Evolving climate-resilient energy infrastructures

A proof-of-concept model

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1 Research background

The “proof-of-concept” model described in this paper is part of a larger research project being carried out in the Energy & Industry Group of the Faculty of Technology, Policy and Management at Delft University of Technology. This research project involves the development of a suite of models exploring the adaptation of energy infrastructures to climate change. This section provides some background on the problem and purpose of this larger research project.

Research problem

Climate change is expected to impact energy infrastructures in the Netherlands in a variety of ways. Rising sea levels and an increasing occurrence of “superstorms” have the potential to generate severe floods in coastal areas where a large proportion of infrastructure components are situated. Higher summertime temperatures may result in increased space cooling demand and cooling water issues at power plants. The range of potential impacts is extensive (See Figure 1).

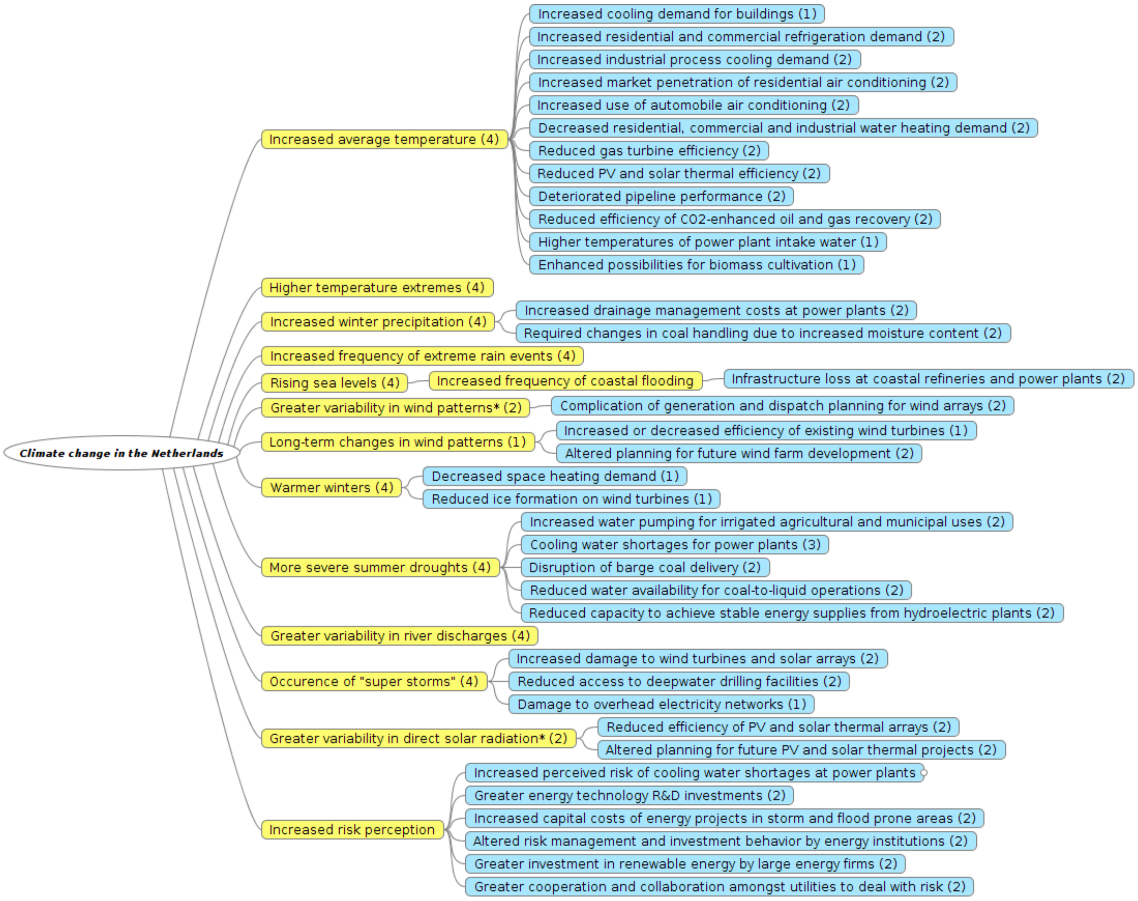

Figure 1: Overview of the potential impacts of climate change on energy infrastructures (compiled from various literature sources: 1 = (De Groot, 2006) , 2 = (Wilbanks, et al, 2008), 3 = (Rothstein and Halbig, 2010), 4 = (Bresser, et al, 2005)

Research question

The main question guiding this research is the following: *How can we support the evolution of climate-resilient and climate-robust energy infrastructure in the Netherlands?*

Research objective

The objective of this research is to foster the evolution of climate-resilient and climate-robust infrastructure networks through the development of a support tool for policy makers. This tool will be composed of 3 components:

1. A (web-based) simulation platform with a user-friendly interface and documentation.
2. A serious game based on the developed simulation models.
3. A full analysis of the results of the developed simulation models, and a thorough discussion of the implications of this analysis for policy development.

