MSc Thesis

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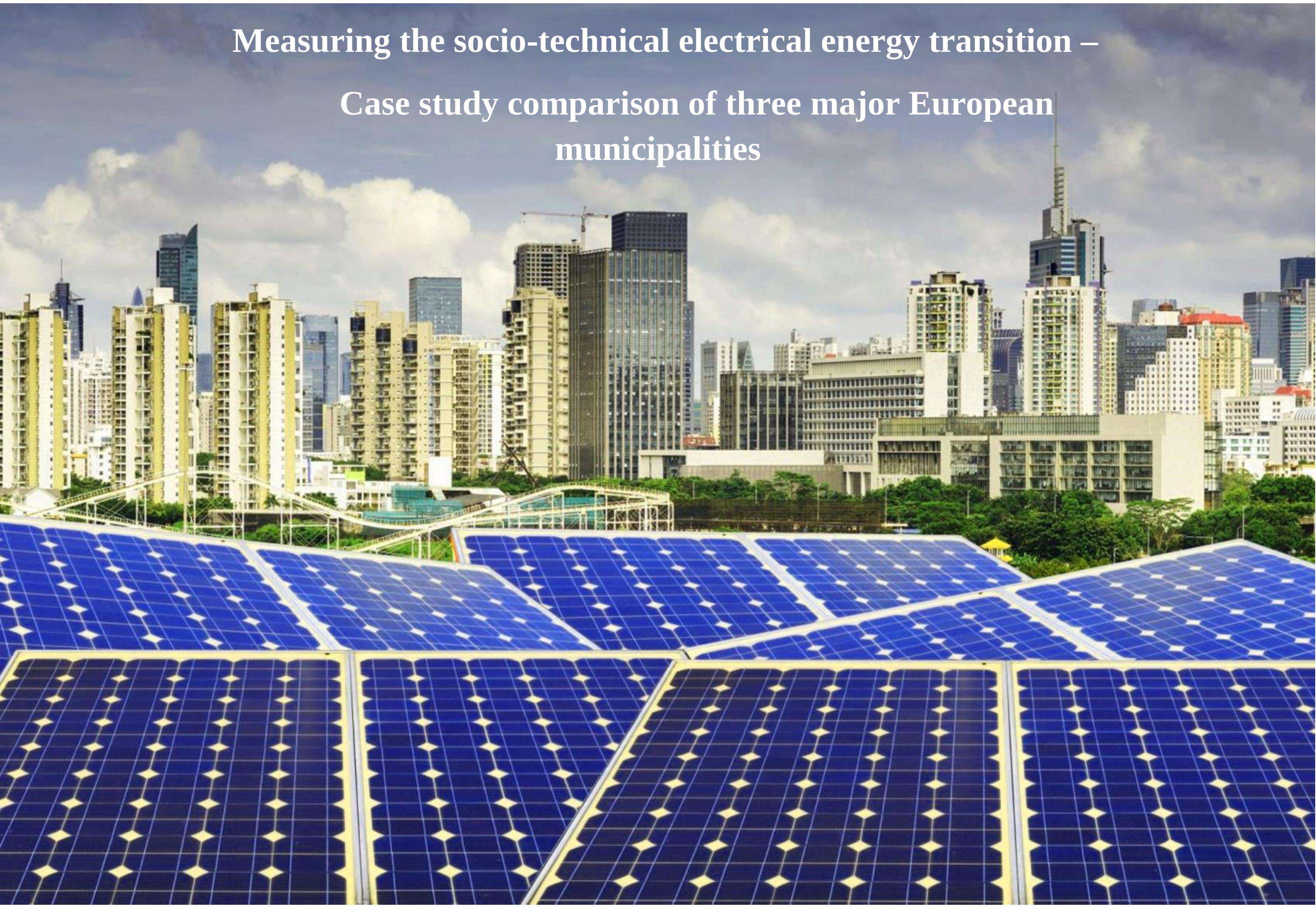
Measuring the socio-technical electrical energy transition – Case study comparison of three major European municipalities



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Source front picture: https://about.bnef.com/new-energy-outlook/ (07-2017). The picture illustrates the increasing deployment of renewable energy sources in the urban environment thereby consistently contributing to local urban energy generation and consumption.

Preface

This master thesis is submitted in fulfillment of the requirements for the Master degree of Urban Environmental Sciences. The objective of this thesis was to describe the differences in the municipalities Amsterdam, Hamburg and Copenhagen by measuring the extend of socio-technical transition towards a more circular electrical energy metabolism and to decipher the barriers that hinder the progression of renewable implementation.

Much appreciation goes out to the municipalities of Amsterdam, Hamburg, and Copenhagen, which I have contacted for obtaining vital data. The municipalities guided and gave access to vital datasets with regard to the renewable energy sector figures and thus led me to obtain a more detailed and robust case study analysis.

Last but not least, I would like to sincerely thank Professor Tejo Spit and Claudia Basta. Both for their role as thesis supervisor and excellent feedback, advice and support throughout the thesis process. Special thanks to friends, family, and colleagues that supported and advised me.

The best wishes to all readers. Hope you enjoy the work.

Wageningen University Hylke Robben
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Abstract

The global energy system is unsustainable. As cities start to expand exponentially in population and size, the continuous input of resources, and in particular the flow energy, raises concerns. Currently, energy flows in urban environments are linear. A circular urban energy metabolism is more sustainable than a linear metabolism. Circular urban energy metabolisms reduce resource depletion and mitigate further climate change impairment. In this respect, cities could be the solution to greenhouse gas emissions. However, transitioning from a linear to a circular energy metabolism requires rigorous transformations and modifications to socio-technical environments. This implies the adoption of new technologies, modifications to the infrastructural network and transformations of existing regimes. Several important domains are taken into account to achieve a stable and successful transition. The domains of technology, function, infrastructure and regime have to equally progress in order for a transition to become stable.

This thesis describes the current state of affairs of the electrical energy transition by presenting a case study comparison of three municipalities: Amsterdam, Hamburg and Copenhagen. This case study is enhanced by introducing a multi-criteria analysis (MCA) utilizing the program BOSDA. The MCA is complemented by important quantified factors in the electrical energy sector in the domains of technology, function, infrastructure and regime. Factors include renewable energy share, future renewable energy targets, electricity tariffs, electrical energy consumption of inhabitant and households, renewable area potential, security of electricity supply, dependency, renewable energy investments/expenditures and the level of ambition in renewable electrical energy policies. Results from the MCA gives detailed information to decipher socio-technological barriers that hinder progression in urban environments and provides an overview with differences between selected cities in terms of the transition status.

This thesis showed that the alignment of investigated cases is not equal. It showed an advantage of Copenhagen compared to Hamburg and Amsterdam. It showed that the Copenhagen advantage in transition process was determined by factors that influenced the regime and technology domain more early compared to Hamburg and Amsterdam. This thesis suggests that the domain of technology and regime exert more influential power compared to infrastructure and function. It also showed that domain of technology and regime are mutually supporting domains. Meaning that the progression of technology domain can be attributed to concurrent progression of regime domain.

Keywords

System transition, socio-technical transition, urban metabolism, renewable energy, electrical energy, built environment, urban environment, sustainable development

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List of abbreviations

CO2	Carbon Dioxide
COP	Climate Conference Paris
GRQ	General Research Question
GHG	Greenhouse Gas
MCA	Multi Criteria Analysis
MLP	Multi Level Perspective
MHW	Municipal Household Waste
MSW	Municipal Solid Waste
UCTE	Union for the Co-ordination of Transmission of Electricity
UM	Urban Metabolism
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
QUAN	Quantitative
QUAL	Qualitative
R&D	Research and Development
RAP	Renewable Area Potential
RES	Renewable Energy Sources
PSO	Public Service Obligation
SD	Sustainable Development
SRQ	Specific Research Question

Wh	Watt hour	= 1000 000 000
KWh	Kilowatt hour	= 1000 000
MWh	Megawatt hour	= 1000
GWh	Gigawatt hour	= 1
TWh	Terawatt hour	= 0.001

1. Introduction

1.1. Background

Urban areas play a vital role in global energy consumption and related emissions. Cities are the most important engine for economic growth and socioeconomic development since they represent around 70% of the total national GDP of the majority of countries in the world (Dijk, 2007). Cities are, and will be increasing rapidly in size, density and complexity across the globe in the future and have been accompanied by increasing resource flows of inputs and outputs which attracted attention in energy and climate research (Kaye et al., 2006) and (Kennedy et al., 2007).

Scholars (Girardet, 1999), (Decker et al., 2002) and (Fischer-Kowalski and Hüttler, 1998) raise the concern that both economic and population growth are significant factors that contribute to an increasing use of energy, leading to environmental deterioration.

Currently, over half of the global population lives in urbanized environments, and this share is expected to increase steadily in the decades to come. Despite the fact that cities and their urban environments only represent a fraction (2%) of the earth's surface area, they are responsible for over 75% of the world's energy consumption (International Energy Agency, 2008) and (Mega, 2010). The majority of this energy is imported from the hinterland (Girardet, 2008). Therefore, cities emit 40% of global carbon dioxide and a wide range of greenhouse gas emissions (GHG). Cities cause indirect environmental damage to the hinterland by extraction of resources (Girardet, 2008) and (Satterthwaite, 2004).

While cities increasingly account for a large proportion of energy consumption and related negative climate effects, they also resemble part of the solution. As early as the 1980s, many efforts have been made to reduce energy consumption and introduce renewable energy sources, benefiting local economies and to mitigate further climate change (Agudelo-Vera et al., 2012) and (Girardet, 2008). In cities, the built environment accounts for a large proportion of total primary energy consumption. The existing built environment offers great opportunities to compensate energy demand with renewable sources (Geels, 2005). Moreover, it is expected that electrical energy will supersede the current primary energy carriers as oil and gas in the urban environments in the near future (World Energy Counsil, 2015). As a consequence net electricity generation increases 38% by 2040 (International Energy Agency, 2016a).

1.1. Urban metabolism

Urban metabolism has emerged as an important concept to analyze and understand resource dependency of various flows. These include material-, energy- and waterflows between urban environments and the hinterland. In line with this trend, The amount of waste, emissions, effluents and resource shortages of a certain energy flow could be estimated by observing its inputs and outputs as organic and inorganic materials, water and energy (Karvounis, 2009). Urban metabolism aims at increasing our understanding of the complexity of (energy) flows in urban environments (Kennedy et al., 2007). Moreover, it supports our understanding of how our current linear energy system is unsustainable. Urban metabolism is essential in order to be able to increase sustainability in cities(Wolman, 1965). It helps to understand the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, generation of energy, and elimination of waste (Kennedy et al., 2007).

Scholars have increasingly documented the concept of urban metabolism (Girardet, 1999), (Kennedy et al., 2007) and (Fischer-Kowalski and Hüttler, 1998). Changing a flow that has embedded itself deeply in existing mainstream technologies and the society requires a dramatic shift; a socio-technical transition. There is a growing number of studies that are researching socio-technical transitions, and specifically, the transition from one energy society to another (Geels, 2005).

1.2. Energy transition

To increase sustainability in urban systems, energy is one of the flows that need to be changed in the urban metabolism. Improving urban energy systems mitigates further climate change impairment cities may serve as the solution to greenhouse gas emissions (Dodman, 2009 p197). Greenhouse gas emissions will be mitigated by the projected increase in electrical energy use in a changing urban energy system. The (International Energy Agency, 2008) expects electrical energy to be human's primary energy source, superseding fossil fuel sources in the future. Electricity as a fuel may possibly address solutions to problems as local pollution by vehicles and coal plants that provide power. Surely, not all modes of transport can be electrified although this should be highly promoted (Mathiesen et al., 2015). Energy is inevitable for human life and a secure and accessible supply of energy is crucial for the sustainability of modern societies. With an ever-increasing demand in fossil fuels humanity might have to resolve future major conflicts with sticks and stones, unless humanity transition post fossil era.

We may be able to achieve transitioning to a post-fossil era if countries ratified the United Nations Climate Change agreement of 2015 (UNFCCC. Conference of the Parties (COP), 2015). Once ratified, effective intervention is needed to keep the global average temperature to well below 2°C. In order to achieve this, integral strategies demand more action in the sector of energy efficiency by means of new construction techniques, construction materials and renewable energy deployment (UNFCCC. Conference of the Parties (COP), 2015). In addition to the Paris Climate Change Agreement, the European Union aims at achieving a drastic transition to near-zero carbon energy system (60 to 80% GHG reduction) by 2050 (Wachsmuth, 2012).

Countries and major underlying cities in the European union are well aware of the need for energy transition. Energy transitions are initiated in Amsterdam The Netherlands, Hamburg Germany and Copenhagen Denmark.

The Netherlands are considered to be one of the most fossil fuel intensive economies (International Energy Agency, 2016). To meet energy demand, The Netherlands have been a reliable customer of fossil fuels such as oil, gas, and coal. Consequently, The Netherlands is one of the worst contributors regarding retrieving energy from sustainable sources compared to other EU-member states. In fact, less than 5% of the total energy mix originates from sustainable sources, whereas the EU retrieves 17% from renewables (TNO, 2010). Of which the residential building sector accounts for approximately 17% of total energy consumption. This is initially fueled by the concerns over the environment and climate change, in which energy efficiency has played a major role in the energy policy since the 1970s resulting in active measures. Of course, there are enormous economic benefits of extracting fossil fuels and to trade the commodity as a state product. This also implies for The Netherlands, oil and gas revenues make up a large proportion of the state budget (approximately 20%) (TNO, 2010). Because the government has chosen the path of an energy mix dominated by fossil fuels, likewise, lower the micro and meso scales are also subjected to the use of less sustainable energy.

In a study *'Naar een toekomstbestendig energiesysteem in Nederland, TNO 2010',* To a future-proof energy system in The Netherlands, TNO has concluded that The Netherlands does not have a consistent transition strategy. Which is a worrisome development because The Netherlands and major cities are thus not sufficiently prepared for a transition that will affect their vital economic interests (TNO, 2010). There is a strong urge to provide a consistent transition strategy based on a thorough and broad-based long-term vision precisely because the energy sector is a vital part of economic interests in The Netherlands.

Aside from the governmental perspective, civic initiatives as Urgenda are using the concept of linear to circular metabolism to promote energy transition. A Dutch initiative aiming to transform the metabolism of The Netherlands in its entirety by 2050 by focusing on systems as energy, water, food e.g. Urgenda is a platform consisting of leaders from business and governmental sector seeking to merge science and enterprise. Urgenda also helps with existing acceleration to sustainable initiatives and to break down barriers (lock-ins also further elaborated in 2.3.3) in order to speed up sustainable development.

The German government made a correct turn by transitioning towards a more carbon neutral future. Mainly due to the 1970s energy crisis the government had to rethink its current energy path. As response, the government aimed to increase coal and nuclear energy generation. Although mid-70s nuclear became increasingly controversial with the public (Schmitt, 1983). Ever since the 90s nuclear is on decline in Germany while the support amongst the German public for deployment of renewable grew considerably during the 2000s. As the largest energy consumer in the European Union Germany felt the responsibility to transition to a post-carbon future. The expansion of renewables has made the country in a pioneer of renewable energy deployment and an example for other European countries. The countries *Energiewende* or "Energy transition" consist primarily of the deployment of photovoltaics and wind energy.

The Municipality of Hamburg has prioritized energy saving and deployment of renewables the key objective for meeting sustainability targets, The municipality envisions itself as the leading centre for management, engineering and innovative services for renewable energy, not only targeting deployment of renewable energy, also contributing in renewable markets by providing a solid renewable basis of product development, materials, R&D e.g. (Municipality Hamburg und Schleswig-Holstein, 2016). Since the 1990s the metropolitan region has been actively implementing wind energy and has effectively tripled its use of renewable sources since 2004 (Municipality Hamburg, 2016). Hamburg is docile to its governmental path of the deployment of photovoltaic and wind energy although a large part of its renewable energy generation originates from bioenergy. The municipality sees the opportunity to utilize MSW and generate electricity and heat. With the implementation of the Municipal Climate Protection Act, adaptation and research programmes, the Municipality aims to cut back CO2 emissions considerably by investing approximately €22.5 million a year in the deployment of renewables (European Commission, 2016). Furthermore, the partnership Enterprise for Resource Protection aims to encourage voluntary investments in increasing energy and resource efficiency enterprises (European Green Capital, 2016).

Denmark has been a role model and pioneers in the energy transition aiming for full post-carbon energy transition by 2050 which includes measures to transition from fossil to full renewable energy. With ambitious targets in all energy sectors from efficiency measures to the deployment of renewable sources, Demark is one of the first in implementing the green energy transition (Ropenus, 2015). Transitioning from a conventional and centralized fossil energy system towards a renewable and mostly decentralized system. It should be noted that, offshore windfarms are mostly centralized. An important feature of the Danish energy transition is the integrated approach across sectors enabling a steady transition process. Thus far, in terms of renewable energy integration, the Danish grid accommodated increasing renewable energy feed-in very well (Ropenus, 2015).

At meso level, the municipality received international recognition for its work in climate adaptation and mitigation as the city was elected as European Green Capital in 2014 by the European (Municipality of Copenhagen, 2015).

1.3. Scope

When analyzing urban environments one can identify three sectors for energy consumption: industry, transport and the built environment (Opstelten et al., 2013) . This study skims the surface of all three sectors, but the focus will be primarily on the built environment because this sector offers great opportunities in energy consumption and generation solutions (Geels, 2005). Moreover, the built environment is one of the largest energy consumers in the European Union (European Environment Agency, 2016).

Successful transitions are characterized by an alignment of domains (Geels, 2002). This study focuses on three domains (function, technology, infrastructure) and one overarching domain (regime) that are relevant for an energy transition. It is assumed that technology has a greater influence on the other two domains and overarching domain of regime, because the domain *technology* enables the existence of the domains *function* and *infrastructure*. The domain *regime* tunes into the changes of society and is thus an effective partner for the other domains.

In terms of energy transition, cities are the problem yet also the solution. Academics recognize that further research in this field needs to address critical issues and bottlenecks that cities oppose during a transition process. According to (Bulkeley et al., 2011) academics need to theoretically and conceptually contribute more on the role of cities in the transition process beyond limited characteristics as historical, political geographical and sociological, but also a more practical engagement through system approaches and analysis. This thesis contributes to this gap of knowledge using a system approach in order to identify points of interventions to improve city's metabolisms (da Silva et al., 2012).

