of fostering climate resilient infrastructure systems. Before exploring these insights more fully – a task we will undertake in the next chapter – we take a brief detour to reflect on the role and the use of modeling in the study of infrastructures.

Some of the most important problems in the infrastructures domain span multiple scales of time and space, and feature multiple valid perspectives. Infrastructure adaptation to climate change is a case in point. In seeking to foster climate resilient electricity infrastructures, we must consider short-term processes (e.g. failure cascades) and long-term processes (e.g. infrastructure evolution), as well as local-scale dynamics (e.g. infrastructure interdependencies) and national-scale dynamics (e.g. power flows through the transmission grid). And we need to account for the existence of multiple valid perspectives, e.g. with respect to the definitions of key concepts, the severity of future climatic changes and the key drivers of infrastructure change. How can modeling and simulation be more effectively used to address multi-scale, multi-perspective societal challenges such as infrastructure adaptation to climate change?

## 10.2 Models as single-use products

Many models in the infrastructures domain, as in many other domains, may be classified as *single-use products* – they are constructed to address a particular problem within a particular context. The choice of technique and the design of the model are tailored to its purpose and bear the marks of the context in which it was developed. To some degree, this is necessary and inevitable – infrastructures are complex open systems which no single model or theoretical perspective can definitively represent.

As such, every computer model represents one of multiple – sometimes many – valid epistemological and ontological perspectives. A model is a "leaky abstraction" (Spolsky, 2002), and reflects the subjective beliefs and limited knowledge and skill of the individuals involved in its development as much as it does the composition of the real-world system. This hinders possibilities for the use of models beyond their original context, a difficulty which is compounded by the fact that models are often developed in disciplinary communities with their own vocabulary, perspectives, theories and tools (Davis et al., 2010). Thus, even in cases in which model reuse may be epistemologically/ontologically feasible, it can be hindered by an inability of the development team to fully grasp the conceptualization of reality underlying the model.

Moreover, models of infrastructure systems normally pertain to a particular place and time, yet infrastructures are constantly changing and their composition varies from place to place. The model introduced in chapter 6, for instance, relies on a number of place-specific datasets which may not be readily available for other geographies. Moreover, the infrastructure configuration represented in that model reflects the 2010 state of the Dutch electricity infrastructure, a representation which is already obsolete given a number of changes that have occurred in the meantime. The complex open nature of infrastructure systems, and the rapidity with which these systems may change, severely limit our ability to develop models that may be useful beyond the context, place and time in which they were originally created. Despite these difficulties, it is clear that a knowledge ecosystem based around single-use representations of reality wastes effort and resources, and restricts possibilities for effectively addressing multi-scale, multi-perspective problems.

How can we enhance the sustained usefulness of our models? Traditional means of publication and knowledge dissemination – such as journal articles, books and conferences – undoubtedly facilitate this. But such means are geared towards the sharing of *unformalized knowledge* rather than *formalized representations*. Emerging methods and tools from information science and technology can help to fill this gap – serving as a vector for the integration, reuse and adaptation of models and model components. By enabling the integration of models featuring different scopes and representing different perspectives, such methods and tools can enhance our ability to address multi-scale, multi-disciplinary and multi-perspective problems. In order to realize their full potential, however, they need to be applied with an understanding of the context within which models are developed and the processes underlying their development.

With this need in mind, we continue in the following section with an overview of existing work in the area of model integration and reuse, and elaborate on the notion of models as elements in complex socio-technical systems. Following from this, we introduce the notion of *multi-model ecologies* – defined as interacting groups of models and datasets co-evolving with one another within the context of a dynamic socio-technical environment – and describe their components and the mechanisms of their evolution. To illustrate the use of this concept, we introduce and analyze an existing multi-model ecology – the Energy Modeling Laboratory – of which this research is a part. We conclude this chapter with a set of guidelines for infrastructure modelers and the infrastructures community at large for facilitating model integration and reuse in the context of multi-model ecologies.

## 10.3 Model integration and reuse – an overview

Researchers in the infrastructure domain make extensive use of models of different types – linear/nonlinear/stochastic/mixed-integer programming models, power systems models, activity-based models, system dynamics models, agent-based models and others. In the context of these efforts, the need for model integration and reuse has not gone unnoticed. This is reflected in a large number of integrated modeling efforts – integrated transportation/land-use modeling (Berryman et al., 2013; Waddell, 2002, 2011), integrated energy/environmental models (e.g. integrated assessment models) (Kraucunas et al., 2014; Seebregts et al., 2001; Stocker et al., 2011), integrated water/socio-economic models (Davies and Simonovic, 2011; Qin et al., 2011), urban multi-infrastructure models (Cesanek et al., 2010; Goodall et al., 2013; Urich et al., 2012), infrastructure interdependency models (Ouyang, 2014) and others. It is also reflected in a number of parallel modeling efforts and model comparison efforts (Luderer et al., 2012; Strachan et al., 2008; van Noortwijk and Frangopol, 2004), which compare multiple perspectives/approaches to the same problem. How can we conceptualize such efforts, and how can we coherently guide them?

### Representing complex systems

Ideally, we would like our models to be simple – easy to develop, interpret and understand. However, the need for model complexity is not unfounded. The complexity of the problems with which we deal – or, more precisely, of the system(s) underlying these problems – demands a certain minimum degree of complexity on the part of the models we construct (see Ashby's *Law of Requisite Variety*[1] (Ashby, 1956)). As such, we need to strike a balance between complexity and simplicity. This necessity is reflected in Grimm's notion of the *Medawar zone* (Grimm et al., 2005), which suggests the existence of an optimal zone of model complexity that balances requirements for structural realism with those for manageable development and analysis.

While we cannot circumvent the need to develop complex models, we can choose different approaches in doing so. Voinov and Shugart (2013) describes two distinct

[1] Ashby's Law of Requisite Variety suggests that our efforts to control a system must feature a degree of variety matching that of the system itself, suggesting that the complexity of a model must match the complexity of the system it seeks to address.

approaches to the development of complex models – *integral* modeling and *integrated* modeling. Integral models are generally constructed by a closely-knit modeling team which "collects data and information from various scientific fields, processes it, and translates it into one formalism" (Voinov and Shugart, 2013). Such models are most often built from scratch and their components cannot be easily separated and reused. An example is the Club of Rome's *World3* model (Meadows, 1974), which integrates information about food production, industry, population, non-renewable resources, and pollution.

Integral models such as this were famously criticized by Lee (1973), who pinpointed a range of shortcomings in early large-scale urban models – the "seven sins of large-scale models" – including hypercomprensiveness, grossness, hungriness, wrongheadedness, complicatedness, mechanicalness and expensiveness. As a remedy, Lee (1973) provided three guidelines for model building: (1) balance theory, objectivity, and intuition; (2) start with a particular policy problem that needs solving, not a methodology that needs applying; and (3) build only very simple models.

*Integrated modeling* helps to alleviate some of the "sinfulness" of integral modeling by leveraging the "nearly decomposable" nature of complex systems (Simon, 1991). Integrated models are generally assembled from existing or simultaneously developed components, which can work in combination or independently (Voinov and Shugart, 2013). Such models may be gradually assembled and improved over time, and their components may be developed (relatively) independently by specialists from different scientific disciplines. An oft-cited example of an integrated model is the Chesapeake Bay modeling suite (Chesapeake Bay Program, 2012). This modeling suite includes multiple sub-models – a watershed model, estuary model, airshed model and land change model – which have been developed over a period of 30 years by a collection of numerous government and academic partners. Another category of examples are integrated assessment models (IAMs) – such as the DICE/RICE family of models (Nordhaus, 1993).

A variation of the integrated modeling approach is *multisimulation*, which entails a set of related approaches for addressing the challenges of problem situations that cannot be neatly captured within a single, unified representation of reality – e.g. problems spanning multiple scales of time, space and organization, as well as problems characterized by multiple valid conceptualizations of reality. Beginning with the work of Oeren (1991), the modeling and simulation community has addressed this topic under the banners of multisimulation and multi-scale, multi-perspective, multi-resolution and multi-aspect modeling (Tekinay et al., 2010; Yilmaz et al., 2007). These approaches entail the modular representation of systems within a set of interoperable models that capture reality from multiple angles and at multiple levels of fidelity. The majority of applications thus far can be found in the military domain (Jalali et al., 2011; Oeren, 2001), though significant progress in multi-scale modeling can also be seen in biomedicine (Erson and Cavusoglu, 2012).

## Advantages and challenges of integrated modeling

Given their modular structure, integrated models offer several important advantages. By enabling the reuse of existing components – including concepts, algorithms and code – integrated modeling can *potentially* reduce redundant efforts and thus the cost of model development (Voinov et al., 2010). Moreover, the loosely coupled nature of integrated models allows them to be adapted to address multiple policy issues over a period of several years (van Delden et al., 2011). Additionally, by directly integrating expertise from teams with different disciplinary backgrounds, integrated models can help to reduce blind spots and disciplinary skewness in system representation. Finally, through the use of interchangeable components, integrated models allow for the simultaneous representation of multiple perspectives on dynamics and structure. In a field such as IE, replete with problems demanding a "post-normal" scientific approach (Funtowicz and Ravetz, 1993; Keirstead, 2014), models capable of representing multiple viewpoints offer a clear advantage.

Despite their potential advantages, integrated modeling and multisimulation have proven challenging in practice. One category of challenges has to do with the technical aspects of integrating multiple software components – potentially developed in different platforms – in a flexible manner that allows for components to be added and removed without disrupting the functionality of the system (van Delden et al., 2011). As evidenced by the emergence of architectures such as high-level architecture (HLA) and standards such as OpenMI, considerable progress has been made with respect to this challenge in recent years. Another category of challenges has to do with aligning the ontologies and semantics of integrated models. This is particularly acute in the case of integrated models due to the often transdisciplinary nature of components and the tendency for ontologies and semantics to change over time (Laniak et al., 2013).

Next to the issues of software, semantic and ontological compatibility is the more pernicious challenge of *overwhelming complexity* (Voinov and Shugart, 2013). Integrated models have a tendency to become larger and more complex over time, "driven by the desire of both modellers and users to specify processes and interactions in more detail and thus developing a more realistic representation" (van Delden et al., 2011). Integrating complexity and uncertainty begets more complexity and uncertainty, and as models become more complex and uncertain it becomes more difficult to analyze, understand and interpret them (Voinov and Shugart, 2013). Moreover, as computational models become more complex, they require more resources to update and maintain, and it becomes more difficult for actors to grasp their structure and discern meaning in their results.

The existing body of literature on integrated modeling and multisimulation largely neglects interactions of models with their socio-technical context, as well as the constantly shifting nature of this context. Moreover, this literature largely discounts the significance of model evolution and adaptation. We argue that consideration of these aspects is key to the success of efforts to enhance the sustained usefulness of models.

## 10.4 Multi-model ecologies – what and why

A *multi-model ecology* may be defined as an interacting group of models and datasets co-evolving with one another within the context of a dynamic socio-technical environment. A multi-model ecology is not an approach, but rather a perspective – a way of conceptualizing systems of interacting models which emphasizes their evolutionary and socio-technically embedded nature. Viewed through the lens of multi-model ecologies, models are not isolated elements in vacuum, but potentially sociable individuals co-evolving with one another in a changing environment. We argue that this perspective better captures the dynamics of model "ecosystems", and in doing so enhances our ability to integrate and reuse models and data. The *socio-technical context* of a multi-model ecology consists of the actors and technologies that make model development a feasible and valued undertaking, as well as the knowledge, information, techniques and theory that inform model development. The actors of the socio-technical context may include stakeholders, policy makers, funding agencies, researchers, scientific reviewers, domain experts, software developers and others – each possessing their own set of mental models. Technologies may include physical technologies such as computational hardware, software platforms and programming languages, as well as social technologies such as participatory methodologies and modeling techniques (Nelson, 2003).

The actors, technologies and information/knowledge in the socio-technical context may change over time. Actors may move on to new organizations or roles, improved software platforms and programming languages may emerge and new methodologies and techniques may be developed. Likewise, funding for and political and/or academic interest in particular topics may periodically emerge or evaporate. Additionally, new knowledge, information or theory may become available, feeding the development of new models.

A multi-model ecology itself is composed of a set of models that interact with one another and (via actions on the part of actors) co-evolve in the context of a common socio-technical environment. Models in a multi-model ecology are constructed with different scopes, resolutions and perspectives, and different models may represent different theoretical viewpoints. Independently, each model provides a partial picture of the components and relationships underlying the problem at hand. Together, they may provide a more multi-dimensional representation of the relevant system(s). The models in a multi-model ecology may come in different forms – conceptual or computational. These models may be hosted on different physical media or software platforms, and may be in different stages of development. Next to and interacting with these models are data, information and knowledge (Ackoff, 1989). Datasets may serve as the inputs to models, constitute their outputs, or sit alongside models as tools for model validation or calibration.

As illustrated by the schematic in Figure 10.1, models and datasets in a multi-model ecology may interact in different ways. Conceptual models may inform the development of computer models (path 1), the results of which may feed back to the conceptual model (path 2). Computer models may dynamically link with one another during runtime or more statically in sequence (paths 3 & 4). Computer models, as well as conceptual models, may develop in parallel, offering alternative perspectives with respect to a given problem (elements 5 & 6). Conceptual models may serve as a basis for the development of multiple computer models (paths 1 & 7). Datasets may feed into one or more computer models, and may constitute the output of other models (paths 8 & 9). Certain datasets, conceptual models and computer models may exist in isolation (elements 10–12), disconnected from the rest of the ecology but serving as potential resources as the ecology develops. The links between computer models may be uni-directional or bi-directional, and may constitute different levels of interoperability – technical, syntactic, semantic, conceptual, etc. (Wang et al., 2009). Conceptual models and computer models derive from the mental models of actors, which in turn may be influenced by them.

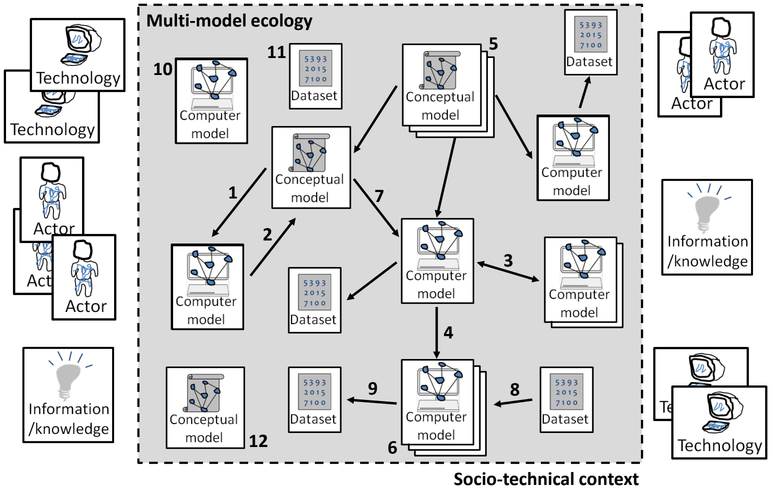


Figure 10.1: Schematic of a hypothetical multi-model ecology and the relations within it. Links with the socio-technical context have been excluded. Numbers refer to the paths/elements referenced in the text.