2 Approach

The proof-of-concept model described below applies a simulation modeling technique called *agent-based modeling*.

What is agent-based modeling?

Agent-based modeling (ABM) is a simulation modeling technique centered around the concept of *agents* – autonomous software entities with the fundamental ability to make independent decisions. In the process of developing an agent-based model, agents are conceptualized to represent actors in a real-world system, such as individuals, organizations or nations. These agents are assigned various attributes and decision making rules and then are released and allowed to interact within a defined digital simulation environment. Macro-level patterns emerge as a consequence of these (multitudinous) interactions.

Why use agent-based modeling?

The energy infrastructure can be seen as a socio-technical system. Technical components such as generators, pipelines, and electricity grids are tightly linked with a social network that includes energy markets, electricity producers, consumers, network managers and others. Ensuring this energy infrastructure is resilient to the effects of climate change is not only about "climate-proofing" of technical infrastructure components by increasing their robustness, but also about enhancing the capacity of the socio-technical network to adapt to the stressors of a changing climate.

Agent-based modeling has been proven a powerful technique for exploring the systemic impact of adjustments in the behavior of actors in social networks. By combining agent-based models (ABMs) with tools for analyzing flows and failure propagation in technical networks, it becomes possible to explore the development of climate-resilient energy infrastructures.

The ABM technique is particularly suitable in the context of the proposed research because of the aim to represent infrastructure robustness and resilience as consequences of both social and technical elements. Because of its capacity to explicitly represent actors as software agents, ABM enables the modeling of complex decision-making processes and bounded rationality. Furthermore, ABM allows us to express the evolution of technical infrastructure as a consequence of these decisions. This can provide for a more realistic representation of evolutionary processes and the factors that drive them, including, but not limited to, various types of policy measures.

3 A "proof-of-concept" model

As a first step with respect to achieving the objective stated in section 1, a "proof-of-concept" model has been created. The proof-of-concept model is a highly simplified representation of the studied system. The purpose of developing this model was not to produce useful quantitative results, but to generate some lessons to aid in the realization of a more extensive model, which will be developed over the coming 1-2 years.

The proof-of-concept model focuses on the 380kV electricity grid in the Netherlands, including the technical components and actors associated with it. Climate change is represented in a highly abstracted manner as a combination of temperature rise and increasing occurrence of extreme weather events.

The proof-of-concept model links 2 techniques – agent-based modeling and power flow analysis. Agent-based modeling is used to capture the long-term evolution of the electricity infrastructure as a consequence of actor decisions. Power flow analysis is used to calculate the flows of power through the components of the grid, and the degree to which consumer demand for electricity is met at each timestep. The agent-based model has been constructed and simulated in an agent-based simulation platform called Netlogo (http://ccl.northwestern.edu/netlogo/). Power flow analysis is carried out using a MATLAB package called Matpower (http://www.pserc.cornell.edu/matpower/). A software link between the Netlogo platform and Octave (an open-source MATLAB-type program) has been custom-developed to enable dynamic interaction between the two software platforms.

Components of the model

The proof-of-concept model can be thought of as being composed of 4 components – *agents*, *technologies*, *decision rules* and an *environment*. *Agents* are the social components of the system. Each agent possesses a particular *technology*, or set of technologies. During the course of a simulation, agents have to make decisions (e.g. how much electricity to use, how much to produce, how to invest). These decisions are made according to defined *decision rules*. Financial variables do not currently play a role in agent decision making – this will be included in the next iteration of the model. Agents, together with their technologies and their decision rules, exist within an *environment*. This environment affects the decisions that agents make. The paragraphs that follow describe these 4 components in more detail.