For society, the transition towards a more circular energy systems is highly desirable as it addresses several issues related to energy and climate change. Amongst these are (local) pollution and distribution and transmission cost of energy that requires vast amounts of materials, for an ever extending grid and make up approximately 31% of electrical energy tariff (International Energy Agency, 2016a). Eventually, improving urban metabolism increases cities self-sufficiency and improves their energy security. This enables a safe and healthy environment for future generations.

The existing built environment sector offers huge benefits by implementing renewable technologies. Understanding to what extend cities may be able to transform their energy system is essential for further application of renewable energy in the urban environment. To meet future renewable energy targets, (Mathiesen et al., 2015) suggest that cities plays a key role in the transition. It has been argued that urban environments are one of the most difficult areas to deploy renewables because of spatial and social limitations. However, once this step has been taken, other steps can be relatively easily made.

1.4. Objectives

This study contributes to the existing literature on urban metabolism by providing a description and analysis of electrical energy flows within the urban environment. The primary objective of this thesis is to compare the electrical energy metabolisms of three European cities: Amsterdam, Hamburg and Copenhagen. This comparison will ultimately lead to lessons-learned in relation to energy transition. These cities are selected because of the comparability of various aspects such as, spatial, demographic, political, and climatic characteristics and their relatively comparable ambitions related to renewable energy solutions and technologies. A system approach offers robust and analytical tools and thinking patterns.

The following sub-objectives support the primary objective:

- to measure the extend of socio-technological transition focused on renewable energy in each selected city;
- to decipher current socio-technological barriers that hinder the progression of renewable implementation in urban environment itself and in the existing built environment;
- to compare important differences between the selected cities in terms of renewable energy implementation and transition status.

The aforementioned objectives will be achieved by

(I) Providing a detailed understanding of the dynamics of a renewable energy transition in selected urban environments, and analyzing what activates them efficiently

(II) Assessing the state of Amsterdam, Hamburg and Copenhagen's energy transition by introducing a generic MCA analysis tool

(III) Exploring the existing metabolic energy system in Amsterdam, Hamburg and Copenhagen

(IV) Formulating recommendations for optimizing the urban energy metabolism

1.5. Research questions

To meet the research objectives the following general research question (GRQ) is formulated

(GRQ) To what extend will the selected cities be able to transition towards a more circular electrical energy metabolism by 2040?

Cities operate as linear energy systems and linear systems have multiple issues. Resources are needed to generate energy. Most times, these resources need to be imported from the hinterland. Currently, renewable energy contributes only very little to electricity generation. This is consistent with the renewable energy implementation in the majority of the European countries. Nevertheless, the European Union, and its ancillary countries and municipalities have been increasingly engaged in the transition from fossil energy to renewables to meet their 2040 targets. This does not come naturally, a city has to perform well in four domains relevant to a successful transition: technology, function, infrastructure and regime.

History has shown us that the majority of countries and cities fail consistently at achieving ambiguous renewable energy targets. This may be due to the underperformance of one or multiple factors in the referenced core domains. Among these factors are low renewable energy investment, predominant fossil fuel share mix, capability of the energy grid to implement renewable sources. It is expected by means of including the domains and comparing derived results from a case study, that more accurate clarifications, and contributions for optimizing the existing system can be made. To be able to answer the above stated GRQ, specific research questions are formulated:

(SRQ1) What factors contribute to a successful sustainable energy transition in Amsterdam, Hamburg and Copenhagen?

(SRQ2) What important differences exist in terms of selected domains between Amsterdam, Hamburg and Copenhagen with respect to renewable energy transition?

(SRQ3) What can be learned from the selected case studies and applied to other urban environments in relation to urban energy transition?

1.6. Approach

The below figure (Figure 1) presents the conceptual model. This model functions as an outline of the main topics studied.

Figure 1 shows that on the one hand, finite resources are extracted from the earth (oil, gas, coal) and consumed for energy generation. On the other hand, infinite resources in the form of solar irradiance are consumed to generate energy. Finite and infinite resources directly relate to useable energy generation in urban (and non-urban) environments. At present, one may argue that the metabolism of a city is dominantly linear, implying the input from non-renewable sources supersedes (>50%) the input from renewable sources. The total amount of energy generated consist of a mix from renewable (circular) and non-renewable (linear) inputs. In addition, a linear energy metabolism is causally related to Greenhouse Gas (GHG) emissions due to the input of finite resources.

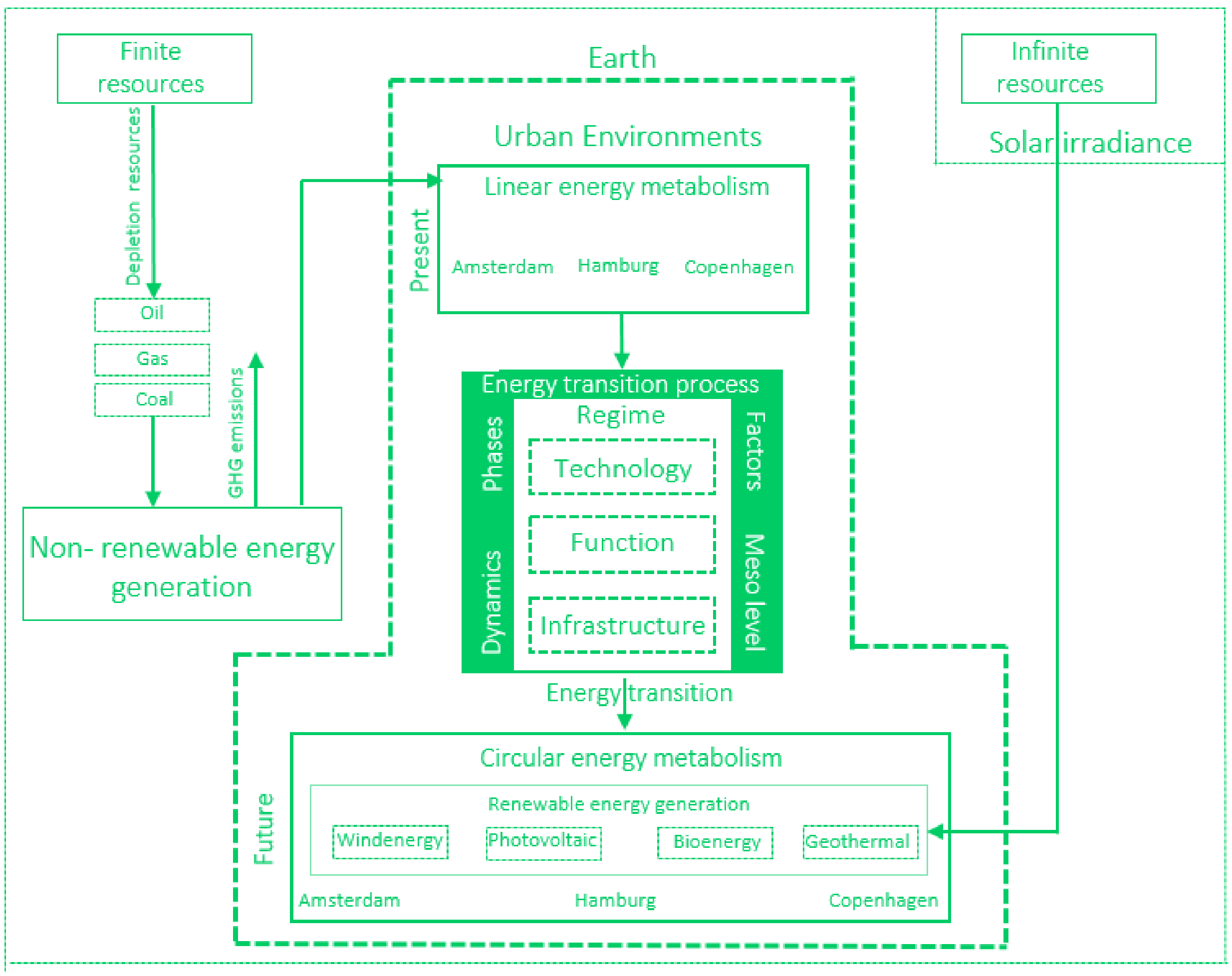


Figure 1 conceptual model

Based on the above presented conceptual model, it is assumed that the current urban metabolisms of selected case studies are linear. Transitioning from the present situation (linear metabolism) towards the desirable future situation (circular metabolism) implies the alignment in progress in the domains of technology, function, infrastructure and overarching regime.

Moreover, it is assumed that the transition towards an electrical energy metabolism is not equal between the three cases. Denmark is the frontrunner in the transition and thus their municipalities are subjected to a wide range of available resources. Therefore, Copenhagen is assumed to be more transitioned relative to Hamburg and Amsterdam.

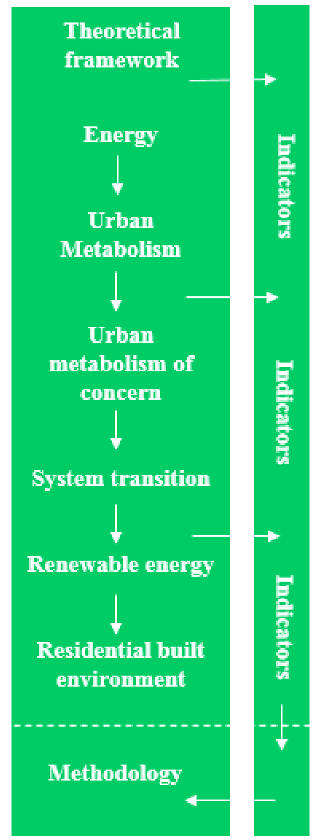
Additionally, it is expected that the selected municipalities do not generate as much renewable electrical energy as on the national level because of urban restrictions and local limitations. It is usually understood that generating electrical energy is not specifically bounded to municipal borders since electrical energy can be easily transported and distributed from one place to another.

"The scientific community should work as hard as possible to address major issues that affect our everyday lives such as climate change, infectious diseases and counterterrorism; in particular, 'clean energy' research deserves far higher priority. And science and technology are the prime routes to tackling these issues."

Martin Rees – cosmologist and astrophysicist.

2. Theoretical framework

The theoretical framework focuses first on providing a precise definition of energy and the flow of concern for this research because energy is regarded as an elusive or intangible term. Chapter 2.1 elaborates energy flow, the energy forms and efficiency limits for renewable energy generation.



Chapter 2.2, describes linear- and circular urban metabolism, the implications of a linear energy metabolism versus a more circular energy metabolism. This part is followed by the concerned cities for the investigation. A brief introduction of the cities is given in appendix 11. Here also the common local characteristcs are elaborated such as the urban, population, geographical location and morphology characteristics.

Then, as it is clear what energy flow is incorporated, the concept of urban metabolism is elaborated, and the cities of concern for the case study comparison are explained. The theoretical framework narrows down to the core of this thesis: system transitions. In chapter 2.3, historical and current energy transitions, the levels in which a transition operates, policies that support a transition, and relevant domains in the transition of urban metabolism in the energy sector are more in depth elaborated.

The quest on how cities might be able to achieve a more circular metabolism is by the application of renewable energy sources. Chapter 2.4 goes into the depth of renewable energy sources, renewable area potential, transmission, distribution and storage (flow of energy).

Lastly, since a transition is a rather ambiguous and general concept, the research narrows it down to the sector of built environment elaborated in 2.5. As one of the three main sectors of energy consumption, the built environment, and its applications towards energy consumption and solutions for more circularity are explored.

Furthermore, throughout the thesis, relevant and feasible indicators are identified and noted in the green bar as seen below. Altogether, a comprehensive set of indicators from a tool to describe the circularity of an urban metabolism. These are consequently arranged in four relevant domains relevant for system transitions. Information regarding the indicators consist of; the sort of data retrieved, the level of accumulated data (meso/macro), and a quantified unit of measurement.

Indicator	*Level*	*Unit*

2.1. Energy

This chapter clarifies the term energy and the form of energy the researcher focuses on. Also energy efficiency limits and its applications are briefly elaborated. Concluding with a clear definition of energy and thus the 'flow of concern' with regard to this research is specified.

According to Merriam-Webster's dictionary, energy is referred to as 'usable power that comes from heat and electricity' (Merriam Webster, 2016a). In physics, energy is referred to as the ability to "work" or the ability to move or yield a change in matter. However, energy is always "conserved": it cannot be created nor destroyed. It can, however, be transferred between objects and systems. For example, due to photosynthesis plants grows and energy can thus be transferred to the people who digest them. Similarly, photovoltaic cells convert photovoltaic radiation to usable (electrical) energy for human-made applications.

Another interesting notion about energy is that it comes in various forms which can be converted to one form or another. The known forms of energy entail *kinetic, mechanical, thermal, chemical, electrical, gravitational* and *radiant* energy. The main distinction between these forms of energy is *primary energy* and *secondary energy* (Yang, 2012). Primary energy is an energy form directly derived from the environment that has not been subjected to any conversion of energy transformation. Whereas secondary energy is the conversion of primary energy into electrical energy or fuel (petrol derived from crude oil and electrical energy) (Yang, 2012). It should be noted that conversion efficiency varies quite strongly. Thermal and mechanical energy conversion are limited due to waste of heat. Other non-thermal conversions such as wind could be more efficient, but wind turbines do not capture all the wind energy. For all energy conversions, there is an optimum of efficiency that can be reached, also known as the Carnot efficiency limits (Yang, 2012). Carnot efficiency limit is often used to discuss geothermal and heat exchange power engines. Betz's law indicates a maximum operating capacity limit for wind turbines (Prentiss, 2015). Photovoltaic panels are limited by the maximum conversable light from our sun, also known as the Shockley-Queisser limit that delimits efficiency of photovoltaic energy generation at approximately 33.7% (Prentiss, 2015). Currently, modern innovation reaches around 22% of photovoltaic conversion.

In the perspective of the above mentioned energy forms, the urban environment primarily consumes two kinds of energy: thermal- and electrical energy. Thermal energy is derived from heat exchange between operating industries and the built environment such as renewable sources that supply channeled district heating to baths and houses. Electrical energy is derived from the consumption of fossil fuels generating electrical energy or renewable sources converting kinetic, mechanical or gravitational energy to useable electrical energy. Although both energy forms contribute to CO2 'free' energy supply, the IEA foresees that electrical energy plays an increasing role as a CO2-free energy carrier (IEA, 2008). The near elimination of CO2 emissions in the electricity sector is the cornerstone of achieving deep CO2 emission reductions. New advancing technologies as renewables are key at achieving this. Aside from energy forms and conversions rate, existing trends predict that electrical energy will become the main energy source to be used in urbanized environments. Electrical energy consumption has drastically risen leading to an increase in the final energy consumption over 40% today (Clerici et al., 2015). Aside from energy forms and conversions rate, existing trends predict that electrical energy will become the main energy source to be used in urbanized environments. Providing emission-free electrical energy for the ever expanding urban environments contributes to a more circular energy metabolism.

Focus on electrical energy

To conclude, electrical energy will be our future primary energy source and thus inherently important to address energy consumption. In Addition, there appears to be a broad understanding of the term *energy*. In literature, *energy* is often used to define a set of processes of energy conversion and transportation fueled by natural energy sources. The absence of a clear definition of energy leads us to opt for the definition of, in this thesis, as '*the usable power that is derived from any form of primary or secondary source which may be used in physical systems in order to work and move*.' Thus, the conversion of (wind, photovoltaic, thermal) energy by renewable sources into directly usable electrical energy needed for everyday appliances such as lighting, heating, cooling, receiving warm water, is the 'energy of concern' of the present investigation.

2.2. Urban metabolism

Now that electrical energy is the primary flow to be investigated, the urban metabolism concept is elaborated to understand the relation between generation of (electrical) energy and the urban environment. This includes the environmental consequences of a linear metabolism how a more circular electrical energy metabolism contributes to supporting resilient cities and self-sufficiency and thus energy security.

The urban environment is able to sustain its current form because a variety of complex life-supporting arteries consisting of for example energy, water and materials. To understand this complex system, the concept of metabolism is conceived in the early 1800s by Karl Marx and renamed urban metabolism. As one can imagine, a continuous extraction of fossil fuels from the hinterland and consuming the fuels to meet energy demand will lead eventually depleted sources and an increasing amount of emissions in earth's atmosphere. In this research, the concept of urban metabolism is used to understand the relation between humans and nature and the extraction and consumption of resources from the hinterland for urban systems and in particular the energy system. To make this more explicit in terms of measurement, the consumption of electrical energy can be quantified by including the indicator of electrical energy consumption commonly utilized by institutions and organizations as (WorldBank, 2016) and (UN, 2016), displays the total electrical energy consumption divided by the number of inhabitants.

Electrical energy consumption per inhabitant	*Level: meso*	*Unit: kWh/inhabitant*

Thus, the urban metabolism is the abstract notion of energy systems in urban environments and can be defined as "the sum of the technical and socio-economic processes in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2011). Understanding the resource flows supports sustainable city planning(Spiller and Agudelo-Vera, 2011). The framework of urban metabolism can be used for a twofold objective: first, it enables to analyze various flows associated with urban environments so to recognize environmental impacts from these flows; second, it helps to understand the relation of 'resource dependency' between cities and the hinterland (Kennedy et al., 2007). The concept of 'urban metabolism' has therefore been introduced so to capture the dynamics of resource flows and their interplay in determining more or less sustainable urban metabolisms (Kennedy et al., 2007). Urban metabolism includes the fundamental idea of being completely independent in resource consumption and generation; in essence self-sufficiency.

Dependency electrical energy (self-sufficiency)	*Level: macro*	*Unit: % in-export*

The concept of 'metabolism' originates from the field of biology, where it refers to chemical changes within living cells similar to the functioning of the human body. Thus the concept of 'urban metabolism' is used to analyze the sustainable development of cities in a way similar to the analysis of metabolic processes of living organisms. This concept is used as a way of enhancing our understanding of complex socio-urban phenomena and processes in the early 19th century (Fischer-Kowalski and Hüttler, 1998) and (Wachsmuth, 2012).