In the case of computer models, the aim of interactions is not necessarily "pure composability" (Davis and Tolk, 2007) – strict plug-and-play capability of components – but rather the cultivation of a set of resources that can be configured and reconfigured to interact with one another in different ways, whether statically, dynamically, directly or indirectly. Like programs in the GNU/Linux operating system, entities in a multi-model ecology can be seen as "filters" for processing and transforming data, and can be linked with other filters in different ways to serve different purposes (Gancarz, 2003). From this perspective, a multi-model ecology may be viewed as a sort of ecosystem, with different species and different forms of possible relationships between them – mutualistic, parasitic, competitive, predatory, etc. New individuals or species may enter the ecosystem, enabling the emergence of new structures or disrupting an existing balance by altering the fitness landscape. Changes in the socio-technical context may likewise affect the fitness landscape, favoring alternative configurations of existing models/datasets or incentivizing the development of new ones.

## 10.5 The evolution of multi-model ecologies

As the outcomes of social processes, models are not objective representations of reality, but carriers of cultural ideas – highly compressed narratives about the world reflecting the perspectives of their developers. The demarcation of system boundaries, choices of elements to include and determination of quantitative relationships inevitably bear the cultural marks of the socio-technical context. From this perspective, models may be viewed as *memes*. Inspired by the biological concept of a gene and first introduced by Dawkins (1990), a meme refers to a unit of cultural transmission which reproduces itself by spreading between human minds. Memes include "everything you have learned by imitation from somebody else ... all the words in your vocabulary, the stories you know, the skills and habits you have picked up from others and the games you like to play" (Blackmore, 1999).

In the case of models, memes not only exist in human minds, but also *in silico* – in the memory drives of computers. During the course of its lifetime, a model may leap back and forth between human minds, between computer representations and between humans and computers. Each of these leaps may introduce modifications in the composition of the meme, improving or weakening its ability to survive and spread.

The theory of *Universal Darwinism* holds that the concept of evolution can be viewed as a generic algorithmic process that may be applied to systems beyond the biological realm (Dawkins, 1983). From a perspective of models as memes, models may be viewed as replicators participating in a continuous process of variation, selection and heredity. *Variation* occurs when models are modified from their previous state; *selection* occurs when useful models are identified and others are discarded; and *heredity* occurs when useful models are disseminated. The differential survival of competing memes/models in their socio-technical environment drives the evolution of the model ecosystem.

Let us explore these processes in more detail. *Variation* may entail the addition or subtraction of variables to/from the model, adjustments in the quantitative relationships between variables or the reconfiguration of existing relationships between variables. When a model is developed from scratch in the context of a participatory process, variation occurs as the mental models of involved stakeholders and domain experts recombine in new ways. This process results in a conceptual model which captures and synthesizes elements of the mental models of the involved parties. The process of model formalization – the translation of mental and conceptual models into computational models – inevitably also constitutes a process of variation. Insofar as formalization requires the translation of concepts from one language to another, its accuracy is limited by available vocabularies and grammars and by the skill of developers. The degree and nature of variation taking place in the course of model formalization may also be affected by the specific modeling technique and programming language being used. Different modeling techniques and programming languages force different logical structures.

The socio-technical context of a multi-model ecology defines the topology of the fitness landscape, and changes in this context – improvements in computer speed and memory, the exit of a key actor from a modeling team, etc. – drive changes in this landscape. As these changes occur, variations push models through the landscape, enhancing or weakening their fitness. These variations may themselves alter the fitness landscape. Like the sticky tongue of the frog altering the fitness of the fly, adaptive moves by one coevolutionary partner may change the fitness and the fitness landscapes of another (Kauffman and Johnsen, 1991).

*Selection* entails a process of gauging the relative fitness of models – evaluating their usefulness, quality and validity. This process may be facilitated by modeling standards. Examples include the ISO 14044 Standard, which defines requirements and guidelines for LCAs (ISO, 2006), and the CoMSES Modeling Standard, which defines requirements for agent-based models (OpenABM Consortium, 2012). Selection processes are also at the core of the academic peer review process, which (ideally) involves a critical audience evaluating the scientific rigor of publications, sometimes based on models. A less formal dimension of the selection process has to do with the usefulness of models to decision makers, who determine the degree to which a model and its results become embedded in the policy process. While the criteria against which "usefulness" is assessed may vary between contexts, McNie (2007) suggests that common selection criteria include salience, credibility and legitimacy. Scientific information must not only have a "substantive core", but must also be transmitted as part of an effective process and be sensitive to the policy context (McNie, 2007).

*Heredity* entails the process by which models are disseminated. Like most memes, mental models and conceptual models have a long history of dissemination by word-of-mouth and textual publications, including but not limited to disciplinary conferences/seminars and academic journals. Next to these forms of heredity are newer methods for disseminating formalized models. A number of Web-based model hosting platforms have emerged in recent years to facilitate the dissemination of computer models – heredity is purely *in silico*[2]. Some of these platforms, such as GitHub and OpenABM, are publicly accessible, facilitating wide dissemination of models. Interestingly, some platforms facilitate multiple steps in the evolutionary process. In addition to allowing for the accessing and copying of code (heredity), GitHub facilitates the variation process by allowing for the branching and merging of code. OpenABM not only hosts and shares models, but plays a role in selection by certifying models according to a set of community standards.

The process by which a multi-model ecology evolves determines the trajectory of its development and the manner in which existing knowledge (in the form of models) is preserved and utilized. The challenge and the gain lie in the *intractability* of evolutionary processes – we cannot control them, but we can benefit from the fortuitous turns they may take. As we will discuss in the coming sections, a key to enabling the sustained usefulness of models lies in effectively shaping processes of variation, selection and heredity, while also being open to the unexpected opportunities they may offer.

## 10.6 Analysis of a multi-model ecology – the Energy Modeling Laboratory

In this section, we introduce and analyze an existing multi-model ecology – the Energy Modeling Laboratory (EMLab) – of which this research is a part. This ecology has grown out of modeling efforts within an energy and industry research group at Delft University of Technology over the past decade. These efforts have sought explicitly to understand and shape the evolution of model systems and ontologies (Davis, 2012; Nikolic, 2009; van Dam, 2009). In this section, we: (1) identify the components of the ecology and the relationships between them, (2) examine the socio-technical context and its dynamics, and (3) identify the key evolutionary

[2] From this perspective, models may be better defined as *temes* – memes which reside in technical artifacts rather than in human minds (Blackmore, 2008)

mechanisms at work in the ecology. Based on this analysis, we identify drivers and barriers of model reuse and integration in EMLab.

## Components and relationships in the ecology

EMLab is "a suite of agent-based models dealing with policy questions on the long-term evolution of the electricity sector" (GitHub, 2014a). Figure 10.2 illustrates the main components of EMLab and the relationships between them. EMLab consists of three distinct models – EMLab-Generation, EMLab-Congestion and EMLab-NetworkEvolution. Each of these models has been developed with a different purpose in mind, and represents different dimensions of the long-term development and operation of Northwest Europe's electricity infrastructure. *EMLab-Generation* (EMLab-G) explores the long-term effects of interacting energy and climate policies by representing how power companies invest in generation capacity; *EMLab-Congestion* (EMLab-C) explores dynamics in an electricity market subject to congestion; and *EMLab-NetworkEvolution* (EMLab-NE) explores possible development trajectories of the Dutch electricity transmission network.

EMLab-G is the most complex of EMLab's models, consisting of a core module (the "engine") to which different sub-models can be connected and disconnected in different configurations to address different research questions. Modules include a *market algorithm* for representing electricity spot markets and $CO_2$ auctions, an *investment algorithm* for representing processes of investment in generation capacity, a *unit dispatch algorithm* for calculating the dispatch of power plants, and others (De Vries et al., 2013). Different versions of each of these modules exist, some representing previous versions of the same module and others representing distinctly different conceptualizations of the relevant process. Switching out of modules allows for the testing of different assumptions and addressing of different research questions.

EMLab-NE has been constructed using a different software platform, and is not directly compatible with the models of EMLab-G. However, a static one-way link between EMLab-G and EMLab-NE has been developed in the form of an R script which outputs a reformatted CSV file – allowing for the results of EMLab-G to serve as input to EMLab-NE. EMLab-NE is itself composed of multiple components, an agent-based submodel developed in Netlogo and a contingency analysis submodel developed in Matlab. The contingency analysis submodel in turn makes use of an externally developed model for performing power flow analyses. The dynamic (run-time) link between the agent-based submodel and the contingency analysis submodel is enabled by way of a custom-developed Netlogo extension.

The models of EMLab make use of a variety of datasets drawn from various sources. Many of these datasets are housed on a Web-based platform called Enipedia (Davis, 2012; Delft University of Technology, 2013), which uses semantic wiki technology to enable the collaborative cultivation of power industry data. This RDF-based platform allows for the extraction of targeted portions of its datasets using SPARQL queries, enabling the export of customized datasets for different purposes. Via this mechanism, Enipedia is statically linked with several of the aforementioned models.

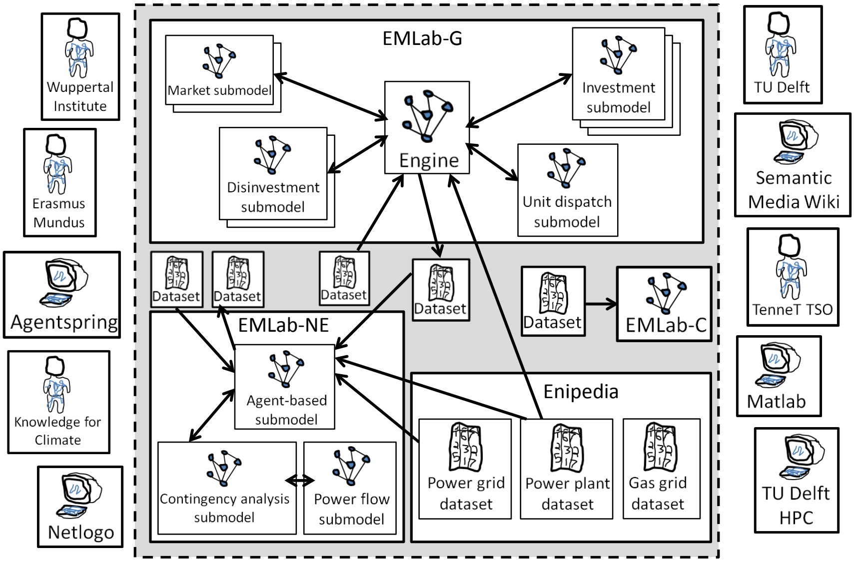


Figure 10.2: Visualization of the EMLab suite as a multi-model ecology embedded within a socio-technical context. Arrows between datasets and models denote the use of a dataset as input to a model, or the extraction of a dataset as model output. Bidirectional arrows between models denote runtime communication (exchange of data) between the models. For simplicity, conceptual models and information/knowledge have been excluded from the figure.

## The socio-technical context

The socio-technical context surrounding EMLab includes numerous individuals, several distinct institutions and a number of computational tools. A partial overview of this context and its relationships with the components of the ecology are illustrated in Figure 10.2. EMLab began in the context of a PhD project at Delft University of Technology, which explored pathways of a low-carbon transition in Northwest Europe (Chappin, 2011). This project itself grew out of a separate multi-model ecology – described in van Dam (2009) and Nikolic (2009) – which focused more broadly on socio-technical energy and industry systems. These three projects were supported by the Next Generation Infrastructures (NGI) (NGI, 2014) research program, and were linked to a research initiative at the TU Delft Faculty of Technology, Policy and Management (TPM) on modeling the operation and evolution of infrastructures. From a technical perspective, the development of EMLab (and its predecessor ecology) were enabled by a high-performance computing cluster, sponsored by the TPM Faculty.

The development of Enipedia proceeded parallel to but separately from this, starting in 2010. Also in 2010, a new agent-based modeling platform called *AgentSpring* was developed, supported by the Energy Delta Gas Research (EDGaR) Program (EDGaR, 2014). Combined with the initiation of several new projects (listed in Figure 10.2) and the conclusion of the initial NGI program, the development of AgentSpring marked a new phase in EMLab's development. The involvement in this phase of several new stakeholders with new research interests resulted in the creation of EMLab-NE and EMLab-C, and drove the branching of EMLab-G to address a further range of topics. The formation of a partnership between Delft University of Technology and the Wuppertal Institute in 2012 furthered the range of topics being addressed by EMLab.

## Evolution of the ecology

Several key evolutionary mechanisms are at work in the ecology. *Variation* has been driven amongst others by the needs of different stakeholders with specific research interests, and the availability of a varied funding diet. For instance, the involvement of stakeholders from the Dutch Transmission System Operator drove the development of new models (EMLab-C and EMLab-NE), which partially utilized the conceptual models of EMLab-G and the functionality of AgentSpring, funded from the EDGaR program. Variation has been facilitated by the housing of all project code on a common revision control system and later on GitHub, both of which allowed for the branching, parallel development and merging of different components.

*Selection* has been driven largely by processes in the socio-technical context. Insofar as AgentSpring comprised a new software environment with different software structures, its development rendered the formalized elements of EMLab-G's predecessor model largely obsolete. However, due to the continued involvement of a key individual in the initiative, the conceptual model could be re-implemented (in modified form) in the new environment. Selection has also been driven by the involvement of industry stakeholders in model development processes. Periodic meetings with experts at the Dutch Transmission System Operator at each stage in the development of EMLab-NE, for instance, drove the addition and removal of model variables and relationships in line with the mental models of these experts.

*Heredity* has been enabled by a range of mechanisms, including meetings/symposia, journal publications, a book (Nikolic et al., 2013a) and code- and data-sharing platforms. When the AgentSpring platform was first developed, a series of weekly meetings between project members facilitated the formation of a shared conceptual model which was subsequently implemented in the components of the EMLab-G model. These meetings were followed up by a series of informal weekly gatherings involving EMLab developers and power system researchers, which have further facilitated dissemination. A 2012 symposium with project participants from Delft University of Technology and the Wuppertal Institute involved a sharing of conceptual and mental models and paved the way for the sharing of formalized models. Next to these social mechanisms, the use of Enipedia, GitHub, a common wiki (wiki.tudelft.nl) and the aforementioned revision control system have facilitated the continual sharing of formalized models.

The evolution of EMLab is visible in the development of its software code. Figure 10.3 shows the development of EMLab-G between March and June 2014, as reflected in the model's GitHub repository (GitHub, 2014a). Each horizontal line in this diagram represents a particular development branch of EMLab-G. Arrows departing from a line indicate variations on the code in that branch. Arrows joining a line indicate the merging of two branches. The end of a line indicates a halt in the development of that particular branch. In combination, these patterns reflect ongoing processes of variation, selection and heredity.

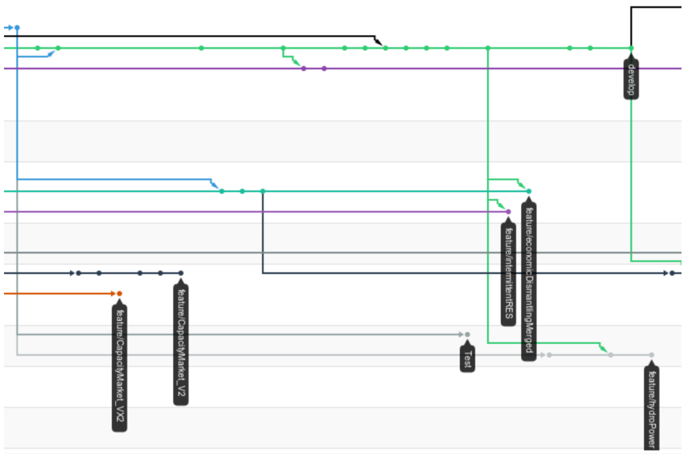


Figure 10.3: Illustration of the development of EMLab-G between March and June 2014, as reflected in the model's GitHub repository (GitHub, 2014b). Horizontal lines represent the different development branches of EMLab-G. Black labels indicate the names of these development branches.