Agents

4 types of agents are represented in the model. Each of these agent types represents a particular category of actor in the real-world system. The types of agents include:

- **Consumers:** Consumers in the model represent all consumers of electricity in the Netherlands. There is no differentiation between different types of consumers, e.g. large vs. small, commercial/industrial vs. private. There are multiple consumer agents in the model. To maintain simplicity, the number of consumer agents does not change over time.
- **Power companies:** Power companies in the model represent all producers of electricity in the Netherlands. There is currently no differentiation between different types of power companies. For purposes of simplicity, the number of power companies does not change over time.
- **Transmission system operator (TSO):** The TSO represents the Dutch transmission

system operator TenneT. There is only one TSO in the model.

- **Neighboring countries:** Neighboring countries represent those countries (including the consumers and producers within them) with which the Netherlands has a high-voltage power link. There are four neighboring country agents in the model, representing Germany, Norway, Great Britain and Belgium.

Technologies

Each of the above agents possesses one or more technologies. Consumers possess a load; power companies possess a generator; the TSO possesses links and buses; and neighboring countries possess both a generator and a load.

- **Load:** All consumer agents possess a *load* technology. The load represents all electricity-consuming devices and facilities possessed by the agent. Currently, a load is characterized by a single property - real power demand. Each load is linked to a particular bus.
- **Generator:** All power companies possess a *generator* technology. The generator represents all power production equipment owned by the power company. There is currently no differentiation between different types of generators. Generators are currently characterized by a single property - a real power output. Each generator is linked to a particular bus.
- **Link:** The TSO owns a number of *links*. These links represent power lines of the Dutch 380kV grid. Links are characterized by several properties, such as capacity, resistance, reactance, a real power input and a real power output.
- **Bus:** The TSO owns a number of *buses*. These buses represent nodes in the Dutch 380kV grid, e.g. substations, busbars. Buses are characterized by several properties, such as a geographical location (coordinates), a voltage magnitude and a real power demand.

Decision rules

Each agent in the model is assigned certain decision-making rules. Consumers decide how much electricity to use; power companies decide how much electricity to produce; the TSO decides when, where and how to make repairs to the grid and add capacity; and neighboring countries decide how much electricity to produce and consume. These decision rules are currently very simplistic in nature – they are placeholders for more complex decision rules which will be implemented in the future.

- Consumers decide how much electricity to use based on the current temperature, and a reference consumption level, which grows over time.
- Power companies decide how much electricity to produce based on the temperature and a reference production level.
- The TSO automatically makes repairs every time a component he possesses fails. The TSO invests in new lines according to one of four pre-defined investment strategies (see below).
- Neighboring countries decide how much electricity to produce and consume based on the difference between the total demand of consumers and the total production of power companies. If demand exceeds supply, neighboring countries are net producers

of electricity, filling the shortfall in the Dutch market. If supply exceeds demand, neighboring countries are net consumers.

Environment

Agents and technologies exist within an environment. This environment is characterized by 2 features: a *temperature* and *extreme weather events*. Both the level of the temperature and the frequency of extreme weather events change over time. These 2 features are used to capture climate change in the model: temperature increases over time and extreme weather events occur with increasing frequency over time. The temperature of the environment is used by agents to determine consumption and production of electricity. Extreme weather events occur at various geographical locations, causing specific grid components to fail.

Simulations and experiments

A simulation proceeds in *timesteps*, with each timestep representing 1 week of real-world time. A simulation proceeds for 1040 timesteps, or 20 years of real-world time. Each timestep, the same sequence of events occurs:

1. *Environmental variables are set*: The temperature is set and extreme events (may) occur. The temperature varies seasonally and increases gradually over time to represent the effects of climate change. Extreme events occur at random locations and times, but with increasing frequency over time.
2. *Agents set supply and demand*: Based on the temperature, consumers and neighboring countries determine their electricity demand, and power companies and neighboring countries determine their electricity supply.
3. *Grid topology is determined*: As a consequence of extreme weather events, grid components may fail. The failure of these components creates a new grid topology.
4. *Load flows are calculated*: The grid topology, together with the demand and supply values of various agents/technologies, are passed on to Matpower, which performs a load flow calculation. The outputs of this calculation are the power flows over links and voltages at buses.
5. *Metric values are calculated:* Based on the outputs of the load flow calculation, the values of various metrics are calculated. Chief amongst these is consumer satisfaction, which is a measure of the degree to which the electricity demand of a consumer has been met in the current timestep.
6. *The TSO invests in new capacity and repairs failed components:* The TSO repairs all failed components, and follows his pre-defined investment strategy to invest in new links and new link capacity. The TSO does not remove old links or buses.