Around, approximately, the '60s of the past century, the understanding of the urban sphere started to change thanks to the crossover between related disciplines such as ecology, biology, and cybergenetics (Elzen et al., 2004). From this point in time onwards, urban spheres are no longer seen as static and isolated entities but an interconnected, dynamic and ever changing systems that are deeply connected to the natural ecosystem surrounding them (Elzen et al., 2004). In the same decade, biology would become biochemistry, and the term 'metabolism' started to represent the processes of organic breakdown within individual organisms and between organisms and their environment. The concept of metabolism is recognized as a widely applicable concept to the processes through which bodies change and reproduce themselves; this wide-range application of the concept of metabolism led, consequently, to a more holistic conception of ecosystems relations (Fischer-Kowalski and Hüttler, 1998) and (Wachsmuth, 2012).

2.2.1. Linear metabolism

A metabolism can either be a linear or circular process. Both processes require an equal amount of resources. Although the extraction or location of resources used and the required energy is inherently different. In a *linear* metabolism as seen in Figure 2, the input of various resources occurs without activating the function of reuse/recycle; the majority of resources equals the output of waste, as shown in (C. Kennedy et al., 2011). This is, therefore, an inefficient process consisting of an equal amount of inputted and outputted resources.

The relevant 'linearity' means that new resources need to be continuously extracted and produced rather than reused/recycled, with the consequence that natural resources (Kennedy et al., 2007) keep being depleted over time. With regard to the energy flow, for instance, preventing such continuous depletion implies a combination of energy efficiency and clean energy technologies (Girardet, 1996).

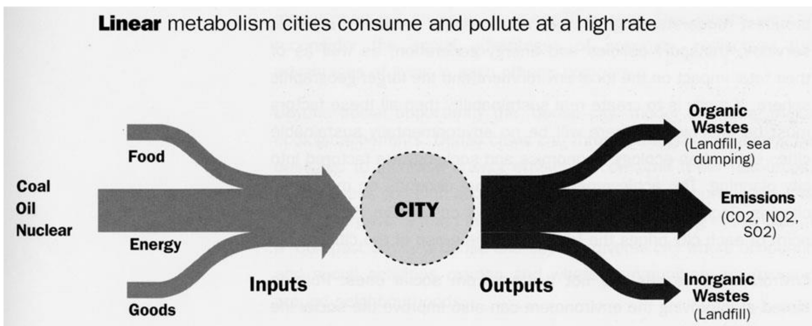


Figure 2 Linear metabolism of cities (Rogers, 1997)

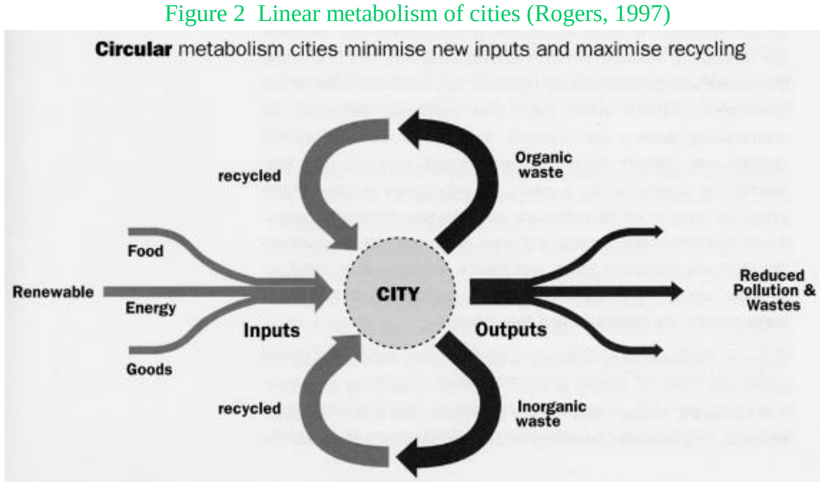


Figure 3 Circular metabolism of Cities (Rogers, 1997)

Transitioning towards a circular metabolism would benefit the resource cycle because of: an increase in resource efficiency, avoiding waste by using it as a resource or input of new valuable products, supporting the resilience of urban systems and achieving environmental sustainability (Girardet, 1999). Global energy demand requires extraction and transportation of finite (fossil) resources.

2.2.2. Circular metabolism

In a *circular* metabolism as seen in Figure 3, the majority of used resources are reused and recycled. This is more efficient because it decreases the need for inputted resources, and thus the pressure on the natural environment

(Kennedy et al., 2007). Also, energy consumption for resource transportation is considerably lower in a circular metabolism, because resources will be reused; thus, reallocation of resources with regard to transport distance (for processing, distribution, transportation and usage) is much lower, also seen in Figure 3. Furthermore, when considering a circular electrical energy metabolism, cities can become more self-sufficient in their energy supply. Independent using generating green energy and store the energy locally improves energy security and thus resilience.

From linear to circular

Keeping in mind these distinctive elements of linear vs. circular urban metabolism, a call for transitioning the former towards the latter has attracted the interest of urban scholars (Elzen et al., 2004), (Geels, 2002) and (Rotmans et al., 2001), international organizations and governments. The term *transition* refers to a change in the dynamic equilibrium in which an existing equilibrium is superseded by a new one. Examples of new systems offering solutions in the environmental field are: the hydrogen economy, the shift from coal to oil, industrial ecology (closing of material streams through reuse mobility) and customized mobility (as an alternative to automobility). Here, the concept of *transition* relates to the process of transformation through which complex systems change in a fundamental way over an extended period of time, 25 years or more (Elzen et al., 2004). However, a transition can also be a rapid changing environment due to nuclear meltdowns (Fukushima) (Elzen et al., 2004).

2.3. System transitions

This chapter explores transitions. The chapter starts with paragraph in 2.3.1. that shows historic energy transitions and provision, their characteristics and events that led up to energy- to energy transitions. Followed by transition phases elaborated in paragraph 2.3.2. paragraph 2.3.3. paragraph 2.3.4. provides an explanation of the meso level, which is primary the level concern. In addition, the important characteristics of a transition will be addressed.

Transitions have occurred throughout history and were part of the socio-technical environment since the existence of humankind (Geels, 2005). According to Webster's Dictionary, transition is "the passage from one state, stage, subject or place to another, or movement, development or evolution from one form stage or style to another" (Merriam Webster, 2016).

Examples of a transition at the level of society as a whole, the transition from a prehistoric hunter-gatherer rural society to urban society is *de facto* a system transition. Another example is the transition from rural to industrial society (Elzen et al., 2004). These examples show here are many scales at which we can observe the phenomenon of transition, such as the transition of transport systems from horse-powered to auto-mobility, or the transition from telegraphic to digital communication (Elzen et al., 2004). There are also transitions at the level of organizations and firms; for example, the transition of card machines to personal computers, and from IBM to Apple operating systems, or the Dutch transition from coal mining to the chemical industry (Elzen et al., 2004).

With regard to urban metabolism, a transition requires taking into account the overall resource flows constituted by energy, water, food and organic/inorganic materials. Transition of each of the resource flows towards a circular cycle can be introduced by new technologies and the respective innovation (Rotmans et al., 2001). Transition of all four flows is not a parallel development since each of the flows are inherently different regarding their measurement, regarding their substance, and thus different regarding the socio-technological innovative solutions that need to be implemented (Elzen et al., 2004).

Likewise, various energy transitions occurred in the past such as the transition of biomass-coal and coal-oil and gas. A short historical insight is given to review how energy transitions emerged and the primary incentive to change the socio-technical energy system. This will give the reader a more in-depth understanding why humankind has chosen fossil fuel as a main and primary energy source leading to environmental deterioration.

2.3.1. Historic energy transitions

The beginning of the 18th century was characterized by biological "energy" use as seen in Figure 4, in this time period biomass was the predominant resource to be used. The consumption of coal and other energy materials were practically nonexistent until later 1900s (Satterthwaite, 2004). Immense agricultural and labor productivity progresses allowed the existing population to create an agricultural surplus that permitted the growth of non-biological urban population (Satterthwaite, 2004). In addition, the industrial revolution between 1840 and 1870 ensured new technological advancements in machinery, improvements to yield food and thus new methods to create cities to accommodate the rising population. To supply demand, resources with a higher energy capacity (per kg) compared to biomass were needed. Coal was the logical resource to replace biomass because it has a much higher energy capacity, can be easily extracted and was most suitable resource to be consumed when taking into account the latest technological inventions such as the steam-powered engine (Satterthwaite, 2004). However, coal is one of the worst contributors to GHG emissions, which was by then, not a concern at all nor was it debated (Satterthwaite, 2004). In addition to the steam powered engine, the infrastructure rollout in America and Europe, such as railroads were extensively developed during this period of time. The increasing amount of networks throughout both continents ensured steady and rapid transportation of high quantities of coal, and thus a greater amount of energy being distributed.

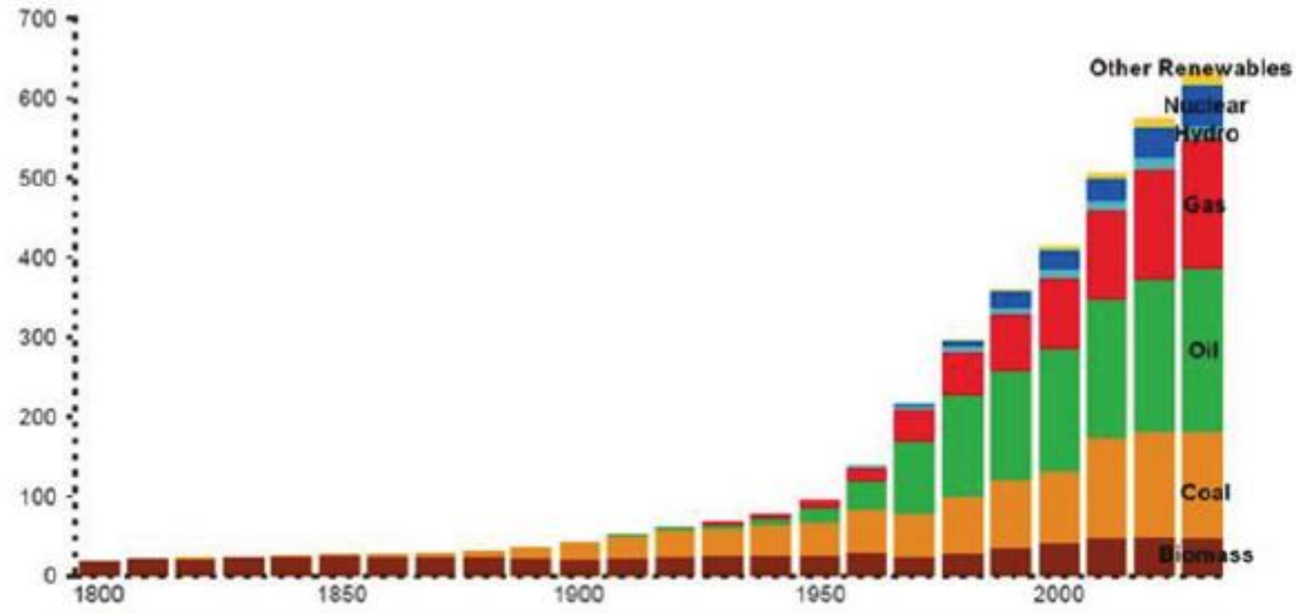


Figure 4 Energy provision 1800-2015 (Exxonmobile, 2016)

Industrial revolution

During the period of 1870 till 1940 coal was becoming the rising material for energy provision. Here we see the transition from a biomass socio-ecological regime to a fossil fuel based regime. Figure 4 shows the rising consumption of coal while simultaneously biomass consumption steadies. The use of coal ensured the rapid pace of urban expansion in height and width (Satterthwaite, 2004), without coal, emerging cities early 1900s wouldn't have existed. In terms of biomass as energy system for creating urban environment – this system was more or less abolished within a matter of decades - although in the first phase of industrialization there was still a coexistence of biomass and coal as an energy resource.

In the time spectrum of 1900 to 1940 oil was introduced to the market, kick-started by the Texas oil boom. Oil was seen as a new resource that could lead to new applications and technologies and would provide the necessary energy provision to accommodate a new generation enjoying economic growth.

Post world war II

Post- world war II the major trend of oil consumption continued virtually unbroken. Within two decades (1950 to 1970) world's total energy mix constituted roughly 50% from oil (Swart, 1992). Not only did oil contribute as a high energy resource to the built environment and the infrastructure market, it also penetrated rapidly into the stationary energy market such as natural gas. The discovery of the Groningen gas fields ensured a new sizeable share of domestic and commercial energy consumption and thus a new market in The Netherlands and Western Europe. In the beginning of 1970s Western Europe was mainly fed by the Groningen gas fields. In the same decade gas from elsewhere in Europe (Russia – Norway) began to flood the market which led to an abundance gas resource and consequently a socio-ecological transition from coal to oil/gas (Swart, 1992).

To conclude, energy transitions are deeply rooted in the existence and development of society by the creation of relevant technologies and urban expansion to accommodate a rising population and economic growth. A firm transition constitutes recurring patterns and mechanics, Rip and Kemp (1998) use the term "configuration." In this context, working configurations cannot easily be bounded from the rest of society. Skills, patterns, and routines of behaviors of institutions of organizations are embedded in such a way that they cannot easily be changed (lock-ins). One particular change is the infrastructure and technologies involved.

A well-developed infrastructural railroad network helped the transition from biomass to coal. Though, the railroads were not purposely developed to transport coal. However, the transition from coal to oil required a different means of transportation purposely designed for the energy provision of oil/gas.

Well-developed infrastructure is impeccable for any new energy source to supersede existing energy sources. A remarkable given in energy transitions consist in the fact that well-developed infrastructure supports the security of energy supply as seen during the shift from biomass to coal, and coal to oil/gas. In a period of rapid transformation, increasing deployment of renewable energy and interconnection due to in- and exports to countries with different technologies and demand patterns, challenges lay ahead in which security of electricity supply is inherently important (Danish Energy Agency, 2015). The Danish recognized the importance of energy supply due to the 1970s oil crisis. Their dependency on imported fossil fuels was a liability to the economic wellbeing of Denmark and its Capital. As such, Denmark began developing and deploying wind energy, concurrent to the technological improvements in the wind energy sector (Möller, 2010), thereby introducing policies and regulation effectively changing the configuration. Changing this requires a socio-technological system shift in every part of the configuration. Therefore the beginning of a transition is practically non-existent for the majority of the population; a slow process of relatively small changes in the configuration. The transition process can be understood by a non-linear development that characterizes four defined phases, multiple dynamics, and interconnected aspects that together form the direction and pathways. The next sections elaborate the different phases that constitute a transition process.

2.3.2. Transition phases

Socio-technical transitions can thus be understood by identifying various phases that constitute a transition process. The phases can be described as a set of continuous changes, which reinforce each other and take place in different areas: technology, institutions, behavior, culture, ecology the economic system and believe system (Rotmans et al., 2001). The four phases described by Rotmans, are illustrated in Figure 5, this is a simple and abstract conversion of the transition phase process. Every transition in history has more or less followed the typical S-curvature. It should be noted that every transition varies in speed and acceleration relative to each area.

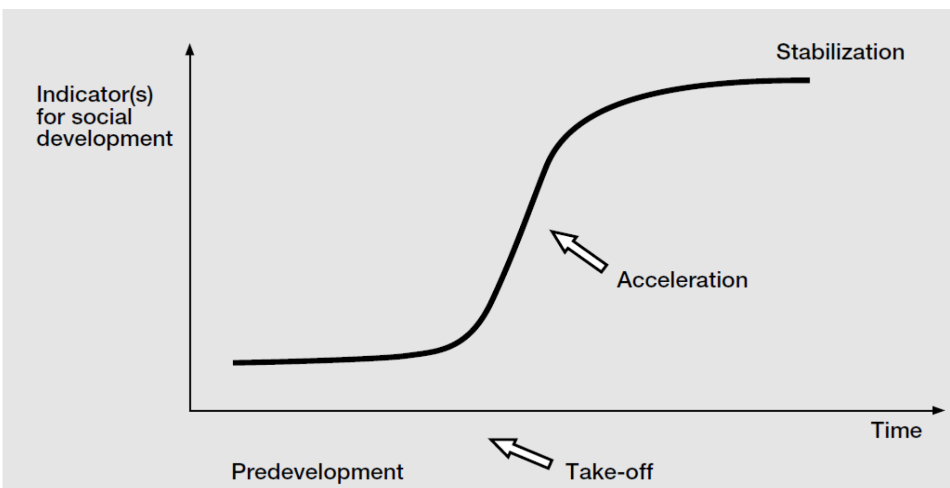


Figure 5 Four phases of transition described by Rotmans (2001)

First phase constitutes the predevelopment emergence of novelty in an existing context – this is a phase in which small-scale initiatives arise and a transition is barely noticeable. Second phase constitutes the take-off: technical specialization in market niches and exploration of new functionalities – here the process of change gets under way because the system in which the regime is in place starts to absorb the transition impulses and shows a start of a change process. Third phase, here finds the socio-technical transition its breakthrough: wide diffusion, the breakthrough of new technology and competition with established regime – structural changes occur and are translated into mainstream practice of many actors. Last phase is the stabilization: gradual replacement of established regime, wider transformations. New system in a dynamic equilibrium is established (Geels, 2005) and (Rotmans et al., 2001).

2.3.3. Transition dynamics

A transition thus undergoes several phases which determine at which state the transition is in – and can be defined as a gradual but spontaneous process of change where the structural character of a society transforms (Rotmans et al., 2001). Transitions are thus not constant nor deterministic phenomena. They involve a large range of possible paths, directions, scales and speed that can be influenced by governmental policy and intervention without, however exerting full control on developments and outcomes.