## Drivers and barriers of model reuse and integration in EMLab

Several features of EMLab and its socio-technical context have been central to enabling model integration and reuse. Foremost amongst these is the relatively small size of the EMLab development group (ca. 15 individuals) and the relatively frequent social interactions amongst project members. While the use of Web-based platforms (e.g. GitHub, SVN) and open standards were important enablers of the sharing of formalized models, processes of variation and heredity would most likely not have occurred to the same degree without these direct social interactions. Moreover, the largely academic context in which the development of EMLab has taken place, and the culture of the involved institutions – which support frequent information exchange and the use of collaborative tools – have fostered an atmosphere in which the sharing models (both conceptual and computational) is encouraged and rewarded. This has further facilitated processes of variation and heredity.

Where the frequency of social interaction and a culture of sharing have contributed to the evolution of EMLab's models, the configuration of the Enipedia platform has played an important role in the evolution of datasets. Because this platform is structured as a publicly-accessible wiki, it enables users from around the globe to extract datasets, and add and edit data entries. While Enipedia's developers initially anticipated large community contributions to the platform, this did not pan out. Many users, both internal and external, viewed and benefited from the data, but few took the initiative to modify it directly. Variation occurred, but expressed itself in unexpected forms. One external user, for instance, is using the data as the basis for constructing a physical sculpture.

Diversity in the socio-technical context has enhanced the resilience of the EMLab ecology. During the first phase of its development, EMLab was fragile – its survival depended on a single individual and on funding from a single research program. With the initiation of the second phase of EMLab's development, a range of other individuals became involved, and with them a host of other research programs. This added diversity in the social dimension has contributed to the resilience of the ecology – the departure of any single individual will not threaten its existence. The same is true of the system's technical composition. The diversity of computational tools used in the ecology means that unexpected technological changes (e.g. the discontinuation of support for a single tool) will not significantly disrupt the ecology.

Still, the technical configuration of the ecology remains vulnerable in some ways. The use of a common modeling platform (AgentSpring) within EMLab-G has facilitated technical interoperability amongst the components of this model. However, as illustrated by the centrality of the AgentSpring "engine" in EMLab-G (Figure 10.2), this configuration is somewhat fragile. Just as the introduction of AgentSpring altered the fitness landscape and made previous models obsolete, the introduction of another new platform or a different core module could eradicate the usefulness of EMLab-G's submodels. A more resilient configuration might be one less dependent on a stable core, with a diversity of decentralized modules – potentially developed in different platforms – that could function independently, but also link together in different ways.

## 10.7 Cultivating multi-model ecologies – guidelines

In this section, we highlight a set of guidelines for the cultivation of multi-model ecologies in the infrastructures domain.

1. **Use open standards and open software** The use of *open standards* implies the use of digital standards that are not proprietary and that can be implemented by anyone – CSV, XML, HTML, KML, RDF, etc. Open standards are advantageous because they prevent dependence on any single organization or software ecosystem, creating flexibility in the technical composition of a multi-model ecology (Davis et al., 2010). *Open source software* (OSS) is "software that can be freely used, changed, and shared (in modified or unmodified form) by anyone" (OSI, 2014). Examples include OpenLCA, Vensim, Netlogo, GNU Octave, R and QGIS. OSS facilitates *variation* – it can be modified to communicate with other software programs, extended by others and tailored to serve particular purposes. This allows your models to go places you never expected.

2. **Document, and use documentation standards** Without documentation, models remain incomprehensible to outsiders and severely limited in their usefulness. The use of *documentation standards* ensures not only that models are documented, but that they are documented in a comprehensive and understandable manner. Different industry organizations and modeling schools offer different standards –the ODD Protocol (Grimm et al., 2010) (agent-based models), the ECOBAS MIF standard (Crout et al., 2008) (environmental models) and the EIA model documentation standard (EIA, 2014) (energy models),

3. **Build simple components** The "nearly decomposable" nature of complex systems can be leveraged by configuring complex system representations as sets of simple, interacting modules. This allows the mechanisms of evolution to act

on a model's components without disrupting the integrity of the ecosystem as a whole.

4. **Leverage the Web, but recognize its limitations** The Web offers an abundance of opportunities – model repositories, semantic wikis, collaboration management services, etc. – for facilitating the dissemination, review and modification of models and data. But posting models and data on the Web is often not sufficient. The usefulness and comprehensibility of model code is often inseparable from the *tacit knowledge* of its developers. Our experiences with EMLab have demonstrated the importance of informal and repeated social interaction as a means of sharing this tacit knowledge and as a complement to Web-based tools.

5. **Prioritize flexibility over completeness** Rather than devoting our limited energy as modelers to the realization of ostensibly complete and polished models, we should strive to develop models that are *sufficient* in light of their purpose, but that can more easily serve as stepping stones for future work. Moreover, we must recognize that we cannot hope to foresee (and should not seek to control) how the products of our efforts might be used by others. Evolution is intractable, and we should be open to the surprises it has in store for us.

6. **Borrow proudly** Evolution is partially driven by heredity, and a multi-model ecology will stagnate if its components do not build on the components of others. As such, model developers should continually seek to maintain an awareness of the models relevant to them, and should consider how these might be productively used in their own work.

7. **Acknowledge your role** A potential benefit of multi-model ecologies is their ability to simultaneously represent multiple perspectives on a problem. Only by clearly delineating the relationship of our own perspective(s) to those of others – in presentations, in articles, and in model documentation – can this benefit be realized. Some software licenses, such as the CC BY-SA license (Creative Commons, 2014) explicitly require this.

## Challenges in implementation

The guidelines above offer a concrete set of actions that can be taken by infrastructure modelers to support the sustained usefulness of models. However, these actions are not always easy to carry out. As modelers ourselves, we find it difficult to always adhere to them. There are several reasons for this. First, several of these guidelines require extra effort on the part of modelers – using open source software may require familiarizing oneself with new programs that require overcoming a steep learning curve, and documenting models according to established standards can be a pain. A second reason is "not invented here" syndrome – a culturally-ingrained tendency for individuals and institutions to eschew externally developed products (Kathoefer and Leker, 2012; Wastyn and Hussinger, 2011). Third is the challenge of "overwhelming complexity" (Voinov and Shugart, 2013). Simple models are hard enough to develop, debug, analyze and maintain. Integrating models only compounds these difficulties.

The first and second challenges can be addressed by actions on the part of the research community. If extra effort is required, it should be rewarded and/or required, e.g. in the form of certifications, intellectual property rights or publication requirements. Moreover, the community should seek to foster a culture that values the application of external models and data – "proudly found elsewhere" rather than "not invented here". The development of modeling communities can promote the sorts of interactions that foster a culture of sharing. Based on this, we offer the following guidelines for the infrastructures community:

1. **Enforce sharing** Journals and public agencies increasingly encourage or require the publication of relevant models or data alongside publications (Bloom, 2014; European Commission, 2013; JASSS, 2014; SPARC, 2014; The Royal Society, 2012). These are steps in the right direction, and can also bring researchers enhanced recognition for their modeling work. However, the publishing of model code and data need not be linked with traditional scientific media nor a conventional scientific peer review process. The publishing of models and data in their own right can and should be incentivized by academic institutions and funding agencies, for instance via the issuing of Digital Object Identifiers (DOIs) for scientific datasets and software code[3].

2. **Foster modeling communities** Sustained model usefulness requires communities. *Fostering modeling communities* entails creating opportunities for multi-disciplinary interactions and supporting the development of multi-disciplinary communities around model ecologies. This includes recognizing the value of long-term funding of software architects and engineers within the research environment (Voinov et al., 2010). It also involves establishing a technical infrastructure – in the form of wikis, model repositories, etc. – which can facilitate ongoing collaboration amongst participants in a modeling community.

As noted above, part of the success of EMLab may be attributed to the relatively small size of the development group. Scaling up efforts such as this can be a significant challenge, as it may hinder actors' ability to maintain an overview of developments within the ecology. However, it should be kept in mind that the scaling process need not be linear – existing multi-model ecologies may "spin off" new ecologies, which may maintain loose links with the original ecology, but tighter links within themselves. This pattern of scaling can enable actors to benefit from developments within the larger ecology without being overwhelmed by them. Modeling communities in particular can play a role in fostering the development and maintenance of weak links within the larger multi-model ecology.

The challenge of overwhelming complexity is perhaps more difficult, and we lack a definitive solution. However, we suggest that the evolutionary process can play a key role here. Grimm's notion of the *Medawar zone* (Grimm et al., 2005) is as applicable to multi-model ecologies as it is to single models – we must always seek to strike a balance between simplicity and complexity. However, simplicity and

[3] Recently, GitHub has enabled the creation of DOIs for GitHub repository archives (Smith, 2014).

complexity are in the eye of the beholder. By nature, the evolutionary process disseminates certain features – in this case models – and eliminates others. Through processes of continued dissemination, we naturally evolve a "common repository" of model knowledge – a shared familiarity with certain models and their underlying conceptualizations. Our shared mental models *co-evolve* with our shared computational models. As a result, that which originally seemed incomprehensibly complex becomes common knowledge. This shifts the boundaries of the Medawar zone, enabling further integration of models and helping us to address ever more "wicked" problems.

Even in the absence of coordinated actions on the part of the community, individual researchers can take several concrete first steps towards enhancing model integration and reuse. These include: (1) investigating possible open source alternatives to proprietary software programs that you are using, (2) documenting your models thoroughly (think about the information others may need in order to utilize and build on them), (3) uploading your models and documentation to online code sharing repositories such as GitHub, and (4) sketching the multi-model ecology within which your modeling activities take place (e.g. as in Figure 10.2), ideally as a collaborative exercise.

## 10.8 Synthesis

The increasing sophistication and complexity of models in the infrastructures domain is a symptom of a growing need on the part of infrastructures researchers to deal with problems spanning multiple disciplines and timescales, and featuring multiple valid perspectives. This reality is highlighted by emerging modeling work, amongst others, in the areas of infrastructure interdependencies and multi-infrastructure systems. Next to this, the emergence of new data sources (Twitter, GPS, embedded sensors, etc.) is opening up opportunities for exploring infrastructures in new ways. In order to progress in areas such as multi-infrastructure systems analysis and capitalize on new data sources, we need better ways to conceptualize systems of interacting and evolving models/datasets.

Building on research in the areas of integrated modeling and multisimulation, we have introduced in this chapter the concept of *multi-model ecologies* – defined as interacting groups of models and datasets co-evolving with one another in a dynamic socio-technical context. Compared with existing approaches to model integration and reuse, the multi-model ecology perspective stresses the *evolutionary* nature of models and their *embeddedness* within a changing environment.

To a limited degree, the modeling work described in the previous chapters of this thesis reflects a multi-model ecology perspective. These models have been designed with complementary scopes, so as to provide different perspectives with respect to the main research question. And they have been designed with integration in mind – the model described in chapter 8 has been designed to link with the model in chapter 6, and a number of the developed models have been designed to make use of the externally developed Matpower model. In chapter 5, we have described a piece of software (the MatpowerConnect extension), which has been specifically developed to enable runtime integration of Netlogo and Matpower. Next to this, we have sought to fully document the developed models, to use (as much as possible) open source software packages and to make these models freely accessible on the Web.

However, the modeling work described in this thesis has largely been carried out by a single individual over a period of several years. Model integration and reuse become significantly more challenging with the involvement of multiple individuals and over long timespans. Given the growing importance of multi-person and even multi-institution modeling endeavors in the infrastructures domain, this is far from a trivial issue. With this in mind, we have introduced and analyzed in this chapter an existing multi-model ecology – the Energy Modeling Laboratory – which has involved numerous researchers from multiple institutions, and has built on work spanning nearly a decade. Based on an analysis of this ecology, we have identified important drivers and barriers of model reuse and integration, and have elaborated a set of guidelines for infrastructure modelers and the infrastructures community at large.

In seeking to foster climate resilient infrastructures, these issues are central. The process of identifying and selecting effective adaptation measures necessitates drawing from models and data in areas from meteorology and hydrology to power systems and transportation engineering. It also necessitates considering multiple timescales (from seconds to decades), multiple spatial scales (from neighborhood to continental) and multiple valid perspectives (e.g. the trajectory of climate change, the definition of resilience). The models and analyses described in this thesis demonstrate one set of ways for dealing with these challenges. Application of a multi-model ecologies perspective can support our ability to deal with these challenges more broadly.

# Chapter 11

# Conclusions

## 11.1 Summary

In the four years since this research began, several events around the world have forcefully demonstrated the potential consequences of extreme weather for electricity infrastructures. These have included, amongst others, the largest Atlantic hurricane in history, which cut power to 8.5 million customers, and the largest power blackouts in history, which were partially incited by drought and cut power to 650 million people. Events like these cannot (necessarily) be attributed to climate change. However, insofar as climate change is anticipated to result in an increase in the frequency and/or severity of various forms of extreme weather, these events highlight the reality that our electricity infrastructures undoubtedly remain vulnerable.

This is not a trivial issue. In many places around the world, including the Netherlands, consumers have become so accustomed to a continual supply of electricity that it is difficult to comprehend the potentially far-reaching consequences of a large-scale interruption, especially one lasting days, weeks or even months[1]. This, of course, is in many ways a supremely desirable situation, and is a testament to the institutions and actors guiding the development and operation of our electricity infrastructures. On the other hand, it means that we are, in some ways, ill-prepared for large-scale disruptions, should they occur.

In light of this reality, *resilience* is increasingly seen as an essential characteristic of future infrastructure systems. The notion of resilience implicitly accepts the possibility of unforeseen disruptions and failures and focuses on the capacity of systems to handle them – to survive unexpected perturbation, recover from adversity and gracefully degrade – as well as an ability to adapt and learn over time.

As we have argued in the preceding chapters, the challenge of enhancing infrastructure resilience is compounded by the fact that electricity infrastructures are *complex* and *interconnected*. Under the right conditions, minor disturbances in one corner of the system can cascade into system-wide failures spanning regions, countries and even continents. Moreover, the interdependencies between electricity

[1] The public's fascination with this eventuality has given rise to a new fictional sub-genre, including the recent books *Blackout* by Marc Elsberg and *Gridlock* by Byron Dorgan, which describe the occurrence and aftermath of massive power blackouts.

infrastructures and other infrastructures – e.g. gas, road, rail, ICT – mean that disturbances may be incited from within and/or cross over to other infrastructures, creating first-, second-, third- and higher-order effects.

Via this research, we have sought to illuminate possibilities for fostering climate resilient electricity infrastructures, taking into account their technical interconnectedness and social/institutional fragmentation. Our research has been driven by the following question: *How can we foster a climate resilient electricity infrastructure in the Netherlands?*

To address this question, we began in chapter 2 by framing electricity infrastructures as complex socio-technical systems, and exploring the consequences of this framing in terms of how resilience is defined and understood. With this framing and this understanding of resilience as a basis, we continued in chapter 3 by defining a suitable approach for addressing the research question, including the research framework, scope and methodology, and a set of suitable techniques and tools. In chapter 4, we sought to more precisely explicate the relationships between climate change and electricity infrastructures. After inventorizing the possible extreme weather/-climate effects on electricity generation, demand and transmission/distribution, we delineated a typology of possible adaptation measures.