This same sequence of events occurs each timestep during the course of the simulation. The chief output of a simulation are the values of a set of metrics over time. The main metrics in this simulation include: the *level of consumer satisfaction* for each timestep, the *number of lines overloaded* (over capacity) for each timestep and the *average load* of all lines for each timestep.

temperature-rise-in-20-years 1.0

On Off print-stuff?

Strategy-TenneT both

Actual temperature 15.83

Average temperature 10.82

Increased average temperature 1.019

Chance of freak event happening 8.158

Working links 30

Broken links 0

Total working buses 23

Total working generators 16

Broken generators 0

Mean consumer satisfaction 1

Figure 2: Screenshot of a simulation.

Experimentation consisted of performing a number of simulations under different parameter conditions. The parameters that were varied during experimentation included the severity of climate change (no climate change -> very severe climate change) and the investment strategy of the TSO. Four investment strategies for the TSO were tested:

1. **No investment:** The TSO makes no new investments
2. **Investment in new links:** The TSO creates new links at predefined locations at set timesteps during the course of a simulation. For the creation of new links, TenneT's "Visie 2030" is used as a guide. The following new links are included: new links in the Randstad area between Rotterdam and Amsterdam, a new link from Tilburg to Zealand, the Brit-Ned interconnection, a link from Eemshaven to Amsterdam, the link from Amsterdam to Dodewaard (near Nijmegen).
3. **Investment in increased capacity:** The TSO does not build any new links, but increases the capacity of existing links at various points during the course of a simulation
4. **Investment in new links and increased capacity:** The TSO both builds new links and increases the capacity of existing links at various points during the course of a simulation

During the course of experimentation, 20 different unique parameter sets were tested – each of the 4 investment strategies was tested at each of 5 different climate scenarios. Several repetitions were performed at each unique parameter set to provide a sense of the "average" behavior produced by each parameter set.

Chief limitations of the model

The main limitation of the proof-of-concept model is the simplicity with which components are represented:

- Agent decision making is highly simplistic. Production and consumption amounts are determined by simplistic equations, and vary only with temperature. Agents do not adapt in response to recurring patterns or extreme events. The nature and timing of grid investments are preset, rather than adapting to occurrences during the course of a simulation.
- Technical components are described in a highly simplistic way. The grid representation only includes 380kV components, and ignores the existence of multiple lines and multiple transformers between nodes. Reactive power is also ignored.
- Climate change is represented in a very simplistic way – in terms of only two variables: temperature and extreme weather events. The interactions between these variables and components of the infrastructure are very limited, and represent only a small fraction of the potential range of interactions.

Together, these limitations cause the model to generate behavior that is not sufficiently realistic and not particularly insightful with respect to the research question. However, development of this model has proven useful in the sense that it has indicated where additional realism is essential.

Further information

Instructions for downloading and using the model, as well as further documentation, can be found on the TU Delft Wiki at: http://wiki.tudelft.nl/bin/view/Research/NetlogoElectricityNetworkResilienceModel (Note: a TU Delft NetID is required to access this site)

4 Next steps

The proof-of-concept model described above is a first step in the development of a more comprehensive and realistic model for exploring the resilience and robustness of the Dutch electricity infrastructure to climate change. The next steps in implementing this model include:

- The elaboration of more realistic and complex agent decision rules. Agents will learn over time and will and will have more options for adapting their behavior to occurrences in their environment and actions by other agents. Amongst others, agents will be assigned a set of financial variables, placing economic constraints on their decision making.
- Technologies will be described more accurately and in more detail. A larger diversity of technologies will be included. For instance, different types of generation technologies will be implemented, and these technologies will be assigned more detailed economic and operational properties.
- Simulations will incorporate multiple timescales. The current timestep of a week is a compromise between modeling the operational performance of the studied infrastructure and the long-term evolution of the studied infrastructure. The former of these plays out chiefly on a timescale of seconds to hours, while the latter plays out on a timescale of months to years. Subsequent versions of the model will link two submodels, each operating with a different timestep. It is still an open question as to how these two submodels will be linked.
- More detailed and extensive policy and climate scenarios will be implemented. Climate scenarios will be based on IPCC or KNMI data. Additional interactions between climate variables and infrastructure components will be included.

5 References

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