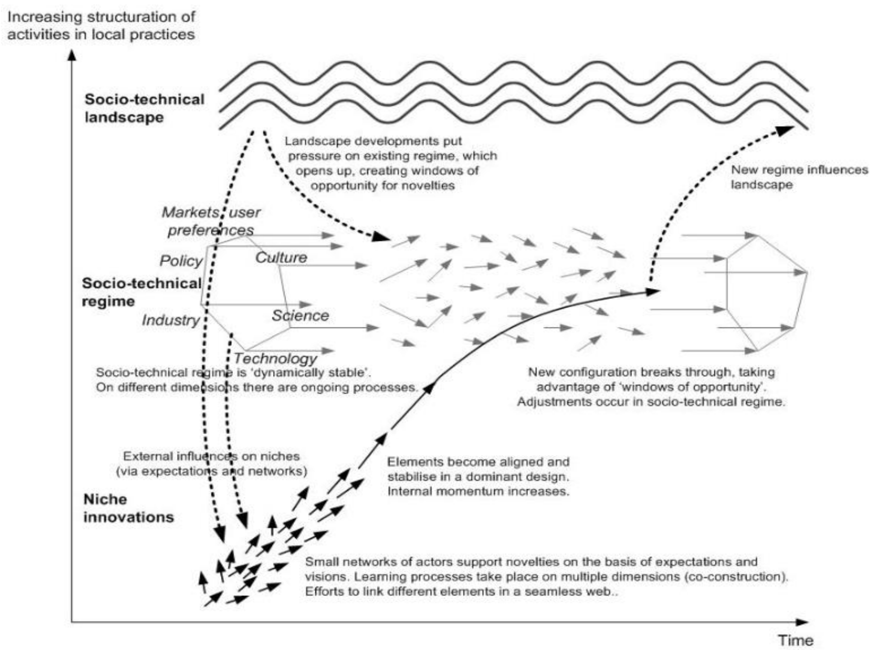


Figure 6 A dynamic perspective of transition in progress described by Rotmans (2001)

The figure above portrays the dynamic nature involved - as Figure 5 showed a more abstract conversion of the phases - Figure 6 displays a more in-depth illustration. Here the transition starts with the emergence of a new innovation influenced by factors as technology, science, industry, policy, culture and markets of user preference with a lot of experimentation and uncertainty involved (pre-development). New technologies and innovations struggle to compete and to breakthrough. The moment these do break through the regime one can expect a take-off of the technology and innovation. The model implies that in the upper-level stability increases therefore the pathway becomes more deterministic. However, Figure 6 also implies that there is an increasing analytical structuration of activities of three levels: niche-innovations (micro), socio-technical regime (meso) and socio-technical landscape (macro).

Altogether these factors direct a transition in a range of possible pathways it may transition to. Also the rate and why it will be picked up by society may vary according to the diffusion of those factors, as Figure 7 Technology adoption rate in the US shows. Different technologies and their penetration in science, technology, culture and level of support is highly heterogeneous. Hence the S-curvature is not as smooth as displayed in Figure 6.

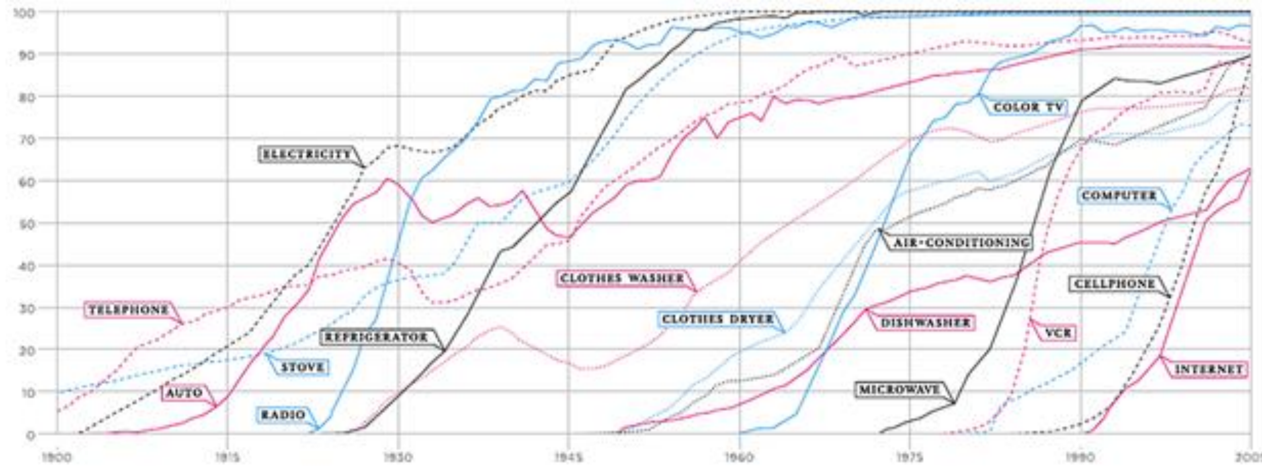


Figure 7 Technology adoption rate in the US (Hall and Khan, 2003)

Instead, the S-curvature follows a highly volatile path with ups and downs. However, the volatile path leads to an S-curvature through time. As seen in the figure above, the steepness of the curvature is thus different for each technological product. Whereas radio, computer, VCR, microwave and the internet are adopted rapidly. Telephone, stove, clothes washer and dishwasher are adopted 'slower.' This is not because these are unable to see the opportunity. But they settle more slow, modest and make incremental improvements. One particular incentive for fast adoption is the drop in the price of cost (Hall and Khan, 2003).

2.3.4. Policies in transitions

Policies are important during the take-off phase and thus establishment of a transition. Disruption of lock-ins and dynamics of the existing regime may be pursued when a wide pallet of policies in the electrical energy sector is implemented that addresses support as economic (subsidies) and regulatory (market) instruments. Therefore the researcher suggest an indicator to measure the level of ambition of renewable energy focused on the electricity sector. The indicator must meet a number of conditions to be included. Distinction if policies will count in the indicator constitute jurisdiction and policy status; national – state/regional and municipal, and the policy status; only enforced or planned policies will be taken into account. Lastly, only in-force policies are included.

Level of ambition renewable electrical energy policies	*Level: macro*	*Unit: # of active policies*

2.3.5. Mesolevel

Depending on the analyzed context; the size of spatial interpretation and range in which organizations or institution will be analyzed different levels are established ranging from micro- meso– macro. Micro; The micro level comprises individuals, actors, companies and or movements. At this level new techniques, alternative technologies, and social practices may be subjected to variations, most often these are supported by public subsidies (Rotmans et al., 2001).

The mesolevel – the level of concern in this research - comprises networks, communities, urban environments, and organizations. Here interests, rules, and beliefs that guide private action and public policy are for the most part focused on optimizing rather than transforming systems. This level consists of three interlinked domains. Firstly, a network of actors and social groups; for instance, actors that operate utilities, the Ministery of Environmental Affairs, large industrial users and households as a collective entity (Geels, 2005). Secondly, formal, normative and cognitive rules. An example of formal rules are regulations and laws; an example of normative rules are relationships and behavioral norms; an example of cognitive rules are guiding principles and belief systems. Thirdly material and technical elements. In the case of sustainable energy sources this means the electricity grid, photovoltaic panels, and the generation of electricity, so on and so forth. The most dynamic changes transpire between meso (regime) and micro (niches) level (Geels, 2005). Macro level comprises institutions, organizations, nations or federation of states. This level is the *socio-technical landscape* which essentially forms the exogenous environment (Kemp et al., 2007).

Notably, the mesolevel is the level of concern because this is the level municipalities/cities operate. The micro and macro levels are, for the most part, thus excluded from the research objective. Though, at times, the macro level will be included when no homogenous data sets at meso-level can be derived. Interplay and dependencies between levels may be analyzed by using a concept called the multi-level perspective (MLP). MLP specifically looks into the relations between various levels Multi-level perspective will <u>not</u> be part of this thesis but has been briefly looked at during the process of gaining knowledge about transitions and the interdependencies between all levels. The thesis focuses on a horizontal (primarily meso-level) analysis instead of a vertical aligned multi-level perspective analysis

2.3.6. Core domains

Transitions are characterized by identification of core domains (Geels, 2002). Successful transitions become a reality once domains are 'aligned' and implemented to a certain level of socio-technological acceptance. Aligned implies the equal advancements and improvements in respect to the domains. It is this alignment and acceptance what contributes significantly to the duration of a transition from 'beginning – take-off ' to 'end – stabilization '. The domains most relevant to a socio-technical transition with an energy character constitute the following; technology, function, infrastructure and regime, these are further delineated for investigation. Arguably, additional domains as culture, social acceptance, distribution and more abstract domains as the relationship with customer base, industrial networks, customer applications channels of distribution and service, technical skills(Geels, 2002) may be contributing to a (socio)technical transition, however the focus is solely on the mentioned domains and will be briefly elaborated below.

Technology is an important aspect because it fulfils the function of the socio-technical transition. Technologies enable societies to push development of newly addressed innovative products supported by regimes (Geels, 2002). Technologies serve pieces of equipment, the necessary scientific instruments to improve a product and are essential to the fulfillment of functions in other regime domains (markets, networks, infrastructures, culture, knowledge) (Geels, 2002). Thus for breakthrough technology there is supporting infrastructure because, in effect, for a technology to exist and survive in a socio-technical environment, whether the technology is 'wireless internet' or a 'diesel engine', the supporting function is the infrastructure that provides the necessary basis to penetrate in the socio-technical environment and thus disrupt lock-ins.

Determining the current state of affairs with regard to renewable energy deployment, as mentioned in indicator *'share of renewable'* provides the researcher insight about possible renewable sources that are currently most popular in the urban environment, and why. Thereby assuming that, obviously, non-renewable sources (fossil) will decline and renewable sources increase with the expectation that renewable sources will supersede fossil sources in the near future.

Geels (2002) argues that the nature of a transition is socio-technical, here the societal relevance is the **function** it serves. For instance, due to socio-technological advancement electrical energy can be distributed and thus consumed meeting demand. In case of a technological transition, the function will remain but the technology is replaced. The technology would cease to exist when the function (in this case consumption) ceases to exist.

These two core domains are interconnected by the **infrastructure** domain that could be interpreted as supporting strings between technology and function domains, without infrastructure both domains (function and technology) would become obsolete. It enables technologies to be applied and thus the function to work as intended.

The overarching domain **regime** can be understood as a marionette pulling the strings on technology, function and infrastructure paving the way for continuous development and directing those through governance. The domains have to be managed properly by the regime generally operating at the macro level that constitutes governments (municipalities or national) or electricity sector with influence to steer and control decisions. Regimes constitutes governments (macro) and local authorities and markets (micro) which are directly related to municipalities (meso). The regime governing the electricity sector in Europe is mainly top-down oriented (Glachant, 2009). This is the primary orientation that gains political and institutional support from the European Commission (Glachant, 2009).

The regime has the influence to manage, steer and govern other domains as technology, infrastructure and function their correlation will be briefly discussed. Hence the regime is an powerful organ that can make or break a transition.

2.3.7. System transitions and core domains

The acknowledgment of three core domains and one overarching domain is not uncommon in innovative transition theories. Scholars (Bergek et al., 2008) recognize the differences between the domains, **technology** *"socio-technical systems focused on the development, diffusion and use of a particular technology (in terms of knowledge, product or both)"* (p. 4), and **function** *"here labeled „functions" – which have a direct and immediate impact on the development, diffusion and use of new technologies"* (p. 5) and **infrastructure** "*complementary assets such as complementary products, services, network infrastructure*" (p. 21).

Similar domains have been applied in economic transitions, however it should be noted that every transition activates different aspects or underlying properties of the domains. By using hydrogen transition example and the process of the Hydrogen Initiative established pre-2000 also displayed in Figure 8 (Sperling and Cannon, 2004), we try to emphasize what factors seem to be important in an energy related transition. Additionally, the importance of interdependency and correlation between domains will be briefly highlighted because a full transition will only become a reality once all domains are 'aligned' and implemented to a certain level of socio-technological acceptance.

Figure 8 reflects the four phases (the S-curvature -Figure 5) in which the first phase (predevelopment) is described as R&D, this implies that the **technology** has yet to be researched and developed and deployed between approximately 2000 and 2030. Hydrogen technology is currently (2016) available to the market and should have enabled the technology to penetrate through markets.

Phase two (take-off) constitutes the transition into the marketplace. In case of the hydrogen transition we do familiarize us with a penetration in the vehicle industry and small household hydrogen applications for energy generation. Hydrogen vehicles are currently being produced and thus accessible to a greater audience. Hydrogen vehicles do not underperform compared to fuel combustion engine vehicles or full-electric vehicles, the **function** that it serves is equal to an existing product, transporting people from A to B using existing (paths) infrastructure.

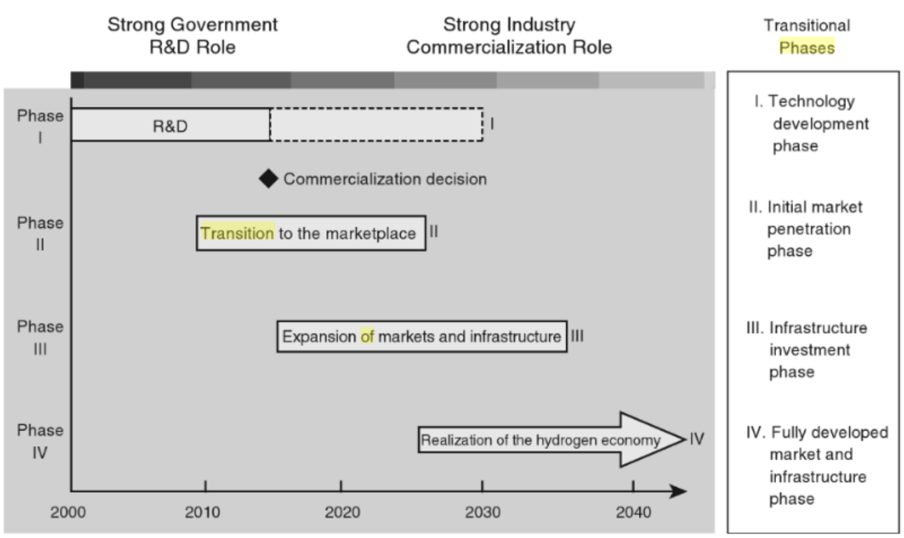


Figure 8 Transition process of hydrogen (Sperling and Cannon, 2004).

The third phase constitutes the expansion of markets and more importantly; **infrastructure**. Here we see the hydrogen transition stagnating, most probably due to lacking refueling infrastructure (Ross, 2002). Instead of relying on an existing infrastructure network, such as the electricity grid, hydrogen relies on a completely new set of refueling infrastructural components. In addition, the highly flammable substance needs to be stored continuously under extreme pressure which raises the cost of infrastructure significantly(Ross, 2002) and(Sperling and Cannon, 2004).

Consequently unsubsidized private sector investment has proven to be very limited. In regard to transport transition, ensuring travel range, quick and simple refueling may be the most critical technical infrastructural barrier to broad consumer acceptance (Sperling and Cannon, 2004). Thus the hydrogen transition imposes high risk and costly investments to overcome the pre-development phase. So what about the renewable energy transition to achieve a more circular energy metabolism? Scholars (Noothout et al., 2016) emphasize that countries with a 'low risk profile' have thus a low risk for renewable energy investments. Risk profiles are based on country risk, the policy design risk, other risks frequently mentioned in the top-3 risk categories are administrative risks (including permit procedures), market design & regulatory risks (including energy strategies and market deregulation), and grid access risks.

A system approach can be used to treat and analyze interactions in complex environments and transitions as a system such as the hydrogen example. The system approach is defined as "*group of interacting bodies under the influence of related forces*" or "*regularly interacting or interdependent group of items forming a unified whole*" (Merriam-Webster, 2016). In urban environment literature system approach is defined as; an ability to deal with interaction relations in complex environments (Cooper et al., 1971) – and to enable cities to better analyze their strengths and weaknesses and identify points for intervention (da Silva et al., 2012). The system approach stems from the principles of systems theory. System theory is a multidisciplinary study of the abstract notion of 'organization' of a complex interrelated system. The systems approach provides a broad perspective on factors and interactions. They support the understanding of the system by providing a snapshot analysis of the current situation. However, system approach does not (unlike multi-level perspective) address the dynamic aspect and relations between levels, nor does systems approach address system behaviors (Ulli-Beer, 2013).

Figure 9 System approach displays the abstract notion of a system that is characterized by a largely self-sustaining system (regime) in which subsystems (technologies, functions, infrastructures) operate. These subsystems are further subdivided by sibling systems.

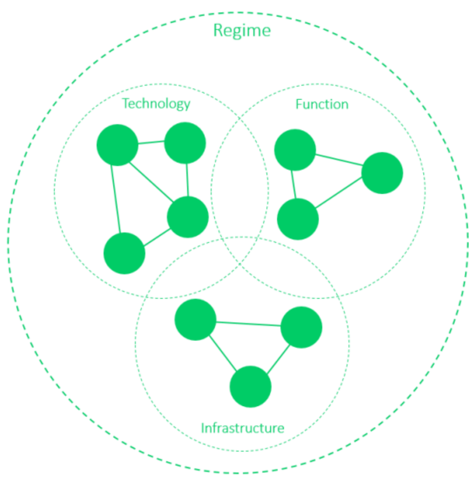


Figure 9 System approach

2.4. Renewable energy

This chapter elucidates the most conventional renewable technologies that generate useable electrical energy. Advantages and disadvantages with regard to energy conversions and application in the urban environment and more particular existing built environment are briefly discussed. Additionally, the renewable potential is discussed and elaborated. It is important to address the most conventional renewable technologies for further delineation and distinction between renewable and non-renewable sources and their potential in the urban environment.

A renewable source is defined as 'capable of being replaced by natural ecological cycles or sound management practices' or 'any natural resource that can replenish itself naturally over time, as wood or solar energy' (Merriam Webster 2016). In any sense, renewable sources uses natural resources which can thus be a biological reproduction or natural resources part of earth's environment. This study focuses on four renewable sources; wind – photovoltaic – biomass and geothermal energy, thereby excluding nuclear energy as a renewable source. Despite nuclear energy, a more or less a 'clean energy' source, its inclusion in the renewable energy list is debatable. The biggest argument against nuclear is that it uses fuel in the form of uranium, a finite resource and it produces harmful nuclear waste which goes against the notion of renewable being a safe and reusable source.

In addition, the research questions may best be answered when analyzing the renewable energy deployment in various cities. This can be measured by gathering data about the renewable energy technology rollout in the relevant municipalities. Various indicators are described in literature and renewable policy documents to measure "energy performance" as the development and goals for renewable energy share of heat or electricity in (%) (European Commission, 2016), and energy consumption and performance of buildings (kWh/m2) (Vera and Langlois, 2007). On the basis of the noted indicators an specific indicator is derived for this research:

Share of renewable sources	*Level: meso*	*Unit: %*

The percentage of renewable energy generation within the municipality includes data from various sources described in the next paragraphs. While the indicator share of renewable sources measures the current state of affairs, similarly, the researcher wants to gain insight about future renewable energy targets and thus future deployment of renewables. Therefore the indicator future share of renewable sources by (2040 or 2050) is derived.