Building on these foundations, we carried out a set of three case studies. The first of these case studies dealt with assessing the extreme weather resilience of electricity infrastructures. In the first part of this case study (chapter 5), we developed a method for assessing the resilience of electricity infrastructures to extreme weather events, and explored different options for formalizing and quantifying the notion of infrastructure resilience. In the second part of this case study (chapter 6), we used the developed method to assess the resilience of the Dutch electricity infrastructure to floods and heat waves, and explored the effectiveness of a set of selected adaptation measures.

The second case study expanded on the first by accounting for the reality that electricity infrastructures are constantly developing, and that these developments may have important consequences for infrastructure resilience. In the first part of this case study (chapter 7), we sought to represent the mechanisms by which electricity transmission networks evolve, and used the developed model to explore how different societal developments might cause such a network to evolve in a different direction. The second part of the case study (chapter 8) built on this work, but adapted it to the specifics of the Dutch situation. Here, we explored how different long-term developments in electricity generation and consumption might lead to different future configurations of the Dutch transmission infrastructure, and evaluated how these different configurations might perform under different extreme weather scenarios.

The third case study (chapter 9) sought to account for the (increasingly unavoidable) reality that electricity infrastructures are interconnected with other types of infrastructures, and that this interconnectedness breeds interdependency – a potentially important determinant of infrastructure resilience. The first part of this case study entailed an investigation of secondary infrastructure vulnerabilities – vulnerabilities of infrastructure components due to their dependence on the electricity infrastructure – in the North Rotterdam area of the Netherlands. The second part of the case study considered the challenge of incomplete knowledge of interdependencies in a multi-infrastructure system, and tested a method for identifying robust strategies for enhancing infrastructure resilience, in light of this key uncertainty.

Drawing from the modeling work carried out in the course of this research, chapter 10 reflected on the role and the use of modeling in the study of infrastructures. Specifically, we dealt here with the issue of model integration and reuse in the study of infrastructures, and introduced the notion of *multi-model ecologies* as a way to address societal challenges spanning multiple scales and featuring multiple valid perspectives. In the second part of this chapter, we re-conceptualized an ongoing modeling effort, the *Energy Modeling Laboratory* (of which this research is a part), as an evolving multi-model ecology, and concluded with a set of guidelines for fostering model integration and reuse.

## 11.2 Insights

The main research question of this investigation has been divided into a set of nine sub-questions, restated below. In the paragraphs that follow, we summarize our chief insights with respect to these sub-questions.

**How can infrastructure resilience be defined from a perspective of infrastructures as complex socio-technical systems?** Viewed through the lens of complexity, the state space of an electricity infrastructure can be conceptualized as a stability landscape composed of multiple *basins of attraction* – each characterized by a set of values for key infrastructure variables (e.g. total generator output, network frequency, fraction of load served). From this perspective, infrastructure resilience may be defined as follows:

*Infrastructure resilience:* The ability of an infrastructure to remain within a given basin of attraction upon exposure to a disturbance.

However, given the reality that it may not always be desirable or feasible to preserve the state of an infrastructure within a given operational regime, we also introduce the notions of *infrastructure adaptability* and *infrastructure transformability*, both of which emphasize the nature of infrastructures as socio-technical systems. Infrastructure adaptability reflects the fact that infrastructures may be actively steered by their operators, who may learn and adapt over time. Infrastructure transformability highlights the (co-)evolutionary processes underlying an infrastructure's long-term development that (may) allow it to respond to changes in its environment. These terms may be defined as follows:

*Infrastructure adaptability:* The ability of an infrastructure to manage shifts between basins of attraction to sustain operation upon exposure to a disturbance

*Infrastructure transformability:* The ability of an infrastructure evolve fundamentally new basins of attraction to maintain or enhance performance in a changing environment.

**How are the components of electricity infrastructures vulnerable to weather events, and what are the possible adaptation measures?** Climate projections suggest that the Netherlands will be exposed over the coming decades to more frequent and/or intense extreme precipitation, extreme hot temperatures and extreme windspeeds. The primary effects of such events on electricity infrastructures may be summarized as follows:

- Extreme precipitation and extreme windspeeds may incite floods that cause damage to and/or induce the shutdown of thermal generation facilities and electrical substations located in flood prone areas.

- Heat waves may be particularly pernicious, given their ability to simultaneously affect electricity generation, demand and transport. Heat waves may induce: (1) decreases in thermal generation capacity resulting from cooling water restrictions and/or thermodynamically-induced efficiency loss, (2) increases in demand due to greater use and reduced efficiency of cooling/refrigeration devices, and (3) decreases in transmission/distribution capacity due to higher thermal losses and the potential failure of lines due to sag-induced flashover.

- Aside from their ability to induce flooding, extreme windspeeds are problematic primarily because of their effects on overhead transmission/distribution lines. Generation may also be affected due to the forced shutdown of wind turbines.

The indirect effects of extreme weather events are more difficult to identify, and may include, for instance, regulatory action, changes in perceived risk perception and supply chain effects. A full listing of vulnerabilities may be found in Tables 4.2, 4.3, 4.4 and 4.5.

Possible adaptation measures may be divided into three broad categories, including targeted infrastructure investments, infrastructure management strategies and infrastructure planning strategies. *Targeted infrastructure investments* include investments in technical infrastructure components such as cooling systems for thermal power plants or backup generators. *Infrastructure management strategies* entail strategies for managing infrastructure operation, and include e.g. overhead line monitoring and demand-side management. *Infrastructure planning strategies* deal with the procedures and incentive mechanisms driving the development of the infrastructure, and include e.g. generation capacity mechanisms, feed-in tariffs and building codes. A full typology of possible adaptation measures can be found in Table 4.6

**How can the extreme weather resilience of an electricity infrastructure be studied and quantified in a manner which captures the pertinent aspects of its functionality and accounts for the infrastructure's socio-technical complexity?** The extreme weather resilience of an electricity infrastructure may be assessed using models that capture the properties, interconnectedness and behavior of key technical components, as well as the relevant behavior and interactions of actors. A listing of the specific elements of such a model can be found in Table 5.1.

A suitable method for quantifying infrastructure resilience should be capable of capturing disturbance-induced changes in system behavior, as well as the degree to which these changes may affect service provision. Multiple methods fitting these criteria may be identified, and are summarized in Table 5.2. Another important criterion has to do with the feasibility of a quantification method for application in a model of the form described above. A suitable resilience metric in light of this additional criterion is 'the mean fraction of demand served across the range of possible extreme event magnitudes', which may be expressed mathematically as follows:

$$R_I = \frac{\sum_{m=0}^{M} \Theta_m}{M}$$

where: $R_I$ is the resilience of the infrastructure and $\theta_m$ is the mean fraction demand served under conditions of an extreme event of size $m$.

**How may long-term changes in weather extremes affect the vulnerability of the Dutch electricity infrastructure, and what measures can effectively support infrastructure resilience?** In this study, we have focused on two types of extreme weather events – floods and heat waves – and have assessed the range of possible consequences that such events could induce in the Dutch electricity transmission infrastructure. Our assessment suggests that this infrastructure displays some vulnerability to both floods and heat waves, though somewhat less vulnerability to heat waves. In the case of floods, the maximum drop in system performance exceeds 20%. In the case of heat waves, the maximum drop is almost imperceptible.

In terms of possible resilience enhancing measures, both substation flood protections and demand-side management demonstrate a clear ability to reduce, and in some cases even eliminate, the infrastructure's vulnerability to floods or heat waves. In the case of demand-side management, a 20% reduction in demand completely eliminates the risk of lost load under heat wave conditions. In the case of substation flood protections, the prioritization of critical substations is shown to significantly enhance the efficiency of vulnerability reduction.

**How can we represent and explore the long-term development of electricity transmission networks in a manner which reflects the role of key societal drivers?** From a perspective of infrastructures as complex adaptive systems, electricity networks do not just develop, they *evolve*. Capturing the long-term development of electricity transmission networks thus necessitates representing the evolutionary mechanisms underlying network development and the manner in which these mechanisms may be influenced by societal factors. Furthermore, given the nature of electricity transmission networks as planned infrastructures in a multi-actor environment, representing their long-term development necessitates bridging traditional top-down and bottom-up approaches to representing network growth.

A possible method for doing this – and the method we have tested – involves representing the development of an electricity transmission network as a consequences of the actions and indirect interactions of a set of agents, including a boundedly rational network operator and a set of power producers. We have demonstrated the ability of this method to simulate networks which respond in different (and explainable) ways to selected societal developments, and to generate networks which exhibit properties similar to those of real-world transmission networks.

**How might a low-carbon transition affect the vulnerability of the Dutch electricity infrastructure to climate change, and how can we harness this transition to support climate resilience?** A low-carbon transition may engender various developments in electricity generation and demand over the coming decades. Each of these developments may have different consequences for the Dutch electricity transmission network, and, as a consequence, also in terms of the infrastructure's resilience. Our results suggest that a future based around diminished domestic generation complemented by large increases in imports from neighboring countries will likely entail massive increases in transmission capacity, and will likely perform relatively poorly in the face of extreme weather events. We find, on the other hand, that a future characterized by rapid growth in distributed generation necessitates only moderate increases in transmission capacity, and demonstrates a high degree of resilience to both flood and heat wave events, as more electricity is generated closer to its point of use.

Additionally, we find that, regardless of developments in electricity generation, low levels of demand growth tend to enhance the system's resilience to extreme weather events – due amongst others to greater levels of buffer capacity in transmission and generation. Taken together, these findings suggest a path towards an electricity infrastructure that is both climate resilient and sustainable. Such a path is characterized by low levels of growth in demand and high levels of growth in the implementation and utilization of small-scale renewables-based technologies (e.g. solar photovoltaics, small-scale wind).

**Which infrastructure assets in North Rotterdam may be vulnerable in the case of a local dike breach, due to their dependence on the electricity infrastructure? Which measures can help to alleviate these vulnerabilities?** A number of electrical substations would be vulnerable in the case of a dike breach at the locations of Schie-Noord, Schie-Zuid or Rotte. Amongst these three dike breach scenarios, a Schie-Noord dike breach poses the greatest risk, potentially resulting in loss of power to more than 30,000 customers, including the Rotterdam-Hague Airport. An extended Schie-Noord dike breach has the potential to result in the failure of multiple sewage and road infrastructure components, due to their dependencies on the electricity infrastructure. These components are illustrated in Figure 9.4. A Schie-Noord dike breach may also pose an issue in terms of possibilities for the manual shutdown of certain 25/10 kV and 10/0.4 kV substations in North Rotterdam, illustrated in Figure 9.5.

Various measures may help to address the vulnerabilities of electrical substations in North Rotterdam, including the elevation of electrical substations, the application of portable generators and the implementation of remote substation shutdown capabilities. Other suitable measures could help to address the secondary vulnerabilities of sewage and road infrastructure assets, including the provision of backup power to traffic signals and the use of portable sewage pumps.

**How can we identify strategies for enhancing infrastructure resilience under conditions of incomplete knowledge of possible interdependencies?** Infrastructure interdependencies are difficult to precisely and comprehensively identify, potentially complicating efforts to assess resilience in the context of multi-infrastructure systems. Suitable models can play a key role in addressing this challenge by facilitating the identification of strategies that are sufficient in light of existing uncertainties. In developing such models, we can start by representing the known elements of a multi-infrastructure network, and then iteratively augmenting this network with various hypothetical interdependencies and assessing its resilience. We have demonstrated the ability of this method to identify robust investment strategies for supporting resilience. More broadly, this method can help infrastructure operators to deal rationally with the different sources of uncertainty in multi-infrastructure systems.

**How can modeling and simulation be more effectively used to address multi-scale, multi-perspective societal challenges such as infrastructure adaptation to climate change?** Our ability to effectively address multi-scale, multi-perspective societal challenges may be enhanced through greater integration and reuse of models. Enabling greater model integration and reuse necessitates leveraging the evolutionary nature of model systems. While traditional means of knowledge dissemination can facilitate this, appropriate use of emerging methods and tools from information science and technology are essential. By conceptualizing modeling efforts as *multi-model ecologies* and following certain guidelines in model development and use, infrastructures researchers can open up opportunities for model integration and reuse, and as a consequence enhance the collective ability of the infrastructures community to address multi-scale, multi-perspective societal challenges. These guidelines include: *use open standards and software*, *document and use documentation standards*, *build simple components*, *leverage the Web but recognize its limitations*, *prioritize flexibility over completeness*, *borrow proudly* and *acknowledge your role*.

## 11.3 Reflection

Before seeking to translate these insights into policy and research recommendations, it is useful to step outside our system boundaries and reflect more broadly on the consequences and limitations of these insights and the work that has been done in the context of this research.

**Resilience:** In framing infrastructures as complex socio-technical systems, we arrived in this research at a conceptualization of resilience inspired by work in the area of social-ecological systems and centered around the notion of attractors. This conceptualization differs from the traditional perspective, which tends to define resilience in terms of the ability of a system to 'bounce back' following a disturbance. From a viewpoint of infrastructures as complex socio-technical systems, however, an infrastructure does not simply return to its original state after a disturbance – the infrastructure's socio-technical composition is constantly evolving. While power was gradually restored to the Northeast US after Hurricane Sandy, the event also incited a number of changes in the infrastructure's technical, social and institutional dimensions. The infrastructure may have bounced, but it did not bounce *back*.

This perspective on resilience, and our attractor-based definitions of resilience, adaptability and transformability, comprise a novel contribution of this research. Though we have not fully fleshed out the implications of this perspective here – and our formalization of resilience does not fully capture it – we expect that this perspective may yield new insights into possibilities for fostering climate resilient infrastructures. In particular, the attractor-based perspective internalizes the notion of infrastructures as complex adaptive systems, and as such may facilitate greater understanding of the relationships between micro-level (social, technical and environmental) processes and system-level resilience. Moreover, this perspective can aid in the identification of strategies that leverage the nonlinear and chaotic dynamics of these systems in support of resilience. Progress in this direction would require more detailed investigation and representation of actor behavior – in particular the behavior of consumers – an area with which we have not significantly dealt in this research.

**Climate change:** In and of itself, climate change does not affect electricity infrastructures – the effects of climate change on electricity infrastructures are mediated by way of *climate and weather events* (see Figure 11.1, originally introduced in chapter 3). In this research, we have focused specifically on the relationships between extreme weather events and infrastructure component behavior, and on the relationships between infrastructure *component* behavior and infrastructure *network* behavior. We have deliberately set aside the quantitative implications of climate change on climate/weather events. Thus, a key limitation of this research is that we cannot draw a direct relationship between possible climate change scenarios and the severity or frequency of infrastructure disturbances.

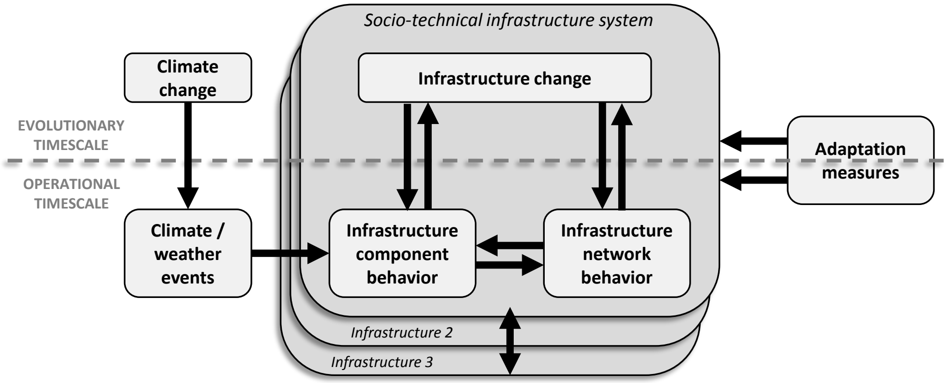


Figure 11.1: Illustration of the research framework (from chapter 3).

Despite this limitation, the manner in which we have studied the links between climate/weather events and infrastructure network behavior, and the resulting conclusions we have drawn with respect to the extreme weather resilience Dutch electricity infrastructure, comprise a novel contribution of this work. The methods we have developed for studying and quantifying extreme weather resilience, and for evaluating the benefits of possible adaptation measures, open up opportunities for assessing infrastructure resilience in other geographical contexts and to other types of events. Additionally, the developed models offer a solid starting point for more comprehensive investigations of the Dutch electricity infrastructure, and an initial idea as to the potential benefits of certain adaptation measures.

**Infrastructure change:** In capturing processes of infrastructure change, we have focused in this research primarily on the role and decision processes of the transmission system operator (TSO). Based on this, we have extracted insights concerning anticipated developments in electricity transmission capacity under different scenarios, and drawn conclusions concerning the implications of these developments in terms of the infrastructure's resilience to extreme weather events. The latter of these represents a particularly novel contribution of this research.

In focusing on the role of the TSO in the context of infrastructure change, we have filled an important gap in existing research. Namely, we have enabled representation of the manner in which electricity transmission networks evolve alongside generation and demand. However, in focusing on the role of the TSO, we have neglected to fully explore the drivers of developments in electricity generation and consumption. These developments – e.g. the diffusion of small-scale renewable generation technologies, the shifting of population and industry centers – may significantly influence the development of the infrastructure as a whole, and, as a consequence, the infrastructure's climate resilience.

Much effort within the research community is currently being dedicated to the assessment of possible transition pathways towards low-carbon electricity infrastructures, both in terms of electricity generation and demand. However, this body of research generally pays relatively little attention to the potential consequences of these pathways in terms of resilience, both to climate change and other sources of disturbance – an area we have sought to illuminate via this research. Further progress in this area may benefit from the assessment of electricity infrastructures as *artificial societies* – agent-based models of social processes in which "fundamental social structures and group behaviors emerge from the interaction of individuals operating in artificial environments" (Epstein and Axtell, 1996). Such an approach would entail the study of technical infrastructure developments in relation to social structures and group behaviors, themselves the emergent consequence of the actions and interactions of numerous boundedly rational agents.

**Infrastructure interdependencies:** The final case study of this research highlighted the nature of electricity infrastructures as interconnected and interdependent nodes in a multi-infrastructure system. While we focused here on the potential for interdependencies to magnify the consequences of disturbances, it is clear that interdependencies may also play a role in mitigating disturbances. Links between transport networks of different types, which allow passengers to shift modes in case of a disturbance, exemplify this sort of mitigating effect. But it remains an open question precisely which types of interdependencies support resilience under which conditions, and which types and conditions tend to detract from it – "whether this complexity augments resilience or not is a subtle question" (Allenby, 2008). Especially given the growing embeddedness of ICT infrastructures within the electricity infrastructure (and pretty much all other infrastructures), this is a question of increasing pertinence.

Moreover, it is important to keep in mind that interdependencies have to do not only with the links between different types of infrastructures, but also the links between infrastructures in different geographical regions. To a degree, this research has accounted for the interconnections between the Dutch electricity infrastructure and the infrastructures of neighboring countries. However, as European electricity infrastructures become increasingly integrated, both technically and institutionally, the validity of studying the Dutch system as an isolated whole becomes increasingly questionable. In particular given the vastly different effects that climate change may have in different parts of Europe, it is important to consider the resilience of the European infrastructure as a whole – a task we have chosen not to undertake in this research.

**Uncertainty:** Uncertainty is an unavoidable reality in the study of future phenomena. In the domain of this research, the chaotic nature of meteorological systems and the myriad factors underlying infrastructure change make precise forecasting of infrastructure vulnerability/resilience to climate change essentially impossible. The challenge for infrastructure operators, however, is not to predict the future, but to prepare infrastructures for climate change in a manner which accounts for the important sources of uncertainty. In the case studies of this research, we have dealt with uncertainty in different ways: through the embedding of random variables in the developed models to capture extreme weather events of different magnitudes and geographical scopes, through the explicit definition of different scenarios for the long-term development of electricity generation and demand, and through the iterative testing of multiple feasible infrastructure configurations.

As we have demonstrated, these methods can aid the identification of adaptation measures and strategies that account for many *possible* futures, rather than a single *probable* future. In doing so, these methods can facilitate the identification of *robust* investment strategies – strategies that perform well across a range of possible futures – and can enable infrastructure operators to deal with existing uncertainties in a rational manner, and to hedge potential risks. We have only begun to explore these possibilities in the context of this research.

In the final case study of this research, we have performed an initial assessment of *adaptive* strategies – strategies that respond to conditions as they develop – versus static strategies, and shown (under certain assumptions) the relative advantages of an adaptive approach. In dealing with climate change and uncertain developments in demand and supply, adaptive measures and strategies seem to hold great potential (Lempert and Groves, 2010). However, given the relatively long lifespans of electricity infrastructure components and the long lead times of many infrastructure projects, an adaptive approach may require upfront investments to preserve future flexibility. This is the core of the *real options* approach, an approach with which we have not explicitly dealt in this research, but which may be key to enabling successful adaptation of infrastructures.

**Multi-model ecologies:** As we have argued extensively in this thesis, the interconnectedness of infrastructures is an essential determinant of their resilience. While this research has emphasized the technical interconnectedness of infrastructures (both within themselves and with other infrastructures), it is important also to keep in mind the the social and environmental dimensions of interconnectedness. Technical infrastructure elements are connected with elements of the social system and of their natural environment, which are, in turn, connected with other elements. Because these linkages are often not visible, they are sometimes easier to ignore. But they are critical nonetheless.

In modeling infrastructures (and other types of systems), we deliberately and necessarily define artificial system boundaries encompassing those elements and relationships that are of interest to us. However, as researchers we are human, and our rationality is hopelessly bounded. Those elements and relationships that are of interest to us are not necessarily the most critical to the problem(s) we are seeking to address. The only way to overcome this limitation is through research (and modeling work) that spans multiple disciplines, reflects multiple perspectives and captures multiple spatial and temporal scales.

The principles of complexity teach us that the best way to organize such research is from the bottom-up. Large-scale, centrally designed models are bound to be brittle. And large-scale, centrally organized research projects can facilitate collaboration only to a degree. The only way to enable the sort of massive-scale, long-term cross-fertilization of formalized knowledge that is necessary to address the wicked problems with which infrastructures researchers are confronted is by deliberately facilitating the fundamental processes of evolution – multiplication, selection and heredity. Conceptualizing modeling efforts as *multi-model ecologies* can enable this. But altering our research methods to facilitate the evolution of these ecologies requires extra effort on the part of researchers. All too often the research community does not sufficiently incentivize researchers to expend this effort.

**Models and policy:** In the domain of this research, models are useful insofar as they improve the ability of policy makers (both in government and industry) to understand the consequences of their decisions in terms of infrastructure resilience. However, it is important to emphasize that the relationship between model development and policy making should not be seen as a linear, one-way process. From a perspective of model systems as evolutionary entities, policy makers must play a key role in *selection* processes – evaluating the usefulness, quality and validity of models. This is essential to ensure that model systems evolve in line with knowledge needs, and in a direction that enhances their usefulness to the policy process.

However, it is important to point out that the priorities of the scientific community and the policy community may differ. Policy makers need information that is salient, credible and legitimate (McNie, 2007). The scientific community rewards theoretical/methodological novelty. These differing priorities may introduce competing sets of selection processes, which may periodically drive the evolution of model systems in directions somewhat misaligned with policy needs. In the course of this research, we have sought to balance the demands of the scientific community with the knowledge needs of involved stakeholders. Though such a balance is not always easy to achieve, it can be facilitated through the use of participatory approaches, in which policy makers are engaged throughout the model development process. Application of such approaches may also help to realize synergies between the competing demands of the scientific and policy communities, in which theoretical/methodological development lead to improved ability to address policy needs. Both modelers and policy makers need to play an active role in enabling this.

## 11.4 Recommendations for policy makers

Based on the outcomes of this research, we offer several recommendations for policy makers with respect to fostering climate resilient electricity infrastructures. As stated in chapter 5, the resilience assessment approach applied in this research is best suited to the evaluation and identification of promising measures or system developments for further study. It is not suited to generating definitive and comprehensive evaluations of specific investments. In light of this, our first set of recommendations for policy makers takes the form of recommended areas for future investigation, based on the results of this research.

**Assess substation flood protection levels:** In reducing the vulnerability of the electricity infrastructure to floods, substations should be the key elements of focus. This research has demonstrated the potential system-wide benefits of flood protection measures for transmission substations, as well as the efficiency benefits of prioritizing the protection of critical substations. It has also described and demonstrated a method for quantifying the resilience benefits of substation flood protection measures. However, data concerning the precise flood protection heights of transmission substations is currently lacking. This data is essential to identifying specific investment needs.

**Investigate possible resilience benefits of distributed generation:** The results of this research suggest possible benefits to the large-scale deployment of distributed generation in the Netherlands in terms of enhancing system resilience to flood and heat wave events. Distributed generation improves the geographical diversity of electricity production and reduces the average network distance between locations of generation and consumption, both of which may serve to enhance resilience. Additionally, distributed generation offers opportunities for leveraging the sustainability benefits of small-scale renewable technologies. However, important questions remain. Importantly, this research has focused on the transmission infrastructure, and has not investigated possible effects of high penetration of distributed generation in terms of resilience at the distribution level. Nor has it investigated how floods and heat waves may affect various distributed generation technologies. Research in these areas is an essential next step.

**Investigate the effects of renewables intermittency on resilience:** In order to realize the sustainability benefits of distributed generation, greater integration of small-scale renewables-based generation is essential. However, given the inherent dependency of these technologies on environmental conditions, it is unclear how or when they may contribute to or detract from infrastructure resilience, particularly in the case of extreme weather events. This is a key area for future research.

**Investigate possibilities for inciting reductions in demand (growth):** This research has shown that reduced rates of demand growth generally correspond to enhanced future resilience of the infrastructure to flood and heat wave events. Low rates of demand growth lead to greater levels of buffer capacity in transmission and generation, reducing the system-wide consequences of extreme weather-induced failures. Additionally, we have demonstrated the ability of demand-side management to reduce the transmission system's vulnerability to heat waves. We do not specify precisely how reductions in demand growth should be achieved, nor evaluate different possible mechanisms for demand-side management. These are essential next steps.

Additionally, this research has demonstrated the particular relevance of certain infrastructure characteristics as determinants of resilience. We suggest that future investigations account for these key characteristics. With this in mind, we offer the following specific recommendations to policy makers.

**Account for infrastructure interdependencies:** Extreme weather-induced disturbances to electricity infrastructures may originate from within or cross over to other infrastructures, such as road, rail, gas and ICT. Understanding these dynamics is essential to understanding the potential consequences of extreme weather events in the context of climate change. Due to the complexity of these dynamics and the large uncertainties involved, simulation is an essential tool for facilitating the identification of robust measures for fostering resilient multi-infrastructure systems. The models developed in this research (particularly those described in chapter 9) provide a starting point for such studies.

**Account for the infrastructure's socio-technical complexity:** The electricity infrastructure is not just a set of disparate components. The technical elements of the system are connected in ways which can magnify or mitigate the effects of disturbances. Moreover, the actors in the system may adapt to changes in unexpected ways, reflective of their own motivations and rationalities. This research has confirmed the relevance of these key characteristics of the electricity infrastructure, and in considering specific adaptation measures, it is essential to account for them.

## 11.5 Recommendations for the research community

Based on the outcomes of this research, we offer several recommendations to the research community. These recommendations address areas that are not of direct policy relevance, but are essential for improving the methodological underpinning of research in the area of infrastructure resilience to climate change.

**Explore the implications of an attractor-based perspective on resilience:** An attractor-based perspective on infrastructure resilience, adaptability and transformability may yield new insights into possibilities for enhancing the performance of infrastructures exposed to disturbances of different types. This perspective offers the advantage that it internalizes the notion of infrastructures as complex adaptive systems. In doing so, it can aid in the identification of strategies that leverage the nonlinear and chaotic dynamics of these systems in support of resilience. This perspective is applicable to electricity infrastructures as well as other types of infrastructures.

**Pursue the study of infrastructures as artificial societies:** The long term development and the daily operation of electricity infrastructures are ultimately driven by the decisions of a diversity actors. In seeking to understand how to support resilience, sustainability and other desirable properties of infrastructures, we need to understand how the micro-level decision processes and social interactions of these actors may give rise to different physical infrastructure configurations and different infrastructure performance patterns. Given the growing role of technologies such as distributed generation and micro-grids, and organizational forms such as community energy systems, this need is especially acute. This necessitates devising sufficiently realistic (but also sufficiently simple) representations of the behavior of different actors, the mechanisms by which they may interact, and the manner in which these interactions may give rise to particular social and insitutional forms, and specific technical infrastructure configurations. A key challenge in pursuing this area of research is the development of models that may be reused and integrated with one another. The concept of multi-model ecologies and the guidelines elaborated in chapter 10 of this thesis may help to address this challenge.

**Enforce the sharing of models and data, and facilitate the development of modeling communities:** Enhanced possibilities for model integration and reuse are essential to progressing with the study of infrastructures as artificial societies, as well as to improving understanding of dynamics and resilience in multi-infrastructure systems. While there are several steps that individual researchers can take to enhance possibilities for model integration and reuse, the ability of researchers to take these steps depends partially on actions by the research community as a whole. To this end, the research community should: (1) encourage or require the publication of relevant models or data alongside publications and/or in their own right, and (2) create opportunities for multi-disciplinary interactions and support the development of multi-disciplinary communities around model ecologies.

In addition to these recommendations based on the outcomes of this research, we offer the following recommendations for building further on this research and for addressing the limitations of its scope:

- Quantify the effects of changes in the frequency of extreme weather events on infrastructure resilience.
- Assess the economic consequences of electricity infrastructure disruptions due to extreme weather.
- Assess the extreme weather resilience of the electricity distribution grids in the Netherlands.
- Systematically investigate and categorize possible indirect effects of climate change on electricity infrastructures.
- Assess the implications of increasing embeddedness of ICT on the resilience of electricity infrastructures.
- Assess the consequences of the geographic variability of climatic changes on an integrated European electricity network.
- Assess the efficiency and effectiveness of adaptive policies and a real options approach for fostering infrastructure resilience to climate change.

## 11.6 Final remarks

How can we foster a climate resilient electricity infrastructure in the Netherlands? In some ways, the focus of this research is rather peculiar. Electricity infrastructures are one of the main sources of climate change inducing greenhouse gases. By supporting their persistence, we are supporting the persistence of an artifact that threatens to undermine human society, as well as – as we have demonstrated in this research – itself. Moreover, the Netherlands is comparatively well prepared for the likely effects of a changing climate, and its electricity infrastructure is amongst the most reliable in the world. Unquestionably more urgent from a societal perspective is to address those many areas around the globe with less capacity to adapt and with infrastructures that are insufficient even under current conditions.

But this misses the point. Electricity infrastructures are essential elements of modern society. By supporting their persistence in the face of impending climatic changes, we are contributing to the persistence of modern society, the well-being of its members, and its ongoing efforts to mitigate climate change. Furthermore, an important contribution of this research lies in the methods and tools that have been developed. These methods and tools are applicable in other geographical contexts, also in those many places where the need for resilient infrastructures may be more immediate. I hope that our efforts find productive use in these contexts.