Future share of renewable sources (2040)	*Level: meso*	*Unit: %*

Advantage and disadvantages renewable sources

One major disadvantage of renewable energy is the consistent and reliable conversion of large quantities of (electrical) energy (UNFCCC. Conference of the Parties (COP), 2015), solution for this is electrical energy storage (UNFCCC. Conference of the Parties (COP), 2015). However, the major advantage of renewable sources is the (net) zero emissions and contribution to a circular energy metabolism by decreasing the dependence on fossil fuels which relates to less extraction from the hinterland. To meet energy demand, the urban and non-urban environment needs to be drastically changed in order to situate sufficient quantities of renewable energy sources to meet energy demand prospected by (local) governments.

Most renewable technologies rely directly or indirectly on sunlight or the photovoltaic intensity, for wind and hydroelectric energy is the result of the sun heating up Earth atmosphere and surface. Photovoltaic panels convert sunlight to usable electric energy or heat for other consumption purposes. Bio(mass) energy is basically photovoltaic energy contained and stored by plants by natural metabolism. Geothermal energy depends on radioactive decay in the earth's crust combined with heat differences. The main renewable sources discussed in the following paragraphs are (on-shore)wind energy, photovoltaic energy, geothermal energy and bioenergy because these are the most usable renewable sources in urban environments. Other renewable sources such as wave-tidal, hydro are largely applied in non-urban environments (Siegel et al., 2010) However, energy generated in the hinterland may of course be transported and distributed to neighboring regions and municipalities, although this is accompanied by the restrictions linear metabolism possess. Restrictions such as transportation and management of directing energy.

Photovoltaic energy

Solar photovoltaic Panels or (PVs) are able to partly convert solar irradiation into usable electrical energy and is the 3th most generating type of electricity in the European Union (Eurostat, 2016.). The conversion occurs by photons absorbed in semiconduction materials that separate particles that serve as an energy carrier. Two main types of cells are currently on the market, silicon-based cells (Crystalline or Amorphous) and non-silicon based cells as Cadmium Telluride, Copper-Indium-Selene/Sulphate or other organic materials (Hoefnagels et al., 2011) PVs may be implemented in centralized systems by large quantities of PVs installations in rural areas, when considering PV systems in urban areas the system can be characterized as decentralized and off-grid systems. The overall theoretical resource potential of photovoltaic electricity generation appear to be vast, also seen in Appendix 4 Solar radiation and photovoltaic electricity potential. Southern Europe tends to have the most irradiation for obvious reasons, although the feasibility of generating usable energy can be defined as good for the entirety of mid-Europe.
Advantages: solar panels are easily applicable in urban environments due to the relatively small size of the panel and thus easy to integrate onto rooftops of buildings. However, one need to take into account the operating peak load of solar panels. The construction and assembly cost of photovoltaic cells is exponentially reducing in price due to mass market production, R&D and innovation. In addition, operating and maintenance cost is low, considerably lower compared to wind turbines per watt.
Disadvantages: generating a small amount of electrical energy requires quite a large amount of solar panel surface. Photovoltaic panels are generally subsidized to lower the price boundary for consumers. The question remains if tariff of photovoltaic panels drop significantly before most subsidies are halted. The future of PVs partly depends on subsidies and economic performance, electricity cost of PVs still exceed the cost of other renewable and conventional sources. Also conversion efficiency of the cells has a limited operating capacity between 8 and 25% (Hoefnagels, et al., 2011).

Wind energy

Kinetic wind energy can be partly converted to useable electrical energy by wind turbines and is the second most renewable generating type of electricity in the European Union (Eurostat, 2016.). Wind energy can be harvested on- and offshore and is dependent on wind speed. In addition, according to (Hoefnagels, et al., 2011) the regime possess a crucial factor that influences energy output. In urban environments, onshore wind-energy pose to be more difficult to situate because of spatial and environmental constrains.
Advantages: wind is a great resource for energy generation because they can be situated at locations where resource potential for wind is relatively high (Hoefnagels, et al., 2011) presented a wind energy potential map Appendix 3 Wind energy resource potential on which one sees that Western-Europe has a greater wind-energy potential compared to South-Eastern and inland-Europe, especially Denmark appears to have favorable conditions. In addition to applicability, wind turbines have a small construction base and can thus be situated in urban areas, might be it in non-residential areas as commercial and industrial zones depending on urban density.
Disadvantages: main disadvantage comprises the factor of reliability. Wind is, and always will be unreliable in terms of consistent and sufficient wind power. Considering the urban environments wind turbines form a social barrier in noise and skyline pollution. Protests and petitions are part of the development process and tend to delay certain wind energy developments. The regime may pose another disadvantage because it influences energy output.

Bioenergy

Biomass is a widely available resource and its utilization for conversion to usable electrical energy offers a solution to reduce harmful emissions by conventional sources. According to the definition of renewable sources, bioenergy is de facto a renewable source because it uses natural resources that can be replenished over time. However, it should be noted that the process of using biomass to generate electrical energy is not completely emissions free. Bioenergy is generated by burning biomass as wheats, crops or biodegradable household waste and gas like products, these are turned into heat or electricity by powering generators.

Here, we focus on Municipal-Solid-Waste (MSW) to be used as Waste-To-Energy (WTE), because municipalities and certainly cities generate mostly solid waste instead of other biowaste (Fischer-Kowalski and Hüttler, 1998). Municipalities as Amsterdam have operational bio-energy plants, these plants are labeled as 'renewable energy' because of low-emissions output. That said, using bioenergy plants in municipalities/cities is only economically feasible and environmentally when MSW is used to generate heat or electricity. If a bioenergy plant would solely consume biowaste specifically produced to feed the bio-plant, controversially, feeding a municipality the size of Hamburg requires a designated biosurface area roughly the size of New York city. Hence MSW is a more feasible option that contributes to a more circular metabolism is materials and energy instead of a bioenergy plant fueled by biowaste specifically grown to be used in the bio to energy process. MSW is being imported by consumers and there is sufficient MSW containing biowaste to be used in bioenergy plants.

Advantages: biomass contains quite a lot of energy when incinerated, thus high quantities of energy and usable electricity can be generated. In almost every EU country biomass (MSW) is the largest renewable energy contributor (Eurostat, 2016.). Transformation from existing fossil fuels, coal and gas fired plant to bioenergy plant is economically feasible. Consequently, over the past 10-15 years in the European Union, heat and electricity production from biomass increased with some 2% and 9% per year, respectively (Faaij, 2006). When considering urban environments, the greatest benefit of biomass is the incineration of recycled household waste. This waste-to-energy process reduces the ever increasing landfills and contributes to a more circular material metabolism of the urban environment, additionally the plants can be built close in proximity in urban areas utilizing local waste to energy (Siegel et al., 2010). WTE/MSW contains biomass materials as cardboard, paper, food, wood, leather and other non-biomass products as plastics. Both bio and non-biomass products can be used for waste-to-energy.

Disadvantages: firstly, as mentioned in the prelude of this paragraph, the process of creating usable energy from MSW is not completely emission free. Secondly, the creation of energy from biomass is not the most efficient process and the inputted materials are lost in its entirety. Thirdly, conventional biomass-to-energy requires a centralized energy plant requiring massive inputs of waste, large quantities of waste have to be transported that utilize fossil driven transport modes. Thus a biomassenergy plant is restricted to urban applications. These energy plants can be implemented in the urban environment but have to be situated in non-household areas thus industry like areas to minimize health risks (emissions) (Siegel et al., 2010).

Geothermal energy

Is essentially heat trapped deep inside earth's crust that can be forested by drilling wells in reservoirs consisting of hot water well above 65 degree Celsius where it condensates to steam (Dickson and Fanelli, 2006). Profitable geothermal systems can be found in regions with a slightly above average normal geothermal gradient, consequently very specific regions have potential to use this limitless energy source (Dickson and Fanelli, 2006).
Advantages: geothermal energy and the operation to extract hot water in the form of steam from the earth's crust is an environmentally friendly process. The reservoirs are naturally depleted thereby one can imagine a limitless source of energy.
Disadvantages: geothermal energy is an energy source not suitable for every country due to a strong variety of geothermal activity. Geothermal reservoirs can be depleted by extraction of steam. In addition to this, the reservoirs have to be managed properly to prevent depletion so to maintain operation throughout the year. Rapid depletion of the source can cause earthquakes and other seismic activities.

2.4.1. Renewable area potential

The advantages and disadvantages of renewable sources is essentially a mix of various renewable potentials. What defines renewable area potential? According to (Hoogwijk & Graus, 2008) the type of potential is defined and distinguished in five types. 1) Theoretical potential; this is the highest level of potential a source can develop to. This type of potential takes into account restrictions with regard to climatic and natural factors. 2) Geographical potential; the geographical restrictions such as land use reduce the theoretical potential. Thus the geographical potential is the theoretical potential limited by natural resources at geographical locations. 3) Technical potential: technical limitations as conversions rates, efficiency affect the technical potential. 4) Economic potential: whether the product/technology is costly and competitive. 5) Market potential: implies the market penetration while taking into account possible variables as energy demand, competing technologies, costs and subsidies and other (non)barriers (essentially the transition itself).

This study focuses on aspects in geographical, technical and market potential thereby excluding theoretical, economic potential. Because of time constrains the study will not go into fully investigate all aspects of the above mentioned potentials. Geographical, technical and market potential are included because aspects in these potential sorts are necessary to measure the degree of circular metabolism.

Firstly, geographical potential is important because it takes into account the land use, land cover and related limitations which make up the urban environment. Each city/municipality has unique limitations in terms of available area for renewable applications in the urban environment. Secondly, the study aims to understand the total amount of energy that may be generated in the urban environments as well as their future potential. Thirdly, the study includes aspect of market potential such as the demand for energy, other competing renewable technologies and the effectiveness of implemented policies. On the basis of these arguments an indicator Renewable Area Potential is presented;

Renewable area potential	*Level: meso*	*Unit: m2/inhabitant*

This indicator will measure the theoretical amount of available area for the deployment of renewable energy sources and will be expressed in square meter per inhabitant.

2.4.2. Transmission, distribution and storage

In a circular electrical energy metabolism the prime importance is the transmission and distribution of the 'product', in this case electrical energy via its infrastructure. Reliability of the grid is crucial when dealing with complex systems as the grid (Rosas-Casals and Corominas-Murtra, 2009) due to its shear dynamical effects that may cause blackouts, economic and human losses (UCTE, 2016). The transition from conventional to renewable sources and thus the increasing deployment of renewables may have negative consequences for the traditional infrastructure network and requires new strategies for the operation and management in order to maintain quality of energy supply. Because the increasing deployment of renewables leads to volatile electricity output, which in turn can cause the aforementioned dynamical effects. To address this issue accordingly, a large amount of spinning reserve is required to maintain the reliability of the grid (Yan, 2015). Spinning reserve is defined by Wood and Wollenberg as 'the total synchronized capacity, minus the loses and the load' by Zhu, Jorden and Ihara as 'the unloaded section of synchronized that is able to respond immediately to serve load, and is fully available in ten minutes'. Solution to a volatile grid is the availability of spinning reserve, practical spinning reserve solution is the battery storage. However, large scale development of storage is still underdeveloped, and thus, while humanity deploys increasing amount of renewables, practical spinning reserve cannot address large scale peakload at this point in time. Other applications of spinning reserve is the traditional coal and gas-fired plants that are modified to able to kickin within minutes to balance out the grid. Without spinning reserve, the grid is exposed to failure affecting reliability and thus the security of electrical energy supply.

In the regard of reliability, the grid can be assessed as 'robust' or 'fragile' (Rosas-Casals and Corominas-Murtra, 2009). Security supply is defined as *"the probability that electricity is available when demanded by* *consumers"*(Danish Energy Agency, 2015, p3). The security and consistency of the flows in relation to the technologies and well-developed infrastructure to support this, the transition was able to set firm foot into society. As a result we suggest the following indicator to measure the security of electricity supply by considering the amount of mins/interruption of the grid. Time of interruption is an indicator used to measure partially robustness of the grid. Therefore we suggest the following indicator to measure the performance of the grid networks on macro level.

Security electricity supply	*Level: macro*	*Unit: min of interruption*

To conclude, every renewable energy source has highly heterogeneous resource characterizes regarding efficiency, (spatial)applicability and future potential. For urban environments photovoltaic energy appears to be the most interesting source to implement due to its applicability in the urban environment itself as well as applicability for buildings. However, their energy generation capacity is small. According to (Ragwitz et al., 2012) the top 3 largest potential source by 2030 in the EU-15 is wind energy (40%) directly followed by photovoltaics (17%) and biomass (15%). However, wind and bioenergy are spatially limited in the urban environments.

Though bioenergy can be fueled by either directly consumed biodegradable waste or MHW, the latter is an important difference for reasons mentioned in the bioenergy paragraph. One may argue that the degree of renewable energy implementation in non-urban areas is more developed compared to urban areas simply because of (spatial, social, e.g.) restrictions. But on the contrary, data suggest that various cities already have gone 100% renewable and are thus actually the frontrunners of renewable energy implementation instead of the hinterland as an entity.

Therefore the study focuses on; photovoltaic energy, wind energy, bioenergy and geothermal energy and aspects of geographical, technical and market potential. The emphasize in the urban environment will mostly consider solar and wind energy because of the applicability. Bio- and geothermal energy is less applicable in urban environments and therefore restricted for future purposes.

2.5. Built environment

As explained in the introduction, roughly three sectors can be distinguished that are responsible for consumption of energy: industry, transport and the built environment (Opstelten et al., 2013). All sectors are equally important to improve in order to transition to a near full circular energy metabolism. The built environment and more in particular, existing built environment offers great opportunities (Geels, 2005). This chapter describes the energy applications in the built environment.

Existing buildings account for approximately 40% of the total primary energy consumption worldwide (UNEP, 2016), and about 24% of CO2 emissions in developed countries (IEA, 2016), although the UN debates that buildings account for 33% of CO2 emissions (UNEP, 2016). Though in any sense, we can safely assume that existing buildings account for at least 1/3th of world's energy consumption, and about 1/4th in the developed world in which fossil fuels account for a large proportion of energy consumed. The building sector is one of the largest consumers of energy in the European Union, consuming over 29% of final energy consumption (European Environment Agency, 2016). The forecast exists that by 2050 at least half of the buildings that will be in use have already been built in the EU. While the scientific community has now recognized that energy use in buildings relates to a reduction of total fossil energy consumption with associated GHG emissions (Sheila et al., 2005).

Improving existing building energy consumption consist of two synergistic approaches: (I) reduce energy consumption through the implementation of energy efficiency (savings) measures and (II) to compensate the remaining building energy demand through the use of renewable energy systems (IEA, 2016) also put forward by (Girardet, 1996) to improve circular energy metabolism.

Energy efficiency measures prompted growing interest amongst policy makers, consumers, scientists, general public and the technical community in addressing and investigating approach (I) extensively. Energy efficiency measures such as decreasing building operational cost over a longer period of time has been incorporated as early as the 1960s. Approach (I) was applied before approach (II) because the investment and energy saving that can be reached is significant and is approximately half of the cost compared to installing renewable energy (IEA, International Energy Agency , 2016).

Approach (II) has been incorporated in the socio-technical environment for only a couple of decades. This is mainly due to the in-synchronous development of both measures – to the larger audience, renewable technology simply was not economically viable until the early 2000s. The supplementary effects and progression of measure (II) in a socio-technical urban environment have yet to be fully understood. Currently, renewable technologies account for almost 7% of the world's total energy demand (IEA, International Energy Agency , 2016). Here, huge improvements to reduce fossil energy demand by incorporating renewable energy resource flow can be made. Therefore we stress the importance to gain a better understanding of how to activate, and the aspects involved in increasing a more circular energy metabolism by the application of renewable energy in the built environment in the residential household sector. On the basis of the section above, an indicator is suggest to measure the electricity household consumption in municipalities.

Electricity household consumption	*Level: meso*	*Unit: kWh/household*

This indicator is also utilized by (International Atomic Energy Agency, 2005) to measure efficiency levels for households, usually over a period of time.

Moreover, the it has been debated that an increase in renewables affect the electricity tariff (Garen et al., 2011). The tariff is consequently related to the amount of electrical energy consumed and is therefore an important indicator of the status of a electricity grid and thus consumption of its energy metabolism.

The electricity tariff is the pricing structure charged by the provider. The tariff in an important aspect of the social-accessibility of electrical energy for households. High tariffs ensures less economic accessibility that may bare the consequence of decreasing consumption because of affordability of the product. Low tariffs accommodates a high economic accessibility to electrical energy as a product, in other words, quantity of demand for energy decreases with increases in tariff (Garen et al., 2011). Additionally, the Municipality of Amsterdam gave rise to a new term related to the expenses of energy: 'Energy Poverty'. Which denotes a situation where low-income households spend more than 10% of their net income on energy bills (Municipality of Amsterdam, 2015). The bill includes gas and or other energy commodities of which electrical energy makes up approximately 40/50% of the bill (CBS, 2016.). Measuring the tariffs will be an indicator for this research and will be done so on national (macro) level.

Electricity tariff households	*Level: macro*	*Unit: €/kWh*

The referenced indicator is interpreted from the perspective of households and thus consumers interests. Although taxes upon the electricity tariff has been rising steadily, the raw electricity tariff that electricity businesses profit on is declining. It has been debated that a deficit in electricity tariff poses dangers to the conventional electricity operators and would therefor require a higher electricity tariff. However, from a consumer perspective a high electricity tariff affects electricity consumption negatively.

Furthermore, the vast majority of scientific literature on electrical energy tariff shows many different views that it would be inherently difficult to investigate an optimum for electrical energy tariffs. Because we study socio-technical transition, and thus reasoning from a social and technical perspective, the researcher assumes that a lower tariff is more optimal for consumers and thus the process of transition because it allows for a better accessibility in renewables. If the tariff were to become increasingly high and the lower brackets of society, which makes up the largest proportion of EU member states, would minimize demand (decrease revenue for renewable technologies).