The methods and tools at the core of this thesis involve computer models. In addressing the issue of infrastructure resilience to climate change, and many other key problems in the infrastructures domain, computer models are indispensable. But models are useless if they do not affect and enhance the mental models that ultimately determine the decisions we (as a society) make. By way of this thesis, I hope that the models developed in the course of this research have expanded and enriched your understanding of this very relevant topic – as they have mine.

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# Appendices

# Appendix A

# Appendices to chapter 6

Table A.1: The 20 substations of the Dutch transmission grid with the highest calculated criticality values. The criticality of a substation is based on the mean drop in system performance caused by the removal of that substation.

| **Substation** | **Voltage** | **Criticality (normalized)** |
|---|---|---|
| Velsen | 150 | 1 |
| Diemen | 150 | 0.841736136073508 |
| AmsterdamHemweg | 150 | 0.82357470906555 |
| Oterleek | 150 | 0.735938616836673 |
| Maasbracht | 380 | 0.690070603652554 |
| Grain | 450 | 0.603107156868416 |
| Maasvlakte | 450 | 0.508488364308437 |
| Nijmegen | 150 | 0.477514643114971 |
| Krimpen | 150 | 0.447790120604592 |
| EindhovenOost | 150 | 0.441255850569982 |
| Maasbracht | 150 | 0.427674818733343 |
| Hengelo | 380 | 0.394330823115558 |
| Eindhoven | 380 | 0.35739938512583 |
| Geertruidenberg | 150 | 0.341608232542191 |
| Diemen | 380 | 0.324215543185364 |
| Klaprozenweg | 150 | 0.323478836269697 |
| Wijdewormer | 150 | 0.321589022877335 |
| Krimpen | 380 | 0.309561481710689 |
| Tiel | 150 | 0.29660825228914 |
| Meeden | 380 | 0.293056043726208 |

Table A.2: The 20 substations of the Dutch transmission grid with the highest calculated criticality-adjusted flood vulnerability values. Criticality-adjusted flood vulnerability is determined by the product of a substation's criticality and its flood vulnerability.

| **Substation** | **Voltage** | **Criticality-adjusted vulnerability (normalized)** |
|---|---|---|
| Diemen | 150 | 1 |
| Krimpen | 150 | 0.531983957221347 |
| Diemen | 380 | 0.38517479444063 |
| Wijdewormer | 150 | 0.382054433800915 |
| Krimpen | 380 | 0.367765465261735 |
| Tiel | 150 | 0.352376759862947 |
| Dodewaard | 150 | 0.309821890309376 |
| Teersdijk | 150 | 0.193234561919651 |
| Lelystad | 150 | 0.190000041744337 |
| Dodewaard | 380 | 0.183801178961294 |
| Druten | 150 | 0.13021849826883 |
| Zutphen | 150 | 0.12465512356729 |
| ZwolleWeteringkade | 110 | 0.103349148906605 |
| Alblasserdam | 150 | 0.102317907768357 |
| Kampen | 110 | 0.0907154936336138 |
| Zaltbommel | 150 | 0.0906850510907873 |
| Zeewolde | 150 | 0.0765064367693526 |
| Lelystad | 380 | 0.070665273864521 |
| Cuyk | 150 | 0.0676438514889925 |
| Ulft | 150 | 0.0667267698863447 |

# Appendix B

# Appendices to chapter 7

Pseudocode for the TSO's decision procedures is as follows:

### TSO decision procedure for linking new components

```
Ask the TSO:
 While you have sufficient funds
  Select one unlinked component
  Identify the least cost path from that component to the existing transmission grid
  Create a link along that path
 End while
End ask
```

### TSO decision procedure for adding redundancies

```
Ask the TSO:
 While you have sufficient funds
  While the fraction of components embedded in loop structures is less the
      desired fraction
   For each substation in the grid
    Calculate network distance to each other substation in the grid
    Calculate the euclidean distance to each other substation in the grid
    Identify the substation pair with the highest network distance / euclidean
         distance
    Create a least cost link between the identified substations
    Identify the other lines in the loop that was just created
    Set the capacity of each of these lines to the maximum capacity of the lines
         in the loop
   End for
  End while
 End while
End ask
```

### TSO decision procedure for upgrading line capacities

```
Ask the TSO:
 Project the topology of the transmission grid for the last year in your planning
    horizon
 Calculate the demand of each large load and each distribution grid under the
    peak scenario of the last year in your planning horizon
 Calculate the output of each generator under this peak scenario
 Calculate the real power flows over each of the lines under this peak scenario
 For each line in the transmission grid
```

```
  If projected real power flows > projected capacity
   Add a circuit to the line
  End if
 End for
```

### TSO decision procedure for building EHV lines

```
 For each 150kV substation in the transmission grid
  If projected real power injections > threshold for construction of an extra-high-
      voltage component
   Construct a 380kV substation adjacent to the existing substation
   Construct a transformer between the new substation and the existing one
   Create a line to the nearest other 380kV substation
  End if
 End for
End ask
```

# Appendix C

# Appendices to chapter 8

Table C.1: Results from the model: List of lines found to experience maximum anticipated loads exceeding their transmission capacities, based on the current (2010) infrastructure configuration. Used for validation purposes.

| **Line name & voltage** | **Ratio of maximum anticipated load to line capacity** |
|---|---|
| Maasvlakte-Grain450 | 1.016 |
| Borssele-Zandvliet380 | 1.243177 |
| Almere-AlmereDeVaart150 | 1.158903 |
| Born-Lutterade150 | 1.580664 |
| Botlek-Geervliet&GeervlietNoorddijk150 | 1.020425 |
| Dodewaard-VeenendaalWageningselaan150 | 1.089405 |
| Driebergen-Nieuwegein150 | 1.089405 |
| Driebergen-VeenendaaltGoeieSpoor150 | 1.089405 |
| Ede-Harderwijk150 | 1.236001 |
| Geertruidenberg-Oosteind150 | 1.747109 |
| Geertruidenberg-TilburgWest150 | 1.548721 |
| Geervliet&GeervlietNoorddijk-RotterdamWaalhaven150 | 1.020425 |
| Hattem-Vaassen150 | 1.508534 |
| Hattem-Woudhuis150 | 1.621701 |
| Nieuwegein-Ouderijn150 | 1.089405 |
| Oterleek-Velsen150 | 1.131289 |
| Oterleek-Westwoud150 | 1.030184 |
| Ouderijn-UtrechtLageWeide150 | 1.089405 |
| Vaassen-Woudhuis150 | 1.391758 |
| VeenendaaltGoeieSpoor-VeenendaalWageningselaan150 | 1.089405 |
| Venserweg-Watergraafsmeer150 | 2.748583 |
| AlmeloMosterdpot-Nijverdal110 | 1.943493 |
| Bergum-Drachten110 | 1.123254 |
| Coevorden-Veenoord110 | 1.585931 |
| Dedemsvaart-Hardenberg110 | 1.359029 |
| Dedemsvaart-Hoogeveen110 | 1.183378 |
| DelfzijlDelesto-DelfzijlWeiwerd110 | 2.210518 |
| DelfzijlSchaapbulten-DelfzijlWeiwerd110 | 1.464693 |
| DelfzijlWeiwerd-SlochterenTjuchem110 | 1.440265 |
| DeventerPlatvoet-Rijssen110 | 2.179803 |
| Goor-Rijssen110 | 1.560432 |
| Harculo-Raalte110 | 1.052785 |
| Hoogeveen-Veenoord110 | 1.455313 |
| Nijverdal-Raalte110 | 1.454024 |

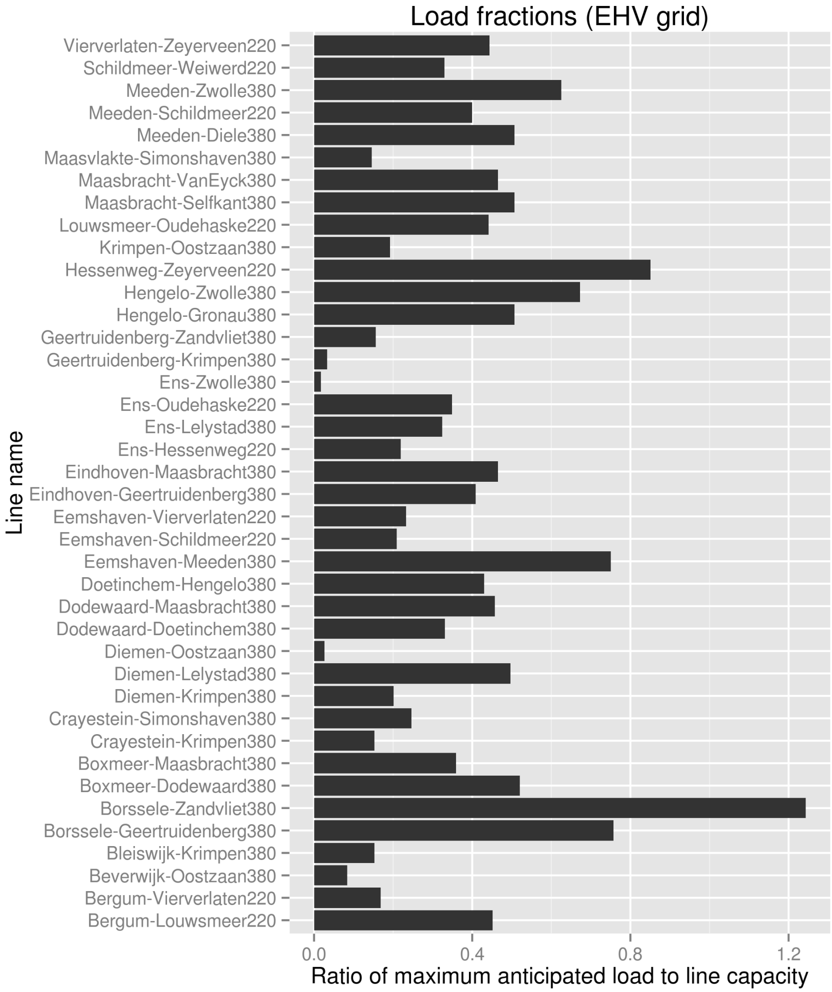


Figure C.1: Results of the model: ratio of maximum anticipated load to transmission capacity for each line of the Dutch extra-high voltage grid based on the current (2010) infrastructure configuration. Used for validation purposes.

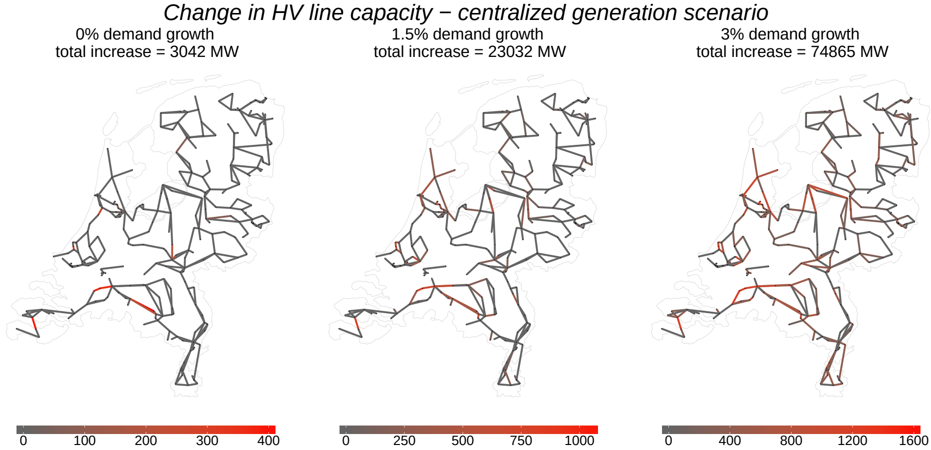


Figure C.2: Geographical distribution of the development of transmission capacity in the high-voltage (HV) grid under the centralized generation scenario, as represented in the model results. Line colors indicate the relative growth in transmission capacity (in MW) between 2011 and 2050. The first year of the simulation is excluded so as to eliminate distortion of the results due to missing line capacity data in the model inputs.

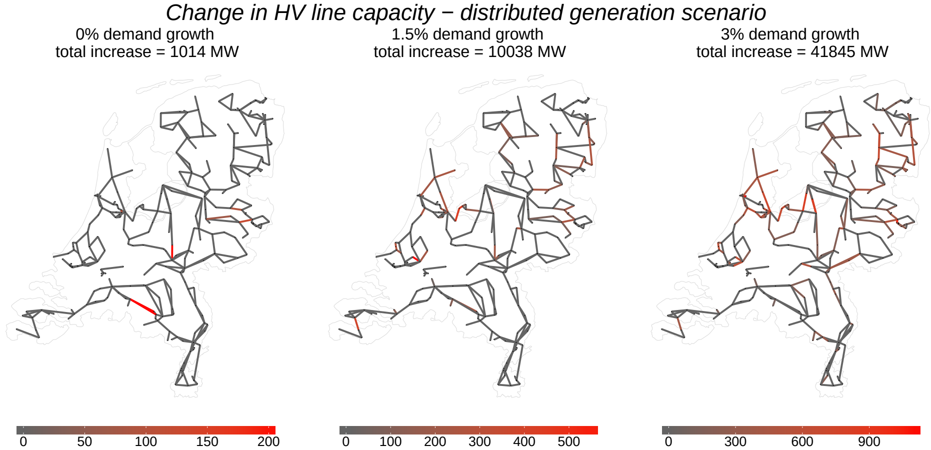


Figure C.3: Geographical distribution of the development of transmission capacity in the high-voltage (HV) grid under the distributed generation scenario, as represented in the model results.

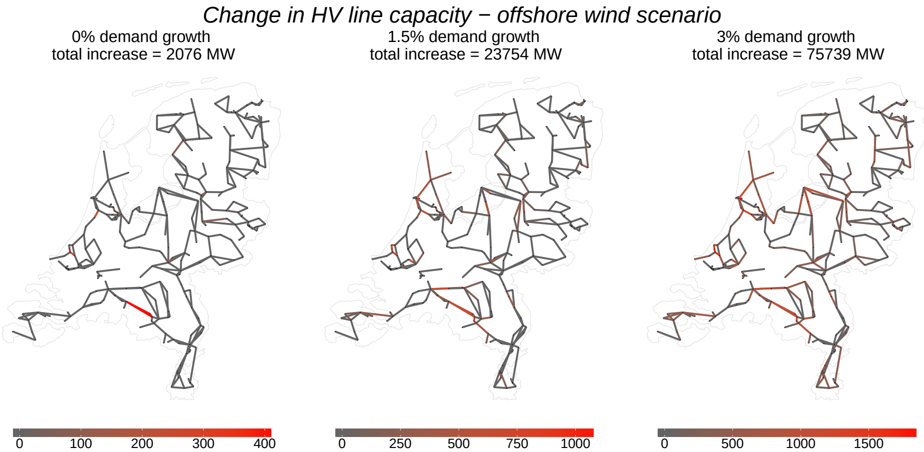


Figure C.4: Geographical distribution of the development of transmission capacity in the high-voltage (HV) grid under the offshore wind scenario, as represented in the model results.