2.6. Conclusions

Electrical energy in urban systems is the core area of interest which is defined as '*the usable power that is derived from any form of primary or secondary source which may be used in physical systems to work and move*.' This is investigated by specifying conventional renewable (RES) sources as wind energy, photovoltaic energy, geothermal energy and bioenergy and non-renewable sources that deliver the usable power in an urban system.

The concept of urban metabolism is utilized so to understanding complexity in cities with regard to the energy flow, understanding this flow supports sustainable city planning (Spiller and Agudelo-Vera, 2011). Whereas a linear metabolism is characterized by the input of various resources occurs without activating the function of reuse/recycle, a circular metabolism is characterized by the latter; reuse/recycle or in the case of an energy metabolism generate energy by using natural resources. Thus an urban energy transition implies transitioning from a linear to circular urban energy metabolism thereby generating energy 'locally' from natural resources. The transition toward a circular energy metabolism entails a full system transition of an existing system or regime that is stabilized through path-dependence and lock-ins, a full transition is thus difficult to effectuate.

The research emphasizes various municipalities that for the most part is investigated at the mesolevel. This level is, focused on optimizing rather than transforming systems by for instance actors that operate utilities, the Ministry of Environmental Affairs or the local Municipal government and households as a collective entity (Geels, 2005). Although research will sporadically shift to the macro-level for obtaining data which is not available at mesolevel.

In a Municipality the sectors industry, transport and the built environment (households) are responsible for the consumption of energy. These sectors are equally important to improve to transition towards a more circular metabolism in which the built environment offers great opportunities for optimization. Therefore the focus within municipalities is the built environment and more particularly households.

The need for a rigorous method to measure the degree of energy transition is inherently critical to delivering guidance for optimization of existing urban systems and to accelerate the energy transition. By comparing different European municipalities the research endeavors to gain a better understanding as to what extent the reference city Amsterdam meets the objective of transitioning towards a circular energy metabolism by 2040. Additionally, observing which factors contribute to a successful sustainable energy transition and the differences between European municipalities should lead to a more conclusive elements for successful sustainable energy transition.

Method to measure the degree of energy transition originates from three core domains (technology, infrastructure, and function) and one overarching domain (regime). Development and optimization of all core domains are necessary for full system transition. Therefore the method consists of these core domains supported by the identified indicators.

Table 1 Examples of functions, infrastructures, technologies and regimes

Technology	**Function**	**Infrastructure**	**Regime**
Photovoltaic – wind – hydro	Power supply	Electricity grid	Electricity sector
WIFI	Wireless internet	Ethernet	Internet sector
Combustion engine	Car transport	Roads	Public transport sector

The example as seen in Table 1 Examples of functions, infrastructures, technologies and regimes, emerging technologies of wind and photovoltaic electricity generation enabled us to generate clean electricity. Function in this matter is providing the necessary electrical power to meet the increasing (worldwide) electricity demand. The infrastructure permits a seemingly smooth distribution of the product because of the existing grid in place. The second example, technology enabled mobile phones to work wirelessly, connecting people all over the world. This alignment was made possible by an ever increasing infrastructure network. WIFI is one of the technologies that enabled us to transfer data wirelessly (Ethernet). Due to technological advancement, a wireless local area network was established. The infrastructure, or in this example Ethernet, needed to expand because of an increasing technology rollout and thus increasing use of the function.

“The shift to a cleaner energy economy won’t happen overnight, and it will require tough choices along the way. But the debate is settled. Climate change is a fact.”

Barack Obama – former president of the United States

3. Methodology

This chapter emphasizes the applied research methods, the chosen study design and data collection followed by the selection of cases and related indicators. The latter is also part of data topics to be collected and analyzed. To answer the GRQ 'to what extent will the city of Amsterdam meet the objective of transitioning towards circular energy metabolism by 2040?' a number of suitable choices are made with regard to the research design, data collection and procedures.

3.1. Research design

The research GRQ question is mainly focused on answering "how and why". According to Yin (Yin, 1993) a case study is preferred to answer this kind of questions. Moreover, other conditions that point into the direction of using a case study are: (a) not able to manipulate the behavior of those involved in the study, and (b) to cover contextual condition because they are relevant to the phenomenon under study or (c) boundaries are not clear between phenomenon and context (Yin, 1993). With regard to (a) we will not study human beings or animals, but an urban environment and (complex) socio-technical systems (b).

Yin identifies some specific types of case studies: exploratory, explanatory, descriptive, instrumental, collective, multiple and intrinsic case-studies. Descriptive multiple case study is selected for two main reasons. Frist, the goal set by the researcher is to describe the data as they occur (McDonough, 1997). Describing the factors that contribute to an energy transition and describing the comparative case study. Second, to develop an understanding of how transitions come about and why do transitions become successful in a bounded system.

Because the context of the study is part of the design there will always be too many variables to assess, therefore the application of standardized experimental design or surveys to derive results are not appropriate (Yin, 1993). However, although issues of validity and generalizability will still have to be addressed properly (Yin, 2003).

3.1.1. Multiple case study design

Case studies offer a flexible solution to collect quantitative and qualitative data. Quantitative such as statistics and figures, qualitative as in observations, notes, and websites – both are generated in this study. A multiple case study is preferred over single case study; this offers robust analytical conclusions which increases external validity (Yin, 1993). Yin also emphasizes that results may be strengthened by using multiple case studies thereby increasing the robustness of the findings. Two approaches to establish replication logic are called literal and theoretical replication. The approaches can be using to further strengthen the research design (Yin, 2003).

Also, replication logic provides statistical validation because multiple case studies rely on more analytical values instead of statistical values. The goal of a multiple case study is to replicate findings across cases or predict contrasting results (Yin, 1993). In this research, we will attempt to replicate findings because the degree of urban energy metabolism transition in all cities is *de facto* linear. If we were to predict contrasting results, this would imply circular metabolism already characterizes in one of the cases.

Although the research will predominantly consist of quantitative data, qualitative data will still be part of the investigation. To operationalize the collected quantitative and qualitative data separately a mixed method approach is applied., this benefits both quantitative and qualitative aspects, enables triangulation (Creswell J. , 2014). Denzin (1978) discussed four types of triangulation: theory triangulation (using multiple theoretical perspectives to interpret results of the study), methodological triangulation (using multiple methods to study the research problem), investigator triangulation (using multiple researchers) and data triangulation (using a variety of data sources). In this study methodological triangulation was used because of the combination of QUAN + qual in this study.

3.2. Data collection and procedures

Keeping in mind that the data collected is primarily quantitative (QUAN) of nature whereas the secondary data is mostly qualitative. Figure 10 Mixed method approach displays a brief overview the research design of the separate mechanism of quantitative and qualitative data. First, data is collected and identified as qualitative or quantitative. Because most data will be quantitative, qualitative data will support the quantitative data and results. Second, mixing data both data strains together to form a tangible dataset. Third, data will have to be merged for comparative analysis. The next section displays a more in-depth understanding of the data collection and procedures.

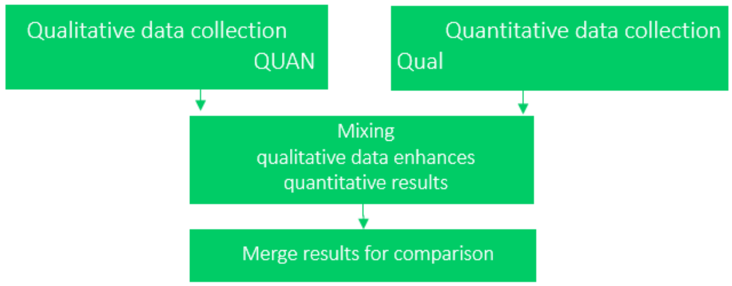


Figure 10 Mixed method approach

According to (Creswell, 2014), four steps are done concurrently to conduct this research design. Step one involves the design of quantitative and qualitative strand-state by identifying the majority of data as quantitative or qualitative. Step two comprises analyzing the strands separately. Step three can be fulfilled by using strategies to merge results, merge of both datasets to compare/contrasting results. Step four is to produce a better understanding of the obtained results. It is here that both datasets are summarized, discussed, merged and interpret correctly. Individual quantitative indicators are compiled from the theoretical framework and meticulously classified in categories/domains.

3.2.1. Indicators

The information in this section is intended to put forward a set of indicators to measure the circularity of the (electrical) energy metabolism in the urban environments by using and referencing to existing indicators commonly utilized in measuring concepts as energy efficiency, energy performance, urban metabolism and sustainable urban development. In its infancy of the research, it became clear that no comprehensive list of indicators was found for the measurement of electrical energy metabolism nor the degree of a transition in urban systems. Consequently, the list Appendix 8 Dependency is complemented by indicators from literature.

As mentioned in paragraph 2.3.6 transition processes can be explored and described in various ways. To provide an overall comparison of the cases; the collected information is clustered in core-dimensions; (1) technology used (2) function it serves (3) infrastructure that is needed (4) regime that has to manage it (Ewijk, 2013) and (Geels, 2005). These core dimensions are complemented by indicators derived from literature and institutions. Indicators from this table will be used and made suitable for quantified research application as shown in the table below.

Additionally, the level of which the information per indicator will be derived ranges between meso and macro. Information for several indicators is not available at the desired mesolevel. Data retrieved from macro-level sources poses a limitation.

Table 2 level of measurement – indicators for the degree of renewable energy implementation

Level of measurement – Indicators for the degree of renewable energy implementation			
No	Dimension with related indicator	Level	Unit *(year)*
K1	Technology	Micro/Meso/Macro	Analysis
K1.1	Share renewable sources	Meso	%
K1.2	Future share renewable sources (2040 or 2050)	Meso	%
K2	Function		
K2.1	Electricity tariff households	Macro	€/kWh
K2.2	Electricity consumption inhabitant	Meso	kW/inhabitant

K2.3	Electricity consumption household	Meso	kW/household
K2.5	Renewable area potential (RAP)	Meso	m2/inhabitant
K3	Infrastructure		
K3.1	Security electricity supply	Macro	Mins/interruption
K3.3	Dependency electricity (self-sufficiency)	Macro	% in-export
K4	Regime		
K4.1	Renewable energy investments - expenditures	Macro	% of GDP
K4.2	Level of ambition- renewable electrical energy policies	Macro	# active policies

3.2.2. Multi Criteria Approach - BOSDSA

Once the right information with regard to indicators is gathered, qualitative data (qual) has been quantified (QUAN) and content analysis is completed, merging data is the next step. To merge data the researcher applied the computer program BOSDA, a Dutch acronym for (Beslissing Ondersteunend Systeem voor Discrete Alternatieven) or (Decision Support System for Discrete Alternatives). In this program a Multi Criteria Approach (MCA) is applied.

MCA holds two important characteristics, the first characteristic involves different evaluation criteria (indicators) in different weights. Criteria's may vary and corresponding criteria scores (units) are mostly different as seen in the table. A second characteristic accounts to the fact that a criteria may be weighted more compared to other criteria. A more important criteria should, obviously, have a more important and weighted impact in the overall result.

Therefore MCA is useful for this study because it supports the analysis of design involving quantitative and qualitative data. Furthermore, in a MCA data can be merged by intermediate values that enable further analysis and derive robust standardized weighted results to process monetary and non-monetary data (Kumar, 2011) and (Hellendoorn, 2001). Non-monetary simply means "no cash" like value, which can thus be expressed in different qualitative manners. Additionally, MCA is helpful in the aiding of specific information and giving an overview of information by providing systematic tables with scores, which can even be easily understood.

In the realm of MCA's a couple of methods can be applied to process data. This research applies the weighted summation method because quantitative data can be easily used for comparison and derive results, moreover, this method is one the manageable and orderly methods to carry out and suits the data that is forested, easy to explain and transparent (Hellendoorn, 2001). The mathematical underpinning of the weighted summation for each adaptation option is calculated by multiplying scores according to their weight followed by summation of weighted scores of all criteria.

$$score(a_j) = \sum_{i=1}^{N} w_i (s_{ij})$$

In this equation, *score (aj)* resembles the total score for each alternative, *N* resembles the number of criteria, *wi* is the weight of the criterion *ci* and *sij* denotes the score for alternative *aj* with respect to criterion *ci* (Hellendoorn, 2001). A couple of steps apply to the method of MCA and weighted summations which will be extensively elaborated in the next section.

Steps that apply to the method of MCA weighted summations (Hellendoorn, 2001):

1. Formulate alternatives and criteria
2. Standardization of the scores.
3. Determine weight per indicator
4. Multiply weights with standardized scores
5. Calculate total score per alternative
6. Determine the position for each alternative

Formulate alternatives.

First the alternatives (cases) will have to be determined. Besides the reference case Amsterdam two other cases had to be selected for which a brief procedure was designed.

The procedure goes as follows; a total of eight municipalities were selected for possible in-depth case study. The eight selected cities comprise: Paris, Riga, Helsinki, Stockholm, Oslo, Hamburg, London and Copenhagen. These have all have equally interesting ambitious renewable energy policies for renewable energy generation and have implemented renewable technologies that contribute to the total energy mix demand. This was further dilated to a wide range of comparable criteria in order to select the best comparable cases.

The following criteria are presented: (1) population: this includes the total population number and population density (2) GDP, gross domestic product per capita and investment compared to GDP in renewable technologies (RETs). (3) Renewable resource potential, this includes the majority of climate characteristics as defined by (Kottek et al., 2006) such as average yearly temperature, average yearly sun exposure, irradiation per kWh/m^2, average yearly wind speed, climate typology, precipitation, river-based or sea-based cities. (4) Number of active renewable energy policies. (7) The cities are situated in countries member the European Union (EU) thereby subjected to EU regulations. (6) Data availability and consistency. Consequently the five most comparable cities were revised and closely analyzed.

Based on these criteria Amsterdam, Copenhagen and Hamburg were selected to be included in the case study. Amsterdam is the baseline city. Copenhagen is chosen for its excellent comparability amongst all criteria including the amount of implemented renewable sources, its ambitious targets (carbon neutral by 2025 – 100% renewable energy by 2050) and because Copenhagen is becoming a testbed for green solutions. Hamburg is chosen for similar reasons, Hamburg has relatively the most implemented renewable energy capacity of all selected cases, although the population amount deviates quite strongly with our reference case Amsterdam. The other cases deviate quite strongly from the main criteria – or in case of the city of Stockholm, which has excellent renewable policies and implemented energy sources had insufficient data available at the municipality level. Moreover, after a brief analysis it appeared Stockholm imported over 85% of its energy from the hinterland generated by hydro. Altogether the similarities and differences between Amsterdam, Copenhagen and Hamburg allow for interesting comparison and analysis.

Standardization score per criteria.

Now that the alternatives are crystalized, standardization score per criteria can be stipulated. Since the criteria's (units) are measured inherently different, no comparable results can be derived at face value. Therefore the units will have to be made comparable; standardization. Standardization is essential to form equal weights for each unit. After standardization the new value of an indicator ranges between 0 and 1. Value 0 is the least optimal result and value 1 is the most optimal result. Standardized scores may display a certain value or utility but must use specific valuation or utility functions. A score of 0.56 does not imply it is slightly above average, it means, given the alternatives and criteria, it is rated at the middle of the optimal situation. To execute standardization, minimum and maximum range will have to be set. Minimum and maximum range is unique for each indicator and determined on the basis of minimum expected/active value vs maximum expected/active value.

Table 3 Indicators minimum - maximum range and weighted summation

Level of measurement – Indicators for the degree of renewable energy implementation					
No	Dimension with related indicator	Unit *(year)*	Minimum range	Maximum range	Weight
K1	Technology	Analysis			
K1.1	Share renewable sources	%	0	20	0.200
K1.2	Future share renewable sources (2040 or 2050)	%	0	100	0.100
K2	Function				
K2.1	Electricity tariff households	€/kWh	0.09	0.50	0.050
K2.2	Electricity consumption inhabitant	kW/inhabitant	2000	15000	0.100
K2.3	Electricity consumption household	kW/household	1200	3200	0.100
K2.5	Renewable area potential (RAP)	m2/inhabitant	0	100	0.100
K3	Infrastructure				
K3.1	Security electricity supply	Mins/interruption	0	600	0.050

K3.2	Dependency electricity (self-sufficiency)	% in-export	-25	25	0.050
K4	Regime				
K4.1	Renewable energy investments - expenditures	% of GDP	0	3	0.150
K4.2	Level of ambition- renewable electrical energy policies	# active policies	0	11	0.100

- K1.1. Share renewable sources; minimum 0, maximum 20% *(current optimal situation with regard to future targets and human activities to maintain a maximum of 2C degrees this century).*
- K1.2. Future share renewable sources; minimum 0, maximum 100% *(most optimal situation and thus 'full circular metabolism').*
- K2.1. Electricity tariff households; minimum tariff in the EU €0.09/kWh in Bulgaria *(optimal situation in perspective of households),* maximum and least optimal situation is a tariff of €0.50/kWh
- K2.2. Electricity consumption inhabitant; minimum electricity consumption in the EU is approximately 2000 kWh/inhabitant (optimal situation), maximum consumption 15000 kWh/inhabitant
- K2.3. Electricity household consumption; minimum household consumption in the EU is 1200 kWh/household/per person (optimal situation), maximum is 3200 kWh/household/per person (optimum determined by (Nielsen, 2009).
- K2.4. Spatial energy potential; minimum is 0m2/inhabitant, maximum is 100m2+/inhabitant (optimal situation)
- K3.1. Security electricity supply; minimum mins of interruption is 0 (optimal situation), maximum is 600 (Romania, Latvia) (CEER, 2015).
- K3.2. Dependency electricity; minimum -25% (optimal situation), maximum 25%
- K4.1. Renewable energy investments (R&D); minimum 0%, maximum 3% of GDP
- K4.2. Level of ambition, renewable energy policies; minimum 0 active policies, maximum 11 active renewable electrical energy policies in the electricity sector Spain (International Energy Agency, 2016a).