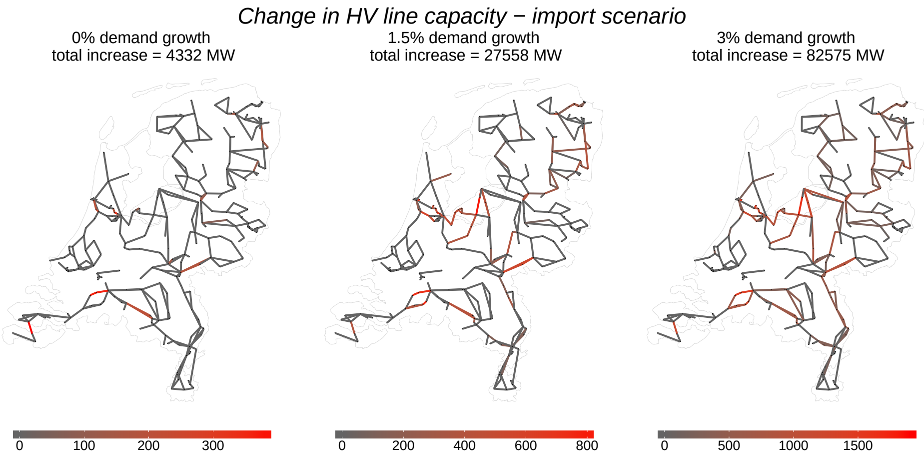


Figure C.5: Geographical distribution of the development of transmission capacity in the high-voltage (HV) grid under the import scenario, as represented in the model results.

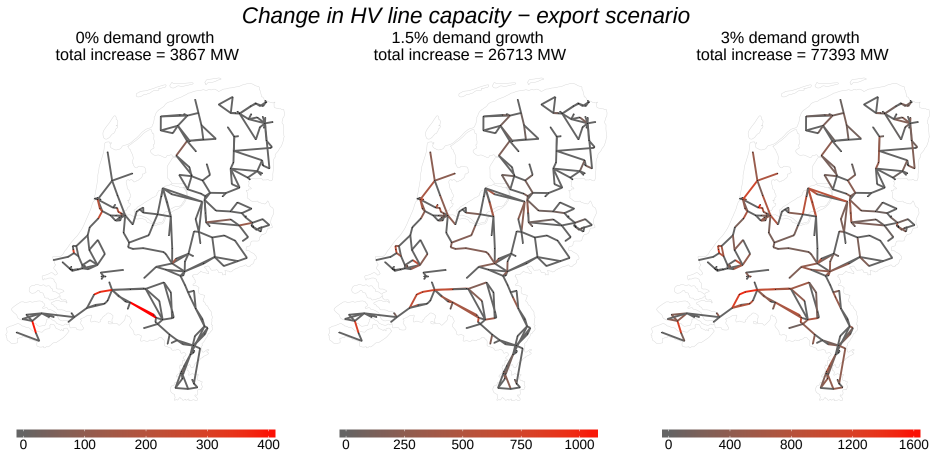


Figure C.6: Geographical distribution of the development of transmission capacity in the high-voltage (HV) grid under the export scenario, as represented in the model results.

# Summary

Recent years have seen several dramatic failures in electricity infrastructures sparked by short-term departures of environmental conditions from their norms. In the summer of 2012, 630 million people lost power across northern India, partially as a result of tardy monsoons that increased electricity demand for irrigation and air conditioning and decreased hydroelectric output (Morrison, 2012; Walsh, 2012). In the fall of 2012, 8.5 million people lost power in the Northeast US, as a result of high windspeeds and extreme flooding associated with Hurricane Sandy (LeComte, 2013). While we can choose to view events like these as isolated weather/climate extremes, overwhelming evidence suggests that such deviations may increase in both severity and frequency over the coming decades (IPCC, 2012).

A growing body of research suggests that these long-term changes are likely to influence the supply, demand, transmission and distribution of electricity in myriad ways. In light of this, *resilience* is increasingly seen as an essential characteristic of future infrastructure systems. The notion of resilience implicitly accepts the possibility of unforeseen disruptions and failures and focuses on the capacity of systems to handle them – to survive unexpected perturbation, recover from adversity and gracefully degrade – as well as an ability to adapt and learn over time. The challenge of enhancing infrastructure resilience is complicated by the reality that infrastructures are *complex* and *interconnected*. Under the right conditions, minor disturbances in one corner of the system can cascade into system-wide failures spanning regions, countries and even continents. Moreover, the interdependencies between electricity infrastructures and other infrastructures – e.g. gas, road, rail, ICT – mean that disturbances may be incited from within and/or cross over to other infrastructures, creating first-, second-, third- and higher-order effects.

This research seeks to illuminate possibilities for fostering climate resilient electricity infrastructures, accounting for their complexity and interconnectedness. The research is driven by the following question: *How can we foster a climate resilient electricity infrastructure in the Netherlands?*

**Foundations:** In addressing this question, the electricity infrastructure is framed as a complex socio-technical system, whose complexity is manifest in the variety, autonomy and dependency of its technical and social components. Building on this framing and drawing from research in the field of social-ecological systems, the state space of an electricity infrastructure can be conceptualized as a stability landscape composed of multiple *basins of attraction*, each characterized by a set of values for key infrastructure variables (e.g. total generator output, network frequency, fraction of load served). From this perspective, infrastructure resilience may be defined as

"the ability of an infrastructure to remain within a given basin of attraction upon exposure to a disturbance".

The methodology of this research is characterized by three phases, a literature study phase, a case study phase and a synthesis phase. The purpose of the *literature study phase* is to generate an inventory of knowledge concerning the anticipated effects of climate change on electricity infrastructure components, and possible adaptation measures to alleviate the effects of these impacts. The *case study phase* aims to assess the performance of the Dutch electricity infrastructure under extreme weather conditions, and to explore the effectiveness of options for fostering infrastructure resilience. The *synthesis phase* focuses on combining and repackaging these results in the form of specific insights and recommendations for supporting the development of climate resilient electricity infrastructures.

The results of the literature study phase suggest that the Netherlands will be exposed over the coming decades to more frequent and/or intense extreme precipitation, extreme hot temperatures and extreme windspeeds. The primary effects of such events on electricity infrastructures may be summarized as follows:

- Extreme precipitation and extreme windspeeds may incite floods that cause damage to and/or induce the shutdown of thermal generation facilities and electrical substations located in flood prone areas.

- Heat waves may induce: (1) decreases in thermal generation capacity resulting from cooling water restrictions and/or thermodynamically-induced efficiency loss, (2) increases in demand due to greater use and reduced efficiency of cooling/refrigeration devices, and (3) decreases in transmission/distribution capacity due to higher thermal losses and the potential failure of lines due to sag-induced flashover.

- Aside from their ability to induce flooding, extreme windspeeds are problematic primarily because of their effects on overhead transmission/distribution lines. Generation may also be affected due to the forced shutdown of wind turbines.

The indirect effects of extreme weather events are more difficult to identify, and may include, for instance, regulatory action, changes in risk perception and supply chain effects. Based on a review of proposed and implemented adaptation measures, it is suggested that such measures may be divided into three broad categories: targeted infrastructure investments, infrastructure management strategies and infrastructure planning strategies.

**Case studies:** The core of this research consists of a set of three case studies, each featuring a different geographic, temporal and/or organizational scope. The first of these case studies deals with the assessment of infrastructure resilience. The first part of this case study entails the development of a method for assessing the resilience of electricity infrastructures to extreme weather events, and explores different options for formalizing and quantifying the notion of infrastructure resilience. It is contended that a method for quantifying infrastructure resilience should be capable of capturing disturbance-induced changes in system behavior, as well as the degree to which these changes may affect service provision. A suitable resilience metric in light of these criteria is 'the mean fraction of demand served across the range of possible extreme event magnitudes', expressed mathematically as follows:

$$R_I = \frac{\sum_{m=0}^{M} \Theta_m}{M}$$

where: $R_I$ is the resilience of the infrastructure and $\theta_m$ is the mean fraction demand served under conditions of an extreme event of size $m$.

Using the model developed in the first part of the case study, the second part of this case study focuses on assessing the extreme weather resilience of the Dutch electricity infrastructure. Emphasis is placed on the nature of this infrastructure as a complex technical network. The assessment focuses on two types of extreme weather events, floods and heat waves. For each of these event types, the range of potential consequences for the Dutch electricity transmission infrastructure is assessed. The results suggest that the infrastructure displays some vulnerability to both floods and heat waves, though somewhat less vulnerability to heat waves. Both substation flood protections and demand-side management are found to demonstrate a clear ability to reduce, and in some cases even eliminate, the infrastructure's vulnerability to floods or heat waves. In the case of substation flood protections, the prioritization of critical substations is shown to significantly enhance the efficiency of vulnerability reduction.

The second case study expands on the first by accounting for the reality that electricity infrastructures are constantly developing, and that these developments may have important consequences for infrastructure resilience. The first part of the case study entails the development of a model representing the mechanisms by which electricity transmission networks evolve, and use of the developed model to explore how different societal developments might cause such a network to evolve differently. The second part of the case study adapts this model to the specifics of the Dutch situation. Using this model, it is explored how different long-term developments in electricity generation and consumption might lead to different future configurations of the Dutch transmission infrastructure, as well as how these different configurations might perform under different extreme weather scenarios.

The results of this model suggest that a future based around diminished domestic generation complemented by large increases in imports from neighboring countries will likely entail massive increases in transmission capacity, and will likely perform relatively poorly in the face of extreme weather events. It is found, on the other hand, that a future characterized by rapid growth in distributed generation necessitates only moderate increases in transmission capacity, and demonstrates a high degree of resilience to both flood and heat wave events, as more electricity is generated closer to its point of use. Additionally, it is found that, (almost) regardless of developments in electricity generation, low levels demand of growth tend to enhance the system's resilience to extreme weather events – due amongst others to greater levels of buffer capacity in transmission and generation. Taken together, these findings suggest a path towards an electricity infrastructure that is both climate resilient and sustainable. Such a path is characterized by low levels of growth in demand and high levels of growth in the implementation and utilization of small-scale renewables-based technologies.

The third case study addresses the reality that electricity infrastructures are increasingly interconnected with other types of infrastructures, and that this interconnectedness breeds interdependency – a potentially important determinant of infrastructure resilience. The first part of this case study investigates secondary infrastructure vulnerabilities in the North Rotterdam area of the Netherlands. In total, 128 electrical substations are identified as vulnerable in the case of a Schie-Noord dike breach, resulting in secondary vulnerabilities affecting at least 6 traffic signals and approximately 23% of sewer pumps within the study area. Based on these results, several suitable adaptation measures are identified – temporary generators and/or sewer pumps, backup electricity for traffic signals and remote shutdown of electrical substations.

The second part of the case study considers the challenge of incomplete knowledge of interdependencies in a multi-infrastructure system, and tests a method for identifying strategies for enhancing infrastructure resilience, in light of this key uncertainty. The starting point for the model developed here is the situation of a hypothetical operator of an electricity infrastructure faced with uncertainty concerning both the interdependencies to which his infrastructure is exposed and the severity of future extreme events. Via experimentation with this model, *robust* strategies for supporting infrastructure resilience are identified. While these results are specific to the infrastructure configuration tested, the developed model offers a template that can be tailored to the specific conditions of real-world infrastructure operators.

**Synthesis:** Drawing from the modeling work carried out in the course of these case studies, it is argued that many key problems in the infrastructure domain – including the problem of infrastructure vulnerability to climate change – span multiple scales of time and space, and feature multiple valid perspectives. Effectively addressing such problems necessitates greater model integration and reuse, which can be enabled by leveraging the evolutionary nature of model systems.

While traditional means of knowledge dissemination can facilitate this, appropriate use of emerging methods and tools from information science and technology are essential. By conceptualizing modeling efforts as *multi-model ecologies* and following certain guidelines in model development and use, infrastructure researchers can open up opportunities for model integration and reuse, and as a consequence enhance the collective ability of the infrastructures community to address multi-scale, multi-perspective societal challenges. The suggested guidelines include: use open standards and software, document and use documentation standards, build simple components, leverage the Web but recognize its limitations, prioritize flexibility over completeness, borrow proudly, and acknowledge your role.

The thesis concludes with a set of recommendations for policy makers and for the research community. Recommendations for policy makers include: (1) assess substation flood protection levels, (2) investigate possible resilience benefits of distributed generation, (3) investigate the effects of renewables intermittency on resilience, (4) investigate possibilities for inciting reductions in demand (growth), (5) account for infrastructure interdependencies and (6) account for the infrastructure's socio-technical complexity. Recommendations for the research community include: (1) explore the implications of an attractor-based perspective on resilience, (2) pursue the study of infrastructures as artificial societies, (3) enforce the sharing of models and data and (4) facilitate the development of modeling communities.

# Samenvatting

In de afgelopen jaren hebben meerdere dramatische storingen in elektriciteitsinfrastructuren plaatsgevonden die werden veroorzaakt doordat de weersomstandigheden kortetermijnafwijkingen van de normen vertoonden.

In de zomer van 2012 kwamen 630 miljoen mensen in het noorden van India zonder elektriciteit te zitten, deels als gevolg van late moessons die de vraag naar elektriciteit voor irrigatie en airconditioning verhoogden en de hydro-elektrische productie verlaagden (Morrison, 2012; Walsh, 2012). In de herfst van 2012 zaten 8,5 miljoen mensen zonder elektriciteit in het noordoosten van de VS, als gevolg van de hoge windsnelheden en extreme overstromingen gerelateerd aan orkaan Sandy (LeComte, 2013). Hoewel we kunnen besluiten om dergelijke gebeurtenissen als geïsoleerde weer/klimaat-extremen te zien, is er overweldigend bewijs dat erop wijst dat dergelijke afwijkingen in de komende decennia kunnen toenemen, zowel in hevigheid als in frequentie (IPCC, 2012).

Een groeiende hoeveelheid onderzoek duidt erop dat deze langetermijnveranderingen waarschijnlijk op zeer vele manieren invloed hebben op de vraag, aanbod, transmissie en distributie van elektriciteit. In het licht hiervan wordt *veerkracht* steeds meer gezien als een essentieel kenmerk van toekomstige infrastructuursystemen. Het begrip veerkracht aanvaardt impliciet de mogelijkheid van onvoorziene storingen en defecten en richt zich op het vermogen van systemen om hiermee om te gaan – om onverwachte ontregeling te overleven, te herstellen van tegenslag en elegant te degraderen – alsook een vermogen om aan te passen en te leren. De uitdaging om de veerkracht van infrastructuur te verhogen wordt bemoeilijkt door het feit dat infrastructuren *complex* en onderling *verbonden* zijn. Onder de juiste omstandigheden kunnen kleine storingen in een uithoek van het systeem uitgroeien tot integrale systeemstoringen die zich uitstrekken over regio's, landen en zelfs continenten. Bovendien betekenen de onderlinge afhankelijkheden tussen elektriciteitsinfrastructuren en andere infrastructuren – zoals gas, wegen, spoor, ICT – dat storingen kunnen worden ontketent vanuit en/of overslaan op andere infrastructuren. Dit kan tot eerste-, tweede-, derde- en hogere-orde-effecten leiden.

Dit onderzoek beoogt mogelijkheden te belichten voor het bevorderen van klimaatbestendige elektriciteitsinfrastructuren, rekening houdend met hun complexiteit en onderlinge verbondenheid. Het onderzoek wordt gedreven door de volgende vraag: *Hoe kunnen we in Nederland een klimaatbestendige elektriciteitsinfrastructuur bevorderen?*

**Fundering:** Bij het aanpakken van deze vraag wordt de elektriciteitsinfrastructuur voorgesteld als een complex socio-technisch systeem, waarvan de complexiteit zich manifesteert in de verscheidenheid, autonomie en afhankelijkheid van de technische en sociale componenten ervan. Voortbouwend op deze voorstelling en puttend uit onderzoek op het gebied van sociaal-ecologische systemen, kan de toestandsruimte van een elektriciteitsinfrastructuur worden vormgegeven als een stabiliteitslandschap bestaande uit meerdere *bassins van aantrekking*, elk gekenmerkt door een set van waarden voor de belangrijkste infrastructuurvariabelen (bijvoorbeeld totale productievermogen, netwerkfrequentie, bediende fractie van de vraag). Vanuit dit perspectief kan de infrastructuurveerkracht worden gedefinieerd als "het vermogen van een infrastructuur binnen een bepaald bassin van aantrekking te blijven bij blootstelling aan een verstoring".

De methodologie van dit onderzoek omvat drie fasen: een literatuurstudiefase, een casestudyfase en een synthesefase. Het doel van de *literatuurstudiefase* is het inventariseren van de kennis met betrekking tot de verwachte effecten van klimaatverandering op elektriciteitsinfrastructuurcomponenten, en mogelijke aanpassingsmaatregelen om de effecten te verlichten. De *casestudyfase* heeft tot doel de prestaties van de Nederlandse elektriciteitsinfrastructuur onder extreme weersomstandigheden te bepalen, en de effectiviteit van de opties voor het bevorderen van infrastructuurveerkracht te onderzoeken. De *synthesefase* richt zich op het combineren en herverpakken van deze resultaten in de vorm van specifieke inzichten en aanbevelingen voor het ondersteunen van de ontwikkeling van klimaatbestendige elektriciteitsinfrastructuren.

De resultaten van de literatuurstudiefase duiden erop dat Nederland in de komende decennia zal worden blootgesteld aan frequentere en/of intensere extreme neerslag, extreem hete temperaturen en extreme windsnelheden. De primaire effecten van dergelijke gebeurtenissen op elektriciteitsinfrastructuren kunnen als volgt worden samengevat:

- Extreme neerslag en extreme windsnelheden kunnen overstromingen veroorzaken, die thermische opwekkingsinstallaties en elektrische onderstations in overstromingsgevoelige gebieden beschadigen en/of sluiting ervan teweegbrengen.
- Hittegolven kunnen veroorzaken: (1) daling van thermische productiecapaciteit als gevolg van koelwaterbeperkingen en/of thermodynamisch geïnduceerd rendementsverlies, (2) stijging van de vraag als gevolg van een intensiever gebruik en een verminderde efficiëntie van koelapparaten, en (3) daling van de transmissie- en distributiecapaciteit als gevolg van hogere thermische verliezen en de mogelijke storing van de lijnen ten gevolge van overslag veroorzaakt door doorhanging.
- Naast hun vermogen om overstromingen te veroorzaken zijn extreme windsnelheden in hoofdzaak problematisch vanwege de effecten ervan op overhead transmissie- en distributielijnen. De productie kan ook worden beïnvloed door de gedwongen uitschakeling van windturbines.

De indirecte effecten van extreme weersomstandigheden zijn moeilijker te identificeren, en kunnen bijvoorbeeld regulatorische actie, veranderingen in de risicoperceptie en leveringsketeneffecten omvatten. Op basis van een beoordeling van voorgestelde en geïmplementeerde aanpassingsmaatregelen wordt gesteld dat dergelijke maatregelen kunnen worden onderverdeeld in drie brede categorieën: gerichte investeringen in infrastructuur, strategieën voor infrastructuurbeheer en strategieën voor infrastructuurplanning.

**Casestudy's:** De kern van dit onderzoek bestaat uit een set van drie casestudy's, elk met een verschillende geografische, tijdelijke en/of organisatorische scope. De eerste van deze casestudy's gaat over de beoordeling van de infrastructuurveerkracht. Het eerste deel van deze casestudy behelst de ontwikkeling van een methode voor het beoordelen van de veerkracht van elektriciteitsinfrastructuren bij extreme weersomstandigheden, en onderzoekt verschillende opties voor het formaliseren en het kwantificeren van het begrip infrastructuurveerkracht. Er wordt gesteld dat een werkwijze voor het kwantificeren van infrastructuurveerkracht in staat moet zijn om verstoring-geïnduceerde veranderingen in systeemgedrag vast te leggen, alsook de mate waarin deze veranderingen invloed kunnen hebben op de dienstverlening. Een geschikte maat voor veerkracht in het licht van deze criteria is 'de gemiddelde fractie van de bediende vraag over de reikwijdte van mogelijke groottes van extreme gebeurtenissen'. Deze is als volgt mathematisch uitgedrukt:

$$R_I = \frac{\sum_{m=0}^{M} \Theta_m}{M}$$

waarin $R_I$ de veerkracht van de infrastructuur is en $\theta_m$ de gemiddelde fractie bediende vraag onder omstandigheden van een extreme gebeurtenis met grootte $m$.

Met behulp van het model ontwikkeld in het eerste deel van de casestudy richt het tweede deel van deze casestudy zich op de beoordeling van de veerkracht van de Nederlandse elektriciteitsinfrastructuur bij extreme weersomstandigheden. De nadruk wordt gelegd op de aard van deze infrastructuur als een complex technisch netwerk. De taxatie richt zich op twee typen extreme weersomstandigheden: overstromingen en hittegolven. Voor elk van deze typen gebeurtenissen wordt het bereik van mogelijke gevolgen voor de Nederlandse elektriciteitstransmissie-infrastructuur beoordeeld. De resultaten geven aan dat de infrastructuur enige kwetsbaarheid voor zowel overstromingen als hittegolven vertoont, hoewel wat minder kwetsbaarheid voor hittegolven. Zowel waterkeringen bij onderstations als vraagsturing blijken het vermogen te vertonen om de kwetsbaarheid van de infrastructuur voor overstromingen of hittegolven te verminderen, en in sommige gevallen zelfs te elimineren. In het geval van waterkeringen bij onderstations is aangetoond dat het prioriteren van kritieke onderstations de efficiëntie van kwetsbaarheidreductie significant verbetert.

De tweede casestudy bouwt voort op de eerste door het feit te onderkennen dat de elektriciteitsinfrastructuur zich voortdurend ontwikkelt, en dat deze ontwikkelingen belangrijke gevolgen voor de infrastructuurveerkracht kunnen hebben. Het eerste deel van de casestudy betreft de ontwikkeling van een model dat de mechanismen waarmee elektriciteitstransmissienetwerken evolueren representeert, en het gebruik van het ontwikkelde model om te onderzoeken hoe verschillende maatschappelijke ontwikkelingen een dergelijk netwerk anders zouden kunnen doen evolueren. Het tweede deel van de casestudy past dit model aan op de specifieke kenmerken van de Nederlandse situatie. Met behulp van dit model wordt onderzocht hoe verschillende langetermijnontwikkelingen in elektriciteitsproductie en -consumptie zouden kunnen leiden tot verschillende toekomstige configuraties van de Nederlandse transmissie-infrastructuur, en hoe deze verschillende configuraties zouden kunnen presteren in verschillende extreem-weer-scenario's.

De resultaten van dit model doen vermoeden dat een toekomst gebaseerd op verminderde binnenlandse opwekking aangevuld met grote toenames van de invoer uit buurlanden waarschijnlijk een forse toename van de transmissiecapaciteit met zich mee zal brengen, en waarschijnlijk relatief slecht zal presteren bij extreme weersomstandigheden. Aan de andere kant wordt geconstateerd dat een toekomst gekenmerkt door snelle groei van decentrale opwekking slechts een gematigde verhoging van de transmissiecapaciteit vereist en een hoge mate van veerkracht vertoont tegenover zowel overstromingen als hittegolven, omdat meer stroom dichter bij de plaats van gebruik wordt opgewekt. Daarnaast wordt geconstateerd dat, (bijna) onafhankelijk van de ontwikkelingen in de opwekking van elektriciteit, een lage mate van vraagtoename de veerkracht van het systeem bij extreme weersomstandigheden neigt te verbeteren – als gevolg van onder meer een hoger peil van de buffercapaciteit in transmissie en productie. Tezamen duiden deze bevindingen op een weg naar een elektriciteitsinfrastructuur die zowel klimaatbestendig en duurzaam is. Een dergelijke weg wordt gekenmerkt door een lage mate van vraagtoename en een hoge mate van groei van implementatie en gebruik van kleinschalige technologieën gebaseerd op hernieuwbare bronnen.

De derde casestudy richt zich op het gegeven dat elektriciteitsinfrastructuren steeds meer verbonden zijn met andere soorten infrastructuur, en dat deze onderlinge verbondenheid afhankelijkheid kweekt – een potentieel belangrijke determinant van infrastructuurveerkracht. Het eerste deel van deze casestudy onderzoekt secundaire infrastructuurkwetsbaarheden in het gebied Noord-Rotterdam in Nederland. In totaal zijn 128 elektrische onderstations geïdentificeerd als kwetsbaar in het geval van een dijkdoorbraak bij Schie-Noord, wat resulteert in secundaire kwetsbaarheden die ten minste 6 verkeerslichten en ongeveer 23% van de rioolpompen binnen het studiegebied beïnvloeden. Op basis van deze resultaten zijn meerdere geschikte aanpassingsmaatregelen geïdentificeerd – tijdelijke generatoren en/of rioolpompen, back-up elektriciteit voor verkeerslichten en uitschakeling van elektrische onderstations op afstand.

Het tweede deel van de casestudy richt zich op de uitdaging van onvolledige kennis van de onderlinge afhankelijkheden in een multi-infrastructuursysteem, en test een methode voor het identificeren van strategieën voor het verbeteren van infrastructuurveerkracht, in het licht van deze hoofdonzekerheid. Het uitgangspunt voor dit model is de situatie van een hypothetische beheerder van een elektriciteitsinfrastructuur die wordt geconfronteerd met onzekerheid over zowel de onderlinge afhankelijkheden waaraan zijn infrastructuur wordt blootgesteld als de hevigheid van toekomstige extreme gebeurtenissen. Via experimenten met dit model worden *robuuste* strategieën voor het ondersteunen van infrastructuurveerkracht geïdentificeerd. Hoewel deze resultaten specifiek zijn voor de geteste configuratie van de infrastructuur, biedt het ontwikkelde model een sjabloon dat kan worden afgestemd op de specifieke omstandigheden van daadwerkelijke infrastructuurbeheerders.

**Synthese:** Op basis van de in deze casestudy's ontwikkelde modellen wordt gesteld dat veel hoofdproblemen in het infrastructuurdomein – waaronder het probleem van de kwetsbaarheid van infrastructuren voor klimaatverandering – zich uitstrekken over meerdere schalen van tijd en ruimte, en meerdere geldige perspectieven omvatten. Een effectieve aanpak van dergelijke problemen vereist een grotere modelintegratie en -hergebruik, hetgeen mogelijk kan worden gemaakt door de evolutionaire aard van modelsystemen te benutten.

Hoewel de traditionele middelen van kennisoverdracht dit kunnen faciliteren, is een juist gebruik van nieuw ontwikkelde methoden en instrumenten uit de informatiewetenschap en -technologie essentieel. Door het conceptualiseren van modelleerprojecten als *multi-modelecologieën* en het volgen van bepaalde richtlijnen voor modelontwikkeling en -gebruik, kunnen onderzoekers van infrastructuren kansen scheppen voor modelintegratie en -hergebruik. Met als gevolg dat zij de collectieve bekwaamheid van de infrastructuurgemeenschap om meerschalige en multiperspectieve maatschappelijke uitdagingen aan te pakken kunnen verhogen. De voorgestelde richtsnoeren zijn onder andere: gebruik open standaarden en software, documenteer en gebruik documentatiestandaarden, bouw eenvoudige componenten, benut het Web maar erken de beperkingen ervan, prioriteer flexibiliteit boven volledigheid, leen met trots, en erken je rol.

Het proefschrift sluit af met een reeks aanbevelingen voor beleidsmakers en voor de onderzoeksgemeenschap. Aanbevelingen voor beleidsmakers omvatten: (1) beoordeel de beschermingsniveaus van onderstations met betrekking tot overstromingen, (2) onderzoek mogelijke voordelen van decentrale opwekking voor de veerkracht, (3) onderzoek de effecten die fluctuatie van hernieuwbare energietechnologieën op veerkracht heeft, (4) onderzoek maatregelen om de afname van de groei van de elektriciteitsvraag te stimuleren, (5) houd rekening met de onderlinge afhankelijkheden van de infrastructuur en (6) houd rekening met de socio-technische complexiteit van de infrastructuur. Aanbevelingen voor de onderzoeksgemeenschap zijn onder meer: (1) verken de gevolgen die een attractor-gebaseerd perspectief heeft voor de veerkracht, (2) onderzoek infrastructuren als kunstmatige samenleving, en (3) stimuleer het delen van modellen en data, en bevorder de ontwikkeling van modelleergemeenschappen.

# Curriculum Vitae

Lynn Andrew Bollinger was born on March 31, 1980 in New York City, USA. He graduated from Ridgefield High School in Ridgefield, Connecticut, USA in 1998, and completed his Bachelor's studies (cum laude) at Dartmouth College in 2002 with a major in Engineering modified with Economics. His Bachelor's thesis focused on the use of building energy modeling to reduce life-cycle energy costs in buildings. Beginning in 2003, Andrew worked for several years for EPEA GmbH, a Germany-based scientific consultancy focused on sustainable product design. In 2005/6, he worked as an English instructor at Zhejiang University of Technology in Hangzhou, China. Between 2006 and 2010, Andrew completed a Master of Science degree in Industrial Ecology (cum laude) in the context of a joint program at Leiden University and Delft University of Technology. His MSc thesis focused on the use of simulation models to identify options for enhancing metal recovery in the global mobile phone product system.

Andrew began his PhD studies in 2010 within the Energy & Industry Group of the Faculty of Technology, Policy and Management at Delft University of Technology. This research took place within the context of *Knowledge for Climate*, a Dutch research program focused on climate change adaptation. Andrew's PhD research dealt with the emerging issue of electricity infrastructure vulnerability to climate change, and emphasized the use of simulation models to identify options for supporting infrastructure resilience. During the course of his PhD studies, Andrew lectured/assisted in courses on agent-based modeling and industrial ecology, presented at numerous international conferences, led the organization and execution of an "Energy Data Hackathon", and participated in a Dutch review of the IPCC WGII AR5 report.

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# Fostering Climate Resilient Electricity Infrastructures

Heat waves, hurricanes, floods and windstorms - recent years have seen dramatic failures in electricity infrastructures sparked by short-term departures of environmental conditions from their norms. Driven by a changing climate, such deviations are anticipated to increase in severity and/or frequency over the coming decades. This will have important implications for the systems that supply and transport our electricity.

In light of this, resilience is an essential characteristic of future infrastructure systems. The notion of resilience implicitly accepts the possibility of unforeseen disruptions and failures and focuses on the capacity of systems to handle them - to survive unexpected perturbation, recover from adversity and gracefully degrade - as well as an ability to adapt and learn over time.

How can we foster a climate resilient electricity infrastructure in the Netherlands? To address this question, this thesis synthesizes insights from multiple computer models using multiple modeling techniques. These models stress the nature of the electricity infrastructure as a complex and evolving system, interconnected within itself and with other infrastructures. Beyond these insights, the thesis contributes a framework, an approach and a set of tools for supporting the development of climate resilient electricity infrastructures in the Netherlands and elsewhere.


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