Determine weight per indicator

Once standardization process is completed and scores are comparable, the next step is to weight the criteria. Purpose of weighting is that indicators have different weights, so to indicate the importance of one indicator compared to other indicators. The allocation of giving weight values of 0.05 - 0.1 - 0.15 - 0.2 is not an exact science and is often purely determined from an objective perspective (Hellendoorn, 2001). Here, the most weighted indicator is share of renewable sources because this indicator reflects the current state of affairs of municipalities with regard to its renewable energy application and transformation status. This indicator also directly reflects the amount of conventional sources. Obviously, municipalities with a greater amount of applied renewables is more transitioned, therefore this indicator has the highest weight allocated.

Multiply weights with standardized scores

A function in BOSDA allows for the standardized scores to be multiplied by the corresponding weights and added together. The purpose to multiple weights is to derive a resulting total score for each alternative which can be ranked against other alternatives, so to obtain a picture of the optimal situation in comparison to other alternatives.

Calculate total score per alternative (case) & determine the position for each alternative

The extent to which criteria are weighted in the end result is determined in the final score of each alternative. This is visualized in the next chapter by using graphs for each alternative and will be positioned according to the most optimal alternative.

3.3. Validity and reliability

Choices made in this research and methods have influence on validity and reliability. This section addresses the aspects that affect both.

When results are derived from BOSDA, a sensitivity analysis is carried out. The purpose of a sensitivity analysis is to determine whether and which information dissolved throughout the process of applying weights and standardize results so to determine the robustness of the acquired results. Sensitivity analysis plays a crucial role in assessing the robustness of the results or conclusions based on primary analyses of data. Although BOSDA is regarded as an excellent tool for multicriteria analysis in the past, new versions of BOSDA showed several bugs and glitches that hindered a full sensitivity analysis. The bug/glitch prevented an automatic sensitivity analysis. Therefore a manual sensitivity analysis was carried out according to a well elaborated BOSDA report from (Reinshagen, 2007).
Manual sensitivity analysis is carried out by repeating steps to acquire different deviations as seen in the figure below. Relevant information subjected to the sensitivity analysis consists of the arrangement between municipalities by the assigned values. Tiny changes should occur by changing the weighting system thereby testing the robustness of the arrangement. However, the arrangement of municipalities (number 1,2 and 3) should be similar regardless of changed weights. Figure 11 displays the weights, and sum of the scores for each sensitivity deviation. A more readable figure is shown in **Error! Reference source not found.**.

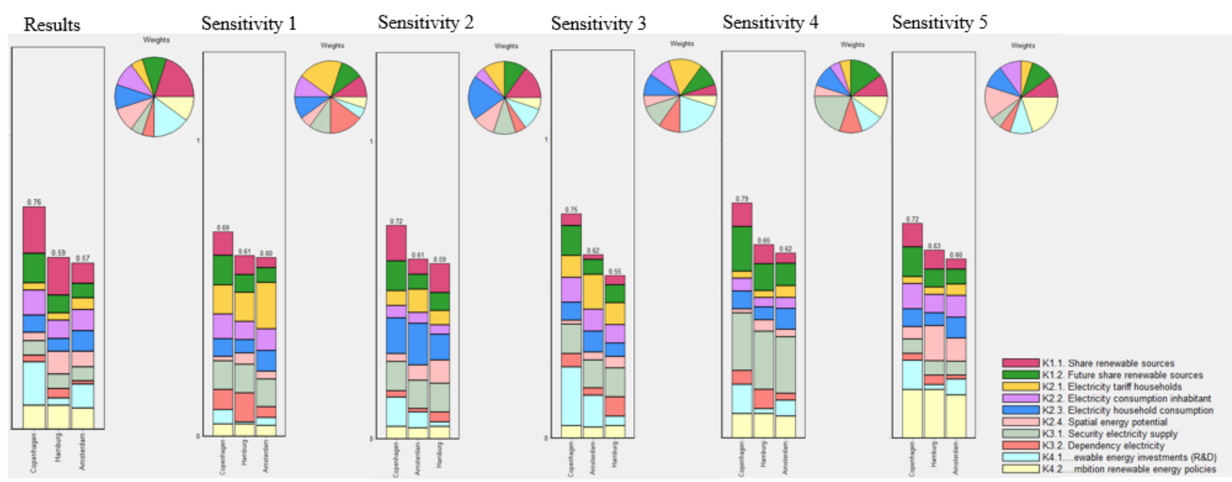


Figure 11 Sensitivity analysis weighted summation

From the comparison in the figure shown above, the percentage of change is calculated as shown in. The Reinshagen 2007 report does not imply there is an optimal or acceptable deviation. Most acceptable deviations range between 0 and 20%. Surely, the smaller the deviation, the more acceptable results. Here the most notable changes are derived from Sensitivity 1 (S1 Copenhagen) 9.21% and (S4 Hamburg) 10.16% deviation. This noticeable deviation is due to the change weight from indicator K1.1. to K2.1. and vice versa. Hence S1, Copenhagen scored less because the weight was allocated to the indicator K2.1. Similar underlying reason apply for the 10.16% deviation in Hamburg S4. Yet, despite the deviations the arrangement equal to the original score and sensitivity analysis shows acceptable deviations. Thus we can say with high degree of certainty that the results are robust.

Table 4 Scores and change % weighted summation

Case and original score	S1	% Change		S2	% Change		S3	% Change		S4	% Change		S5	% Change
Copenhagen 0.76	0.69	9.21		0.72	5.26		0.75	1.31		0.79	3.94		0.72	5.26
Hamburg 0.59	0.61	3.40		0.61	3.40		0.62	5.08		0.65	10.16		0.63	6.77
Amsterdam 0.57	0.60	5.26		0.59	3.50		0.55	6.77		0.62	5.08		0.60	5.26

3.3.1. Validity

The research design and related choices made have an impact on both the external validity. Internal validity can be affected when applying explanatory or exploratory case studies and the extent to which data collection method accurately measures what it intends to measure (Kumar, 2011). Internal validity is thus only relevant when researchers are trying to find a causal link to an effect (Kumar, 2011). Descriptive studies and observations merely report situations.

External validity is an important aspect of quantitative research because the aim is to generalize results and conclusions. Yin (1994) and Kumar (2011) emphasize that multiple case study strengthens the results by replication. To increase the robustness of the findings of which there are two replication techniques, literal and theoretical replication. Case studies rely on analytical findings rather than statistical generalizations.

As mentioned in paragraph 3.1.1, this research we will attempt to replicate findings thus using theoretical replication methods. The threat to theoretical replication may lay in the consistency and data availability, which may pose difficulty in this research because the researcher attempts to find homogenous data sets with regard to municipalities, the majority of homogenous data sets are at national level: Eurostat, Worldbank e.g. . Merging data from various sources, consisting of different units may affect external validity when not considered the converting calculations and interpretations properly.

3.3.2. Reliability

Reliability demonstrates that the operations of a study and can be thought of as consistency – such as the data collection can be repeated with the same results (Kumar, 2011). A threat to the degree to which this design may be repeatable lays in the fact what the definition of a municipality is in the observed country (size and population). Another threat to reliability in this research consistency with regard to renewable energy generation/conversion. Municipalities do not always clarify or disclose the exact generation of renewable energy, often peak-production is given as true-yearly round production. In order to minimize this threat, every figure and fact checking is needed. This implies direct contact and verification of data by the municipality in question.

"The total amount of energy from outside the solar system ever received by all the radio telescopes on the planet Earth is less than the energy of a single snowflake striking the ground"

Carl Sagan – astronomer, cosmologist, astrophysicist, astrobiologist

4. Case analysis

This chapter provides a description of the empirical analysis for each case. The results of the identified factors – technology, function, infrastructure and regime and its underlying factors are elaborated. First, results of Amsterdam (4.1) are described, second Hamburg (4.2) and third Copenhagen (4.3). Each chapter ends with a summary to provide an overview of the important findings. This chapter ends with the interpretation of results (4.4) in an effort to describe important findings.

4.1. Results Amsterdam

4.1.1. Technology

Share of renewable sources

The municipality of Amsterdam generates a total of approximately 10014 GW of electrical energy a year (2014). Renewable energy accounts for (7%) and non-renewable sources account for (93%) respectively. The share of renewable sources comprises 21% wind energy, 2% photovoltaic energy and 77% bioenergy respectively, calculations and references can be found in Appendix 6 Renewable electricity data per city. The leading renewable technology deployed is bioenergy. Electricity and heat are generated by incinerating municipal household waste. It's evident that without bioenergy the city of Amsterdam would generate considerably less renewable energy.

Renewable electricity generation in the municipality is slightly above the national generation of renewable sources 5.5% (Eurostat, 2016.). This is remarkable because one would imply the spatial capacity of a city is less compared to a country as a whole, thereby the spatial availability to implement renewable sources should in theory pose more restrictions and is therefore limited. However restrictions are not accountable when considering a centralized bioenergy plant generates the majority of renewable energy as in Amsterdam.

Non-renewable sources such as energy carriers gas and coal are the predominant energy source for the municipality of Amsterdam. The predominant renewable source is bioenergy fueled by municipal household waste. Inside the municipality the bioenergy plant (AEB Amsterdam) is situated and generates electricity for municipal consumption. Both the electricity and heat is generated by biomass; household waste and other organic biodegradable substances. AEB collects waste from the metropole region of Amsterdam, thus importing waste from the hinterland thereby contributing not only to a more circular material metabolism of the municipality but also reaching neighboring regions to collect waste. AEB needs an overarching collection policy to maintain its generating electricity and heat capacity. All together AEB collects and consumes approximately 1.4 million tons of (household)waste, the municipality itself disposes of approximately 340.000 of waste annually (Municipality of Amsterdam, 2015). Thus the AEB consumes 4-fold of MSW than the municipality generates yearly.

Future share of renewable sources (2040)

The municipality is collaborating with numerous partners in sustainable energy management to effectively transition toward a carbon-free future. That is, reduce dependency on coal, oil or gas as an energy generator. Municipality of Amsterdam aims to generate 20% more renewable energy compared to 2013 and a total of 50% of renewable energy by 2040 per capita (Municipality of Amsterdam, 2015). To achieve this ambiguous target the municipality addresses objectives that aim to increase the share of specifically photovoltaic and wind energy.

Amsterdam aims to effectively increase photovoltaic energy generated power of 9MWh in 2014 to 160MW in 2020 and 1000MW in 2040. In order to succeed this ambitious plan the municipality focuses on a package of actions and measures that includes: private residential sector actively involving in city plans, restrictive local rules, providing insight with regard to national regulations restrictive legislations including tax legislation, simplifying and establishing building rights for the benefit of photovoltaic energy projects, making arrangements with corporations and businesses for the utilization of roofs., utilizing roofs of the public sector, funding initiatives through the national Energy Fund and other regulations (Municipality of Amsterdam, 2015).

This whole package should, according to the municipality, enable the private sector to actively invest in photovoltaic energy and thereby reaching around 1000MW. Reaching a threshold of 1000MW of solar energy, which should be sufficient for the consumption of 450.000 households. And reaching a generation capacity of 400MW of wind energy. The question remains if Amsterdam has sufficient spatial capacity within its municipal borders to employ 1000MW solar. According to feasibility studies the municipality would utilize about 1/3 of the spatial availability (Municipality of Amsterdam, 2015). According to the Renewable Area Potential, this number is consistent with the researcher findings. The employment of solar should not be an issue, in the most optimal situation 1000MW of solar requires 1km2. In the least optimal situation 1000MW requires 2.5km2 (*assuming the optimal situation of 1m2 of solar equals 1000W and least optimal situation of 1m2 of solar equals 400w* (Goodstal, 2013).

Wind energy is one of the important measures of SER-energy agreement. SER-energy agreement is a national agreement of 40 organizations including the Dutch government that has committed themselves to sustainable growth. The core of the agreement comprises agreements on energy, clean technology and climate policy. Implementation of the agreements should result in an affordable and clean energy sector that enables additional job opportunities for The Netherlands in clean technology markets. The municipality aims to increase the amount of wind energy to 85MW in 2020 and 400MW in 2040. In order to achieve this, various measures have been activated that should lead to the 2040 target; vision plan “space for wind turbines” will be the basis for the ambition of Amsterdam by enabling conversations at national and local level, actively pursuing suitable locations for wind turbines in the North of Amsterdam and the harbor, seeking the possibility for residents and businesses to participate and the ability to purchase renewable power. In comparison to photovoltaic energy, wind energy is more limited by environmental restrictions, therefore the amount of wind energy over the course of the years will not increase as much as photovoltaic energy.

4.1.2. Function

Electricity tariff households

Observing the electricity tariff in The Netherlands for household consumption at €0.18/kWh, slightly above the European average but well below Germany and Denmark. The current tariff is partly due to the shear amount of conventional sources meeting demand since the electrical energy derived from conventional sources is cheaper to generate and distribute compared to renewable sources. In addition, The Netherlands imports a considerable electrical energy from Germany. By importing, regardless country of origin, the electrical energy tariff will positively adjust because of an surplus in the grid also known as convergence. Partly due to convergence, the tariff in the Netherlands declined approximately 20% in 2014, according to Tennet (2014), the main grid operator, the drop in energy tariff is due to the effect of convergence, and obviously the generation of energy by coal-plants taking over gas plants and the import of electricity from Denmark and Norway. It is expected the tariff decreases is the forthcoming years because of the increasing import of cheaper electricity.

Electricity consumption inhabitants and households

The gross total electricity consumption per inhabitant in the municipality was 5522 kW (2014). The consumption is well below the national average of 6545 kW that year. In fact, Amsterdam is one of the best performing municipalities in terms of energy consumption per inhabitant. This proves that the municipality has been active to stimulate energy efficiency measures and prompted policy makers to introduce a variety of financial and non-financial instruments to improve. Reducing energy consumption by improving the sustainability of the existing residential housing stock is one of the focal points of the municipality. Amsterdam tries to achieve further reduction by encouraging homeowners to invest in improving energy performance measures of their own property. Agreements that have set the level of ambition include, agreements with housing associations and their properties to commit to the SER Energy Agreement, collaboration between the municipality and housing associations with regard to the energy generation by means of solar panels (Municipality of Amsterdam, 2015).

With regard to households, Amsterdam has one of the best performing household sector in Europe. The average consumption of a person per household in Amsterdam is 1800kW, while the European average is above 3500 kW. Efficiency measures by the municipality enabled the private and non-private sector to redesign the existing housing stock and implement new efficiency standards in the new housing stock.

Renewable area potential

Because of high urban density and geographical characteristics as water, there is limited area available for decentralized renewable deployment in Amsterdam. The technological preference to reach the renewable energy target as put forward by the municipality, is the deployment of solar and wind. As elaborated in the theoretical framework, solar is easily applicable in the urban environment but has limited generation capacity. Wind is less easy applicable in the urban environment but has high generation capacity. The municipality aims to as much wind energy as possible within the municipal borders. Wind energy will be deployed in the industrialized area of the Port of Amsterdam due to limiting aspects as noise pollution, casting shadow (umbra) and safety, that are especially relevant in residential areas. Solar will be deployed in the urban environment by utilizing private and non-private rooftops. In all, the estimated renewable area potential per inhabitant is approximately 38.5m2. Obviously, Amsterdam has limited spatial area potential, thus the municipality has to be creative to the sort of approach and sources to reach their targets.

4.1.3. Infrastructure

Security electricity supply

On the basis of the minutes of interruptions indicator, the Dutch grid operates well compared to other European countries, the amount of failures and thus blackouts are considered minimal. The current grid system in Europe and thus The Netherlands has been designed to operate faultless and satisfy demand with production instantly by the input of electrical energy from centralized sources.

However, the grid has not been challenged to deal with large amounts of highly volatile electrical energy due to the fact that The Netherlands and its municipalities *only* generated between 5 and 7% renewable energy. The grid-operator Tennet ensures that quality and quantity won't be affected, but surely this must be a theoretical estimation given the reason above. In the report *'To a future-proof energy system in The Netherlands'* TNO denotes that the grid has to undergo several major adjustments to deal with large amounts of wind and solar energy (TNO., 2010). To maintain current reliability and security of electricity supply the grid has to be prepared for at least 40% of flexible wind and solar-energy by 2030. Part of the solution to the grid is energy storage, which is currently non-existed as linchpin of the system. In a more recent study of TNO several recommendations have been made to address the aforementioned problems and maintain the security of the electricity supply (Donker et al., 2015).

First TNO recommends to modify the current design of the energy market in order to support the radically transition and allow for more flexibility in the energy market. Second, dynamic modeling of flexibility in the energy system so to analyze possible future cost, energetic ability, spatial implementations and time. Thirdly, economic chances for actors have to be in depth understood because a new form of using electrical energy as a product arises due to variability and external costs. Lastly, learn by practice and living labs, design future scenario's and real experiments to identify and address weaknesses in the process or the system.

Dependency electricity (self-sufficiency)

The Netherlands is quite heavily dependent on the import of electrical energy (12.75% import in 2014). After the liberalization of the electrical market exports grew from 1999. This trend persisted till late 2009 when The Netherlands became net-exporter, partly because imports fell sharply (CBS, 2015). After 2009 export was superseded by import, partly to in the expectation to meet renewable energy targets of consuming an x amount of renewable energy. Norway and Germany, frontiers of renewable energy deployment began exporting clean energy to The Netherlands while electricity trade with Belgium and Britain (less clean energy) declined between 2009 and 2011 (CBS, 2015). The imported electrical energy from Norway is generated by hydro, the imported electrical energy from Germany is generated by (most) wind. In effect, The Netherlands is compensating gray generated electrical energy by importing electrical energy generated by renewable sources. Consequently its cities and municipalities consume domestic as well as non-domestic generated energy. From the 12.75% import, 70% is imported from Germany. Thus the dependency on imported green electrical energy generated in Germany is reasonably large and therefore less prone to energy tariff fluctuations because of external factors.

4.1.4. Regime

Renewable energy investments (R&D)

This indicator is investigated at macro level including nationwide empirical data. Dutch companies and research institutes invest approximately €13 billion euros on research and development in RES (CBS, 2016), compared to total GDP in 2014 of €866 billion (The World Bank, 2016), is considered a great amount of investment. According to the innovation Union Scoreboard (IUS), The Netherlands performs above the average EU-28 ranking (5^{th}) consequently The Netherlands is categorized as innovation follower (European Commission, 2014).

In terms of RES investments, companies and institution in The Netherlands are mostly interested in biomass - waste-to-energy because these appear to be most successful in R&D sector, and probably minimal associated financial risks. Although the innovation level of these renewable applications is less compared to other renewable technologies such as photovoltaic- and wind energy. An explanation for this developed may lay in the fact that the opportunities for existing and well-researched technologies, such as biomass and waste are standardized technologies with less opportunities and thus less prospected innovation. Existing buildings and industrial technologies can be utilized for bioenergy generation and is therefore currently more attractive for investors.

The government invested €0.9b on RES deployment 2014, which is the lowest investment level since 2012, a decrease of 82% (UNEP, 2016), though the sum of €13billion investment of companies and research institutes and €0.9billion of governmental investment equals €13.9billion annually, or 1.605% of their GDP in 2014. Additionally, continuous subsidy reduction is taking its toll throughout Europe in the renewable energy sector causing investments to contract significantly. While investments have contracted, the small distributed capacity investments in renewable applications expanded. Small distributed capacity, a decentralized concept like photovoltaic panels connected to households to mimic the traditional centralized system rose by 22% to €684m ($765m – 2015) (UNEP Frankfurt School of Finance and Management and Bloomberg New Energy, 2016). Yet, the fact that The Netherlands has missed their renewable energy targets consecutively and spend twice as much on conventional energy sources than RES between the period 2005 and 2011 expresses the dependency on conventional sources and their economic lock-ins with the fossil fuel industry.

Level of ambition renewable electrical energy policies

This indicator stipulates the current active national policies that enable the government to transition towards a more carbon neutral future. The active policies enabled the Netherlands to achieve the renewable electrical energy share of 5.5% in 2014. The existing renewable policies should enable the Netherlands to gain 8,5% to achieve their renewable target of 14% in 2020 (International Energy Agency, 2016).

In 2009, the Guarantee scheme for geothermal energy was enforced. Obviously this policy is focused on geothermal in particular. The scheme provides economic instruments for the deployment of geothermal installations and especially to mitigate geological risks due to deep geothermal drilling. The scheme covers over 85% of the investment in case of complete failure (International Energy Agency - Renewable Energy Policies, 2016). Shortly after this policy, the in 2010 enforced policy of National Renewable Energy Action Plan, which is the policy obligatory to all member countries of the European Union, so to draft and submit their renewable action plans. The plans include the government targets, outlined pathways to allow them to meet targets in renewable energy, energy efficiency and GHG cuts (International Energy Agency, 2016b). The Netherlands focuses primarily on wind, solar bioenergy and geothermal energy to meet their targets. Hydro and other renewable sources as wave energy are as to date, not included.

In 2011, the Support Scheme for Solar Panels should lead to an increase of deployment of solar panels in the private and non-private sector. The scheme enabled to release a bracket of €50m to subsidize solar panel and accelerate the adoption of solar PVs.

Table 5 Enforce policies electricity sector - type RE source The Netherlands

All active national (macro) policies	Policy type							Support of renewable source					
Year. Name of policy	Economic instrument	Information and Education	Policy Support	Regulatory Instruments	Research, development and Deployment	Voluntary Approaches		Wind	Solar	Bioenergy	Geothermal	Hydro	Other
2009. Guarantee Scheme for Geothermal Energy	■										■		
2010. National Renewable Energy Action Plan			■					■	■	■	■		
2011. Support Scheme for Solar Panels	■		■						■				
2011. Feed-in Premium Programme SDE+	■							■	■	■	■	■	■
2011. Offshore Wind Energy Green Deal						■		■					
2013. Energy Agreement for Sustainable Growth			■					■	■	■	■	■	■
2015. Netherlands Offshore Wind Energy Act				■				■					
2015. Netherlands Offshore Wind Tenders	■							■					

As enforcement of the Support scheme and thus the expected deployment of solar PVs, a supporting policy was developed; The Feed-In Premium Programme 2011. This programme provides economic instruments as grants and subsidies for small and large, private and non-private costumers in the electricity sector. This initiates a new system for feed-in premium allocation targeting renewable electricity and renewable gas projects (International Energy Agency, 2016b).. The programme also covers the difference in the wholesale market prices of electricity and the cost price of electricity to renewable sources, so to make it more competitive (International Energy Agency, 2016b).. According to EIA, the annual budget increases yearly from €1.5b in 2011 to €3.5b in 2014 to €9b in 2016, in which the emphasize during the first years of the policy is focused on research and development of CHP/bioenergy and wind farms, and the 2016 budget is allocated to CHP/bioenergy and solar project.

In 2011, the Offshore Wind Energy Green Deal enabled the Dutch government to deploy offshore wind energy in a sustainable manner. A concrete goal in this policy in not only the deployment of offshore wind energy, but also the achievement of a 40% cost reduction in 2020 that would make offshore wind more economically feasible and competitive in the future.

The Energy Agreement for Sustainable Growth is a negotiated plan between the government and organization and interest groups (International Energy Agency, 2016a). The agreement stipulates ambitious targets as; an increase of the proportion fo renewable energy to 14% in 2020 and 15% in 2023, and to create at least 15,000 fulltime jobs in the renewable energy sector, and to improve the competitive position of the Netherlands and companies, to invest in energy security and innovation support, to decrease the costs of energy for households, to invest between 13 to 18b between 2013 and 2020, and to reduce the final energy consumption amounting to 1.5% annually.

Netherland offshore Wind Energy Act, adopted in 2015 ensures to accelerate and simplify the decision-making process for the realization of offshore wind energy project in a (last) effort to meet renewable energy targets in 2020. The act focused on taking governmental responsibility over wind investors with regard to spatial planning arrangements and environmental assessments. Therefore the government is responsible for site location of a wind farm as well as technical aspects as grid connect and the underlying risks involved

Following the adoption of the Offshore Wind Energy Act, The Netherlands adopted secondary regulations and opened first technology specific tenders such as; the government aims to auction 700MW annually of offshore capacity between 2015 and 2019. Furthermore the act enables offshore wind energy projects to be commissioned in Borselle.

4.1.5. Summary results Amsterdam

Technology

The municipality of Amsterdam (municipal level) has been transitioning more adequately to employ renewable sources relative to the Netherlands (national level). The fact that the municipality of Amsterdam has a greater share of renewable energy than the Netherlands on a country level is remarkable, because of spatial and other restrictions an urban environment poses. It can be explained by the fact that the major part of renewable electrical energy is generated in a centralized bioenergy plant that makes up more than a third of the share. Minus this bioenergy, renewable energy would account 2% of the total renewable energy share in the municipality. In 2014, the share of renewable sources in Amsterdam was 7%. Yet, with this in mind and the renewable target; to generate 20% more compared to 2013 by 2020, thus generating approximately 26/27% of renewable energy, seems improbable. The target may only be achieved if macro-level investments increase significantly.

With its ambitious targets on renewables, Amsterdam aims at generating 50% of renewables by 2040 by increasing the amount of solar and wind power. However, it is questionable whether an increase of solar (1000MW) and wind (400MW) energy is sufficient to meet the target of 50% renewables by 2040.

The Netherlands is heavily dependent on fossil fuels, as the indicators in the domain Technology emphasized. Not only as consumption, but economically as well since the country has vivid ties with the fossil fuel sector by distributing natural gas. These governmental lock-ins with the fossil energy sector appear to form a bottleneck for municipalities to meet renewable targets. The dependency on these fossil fuels (which makes up approximately 1%-2% of the national GDP) is a worrisome development that needs to be re-directed by policies enabling municipalities to invest more in renewable energy deployment.

The standardized result of the current share of renewables in Amsterdam is 0.53 percent point. Bioenergy makes up the largest proportion of this share and is not entirely carbon-free, e.g. bioenergy is distributed by fossil fuel driven transportation.

The future target of 50% by 2040 and thus an increase of 43% in the remaining 26 years is less feasible when The Netherlands decide not to push for additional funds to implement a wider range of renewables such as geothermal and wave energy. These additional renewables are underdeveloped in The Netherlands, according to TNO.

Function

The tariff for electrical energy in the municipality of Amsterdam is relatively low compared to Hamburg and Copenhagen. However, the tariff is above the European average of €0.15/kWh. Import of electrical energy from neighboring countries suppresses the tariff as well. The electricity tariff could decrease because of the increasing amount of imported electrical energy. On the other hand, meeting renewable energy targets and thus the deployment of an increasing amount of renewables will likely increase the electricity tariff in the future.

The electricity consumption per inhabitant of Amsterdam and the electricity household consumption per person is relatively low. This may proof that Amsterdam has been actively pursuing energy efficiency measures in a variety of sectors to decrease energy consumption. This suggests that municipal policy measures have improved the energy efficiency.

Between 2000 and 2010, the average rate of energy savings in The Netherlands was over 1.1% per year, ramping to 12% in a decade. Why is it that energy saving measures are more promptly addressed and implemented compared to the actual energy provision? The answer might be simple: the amount of available area, existing legislation and technological improvements restrict the share of renewables. Energy efficiency measures are less restricted because: 1) they are not bounded to the amount of available area 2) utilize existing product and technologies (isolation and energy efficient devices) and 3) no legislation prohibits the use of existing products and technologies since they do not pose danger to the public as seen in the deployment of wind-turbines e.g. .

The potential area for renewables (52.2 m^2/inhabitant) is limited in Amsterdam. The urban environment has been expanding at the expense of the hinterland. Consequently, renewable area potential has decreased considerably. This hinders the deployment of certain types of renewables, such as wind energy that requires spatial characteristics to deploy. Amsterdam has almost reached its capacity for wind-turbines. This indicates that solar is the only decentralized renewable energy source that can be deployed in great quantities. Disadvantages of solar energy are the relatively low generation capacity compared to wind energy, and the need for additional energy storage.

Infrastructure

While the national grid operates practically faultless, only 33.7 minutes of interruption, several future challenges could be identified. The increasing deployment of renewables throughout the country and municipality of Amsterdam requires careful planning and preparedness to acquire additional features to improve and maintain grid reliability. Examples are the need for increased energy storage in order to minimize grid load and grid instability. The aimed increase in solar, up to 75% by 2020 in Amsterdam, increases variable energy output. The requires the grid to transition from a centralized energy grid to a decentralized grid, leading to amongst others high energetic volatility. Therefore, dynamic modeling of flexibility in the energy system to analyze energetic ability, one of the key recommendations of TNO, should be permanently embedded in baseline assessment when setting targets.

Furthermore, the in-export surplus of the Netherlands of 12.75% is one of the highest in the European Union. The Netherlands imports almost 1/5th of its electrical energy consumption. This implies that the Netherlands:

- is not able to meet the electrical energy demand;
- Is compensating renewable energy targets with 'green energy' from neighboring countries;
- Faces an increased domestic energy production tariff, and it is thus cheaper to import electrical energy.

According to (CBS, 2014), the domestic energy production tariff has increased significantly, resulting in an increase in import of electrical energy. Energy is especially important from Germany, because of the adequate and efficient the high voltage cables between the Netherlands and Germany. These cables operate faultlessly, and form no technical bottlenecks to import energy, whereas other (international) grids pose technical risks and bottlenecks. Additionally, TenneT, the grid operator in the Netherlands, operates in Germany as well. 2/3th of Germany's electrical energy system is operated by Tennet and interconnected throughout the Dutch and German grid.

Regime

The investment indicator at macro-level displayed public-private investments up to 1.60% of total GDP in the Netherlands. At face value, current investment levels appear to be insufficient to meet the national renewable energy targets for 2020. Even though the Netherlands performs well on the innovation Union Scoreboard, the renewable targets lack behind schedule. The Feed-in Premium Programme SDE+ should enable to stimulate renewable energy deployment for the upcoming 5 to 15 years. Private and non-private investments need to increase. The SDE+ policy has provided an annual increase of investments until 2016.

A solution on macro-level in terms of investment and achieving targets could be found in existing coal and gas-fired power plants. These plants will have to be closed down to meet national targets on renewables, and as a consequence of the Paris Climate Agreements. Transforming these plants to bioenergy plants has proven to be economically feasible (Donker et al., 2015). However, for the municipality of Amsterdam, bioenergy will not increase the potential to meet energy targets because of the already existing centralized bioenergy plant in Amsterdam (AEB). Deploying an additional centralized bioenergy plant would consume tremendous amount of biodegradable substances and is therefore probably unfeasible.

The level of ambition at macro-level is as expected. Several examples, such as the Feed-in Premium Programme SDE+ and Netherlands Offshore Wind Energy Act/Tender, confirm that Dutch governmental policies are mainly focused on wind energy. Offshore wind is the best solution on the short term at macro-level. However, allowing municipalities to equally progress requires additional policies that enables them to support renewables in the urban environment. The in 2011 adopted policy Support Scheme for Solar Panels supports the deployment of solar PVs only in an economic sense. Even though the requirement in municipalities is two sided; on the on hand one needs sufficient subsidies to push deployment of solar PVs, on the other hand spatial flexibility has to be guaranteed by regulatory Instruments. Both are currently lacking in Amsterdam.

Table 6 Overview standardized results Amsterdam

K1	Technology			
K1.1	Share renewable sources	Meso	7 %	0.35
K1.2	Future share renewable sources (target 2040 or 2050)	Meso	50 %	0.50
K2	Function			
K2.1	Electricity tariff households	Macro	0.18 €/kWh	0.78
K2.2	Electricity consumption inhabitant	Meso	5522 kW/inhabitant	0.73
K2.3	Electricity consumption household	Meso	1800 kW/household	0.70
K2.5	Renewable area potential (RAP)	Meso	52.2 m2/inhabitant	0.52
K3	Infrastructure			
K3.1	Security electricity supply	Macro	33.7 mins/interruption	0.94
K3.3	Dependency electricity (self-sufficiency)	Macro	12.75 in-export	0.24
K4	Regime			
K4.1	Renewable energy investments (R&D)	Macro	1.60 % of GDP	0.53
K4.2	Level of ambition renewable energy policies	Macro	8 active policies	0.73

4.2. Results Hamburg

4.2.1. Technology

Share of renewable sources

According to the data of 2014 the municipality of Hamburg generates a total of 13% renewable energy, almost half of the national generation of 27.4 (BMWi, 2014). Consequently 87% is generated by non-renewable sources primarily from coal and gas. The share of renewable sources comprises 29% wind, 9% photovoltaic, 62% bioenergy.
Remarkably similar to Amsterdam, bioenergy is the leading renewable source similar to the renewable energy. The aim of the municipality is to utilize the local possibilities of bioenergy. Several bioenergy plants are generating electric and heat energy for primarily local municipal consumption.

Future share of renewable sources (2040)

The projected path of Hamburg is ambitious but seemingly realistic, the Municipality aims to increase the share of renewable sources from 13% (2014) to 60% (2040), an increase of 47% in 26 years thereby aligning itself with the federal objective. Achieving this target is deeply rooted in the macro policies and meso policies the municipality has recently put forward. Not only does Hamburg aims to deploy additional renewables, the municipality itself is turning into a renewable energy hub. Employment and innovation within the municipality and thus the fast extraction of management, engineering and knowledge resources for local implementation should enable Hamburg to meet its future target. Currently approximately 1,500 renewable energy companies in the field of photovoltaics, wind and bioenergy have settled in the municipality employing over 25,000 (Municipality Hamburg und Schleswig-Holstein, 2016).

4.2.2. Function

Electricity tariff households

The German electricity tariff has been rising in recent years. Despite the increase of electricity tariff, the majority of the German population remained in favor of the energy transition (Bunderverband der Energie- und Wasserwirtschaft, 2016). The composition of the German electricity tariff is as follows; acquisition/sales, grid fee, value-added tax, concession fee, CHP-surcharge, electricity tax and renewables surcharge to the total sum of 0,298€/kWh . From 2004 to 2014 the German tariff saw a steep increase of the renewable surcharge mainly due to the increase of renewables in the total share of the electricity mix. Consequently, in this time period German household electricity tariffs has been at one of the highest in the European Union (Bunderverband der Energie- und Wasserwirtschaft, 2016). (Strom-Report., 2015) suggests that consumption of electricity is declining and the amount of consumers switching to other providers ensuring more payable electricity is increasing.

Electricity consumption inhabitants and households

The electrical energy consumption per inhabitant was measured at 6920kW (2014), slightly below the national average. The port of Hamburg accounts for a large proportion of consumed electrical energy, hence the rather high consumption figure. Therefore, to reduce electrical energy consumption the Port of Hamburg initiated the programme 'Enterprises for Resource Protection' enabling the port-based companies to can account up to 40% of the municipals energy savings (HPA, 2016). Household consumption in the municipality of Hamburg was measured at 2325 kWh annually, well below the national average of 3079 kWh (World Energy Counsil, 2015).

Renewable area potential

The municipality of Hamburg comprises satisfactory amount of area that can be allocated for the deployment of renewables, the estimated renewable area potential per inhabitant was measured at 77.9 m2. Compared to the municipality of Amsterdam, Hamburg comprises half of the urban density. In effect, this implies there are less spatial restrictions as there is more area available for the deployment of renewables. Therefore, wind energy is a viable option for the municipality in areas that do not pose social or other restrictions. The Port of Hamburg is, similar to the Port of Amsterdam, a location in which wind energy can be allocated without the mentioned restrictions. The municipality aims to deploy wind energy in area's less populated areas as the harbor, to prevent noise pollution, casting shadows and safety concerns.

Furthermore, Hamburg identifies itself as an international service hub for the renewable industry by the development of companies and employees in the renewable industry. Locating the sources close to the municipality offers a chance to have service, maintenance and deployment in one region improving employment while keeping in mind other sustainable aspects such as the 'material metabolism' of wind-turbine parts that can thus be recycled within its municipal borders.

4.2.3. Infrastructure

Security electricity supply

Germany's renewable energy sector is one of the most innovative sectors worldwide. The increasing deployment of renewable sources to the grid may face reliability issues. According to various studies measuring the reliability of the national grid the German grid is amongst the best functional and reliable grid in the European Union (Rosas-Casals and Corominas-Murtra, 2009). With 14.9 minutes of interruption in 2014 the amount of time of interruptions extraordinary slim and can therefore be called robust. The German grid, even with their current amount of renewables in the total share of electricity generation is certainly ready for the increasing deployment and expected effects as electrical energy fluctuations (Rosas-Casals and Corominas-Murtra, 2009). Developments that lead Germany to to maintain its current security comprise the integration and balance of high shares with modest changes to the grid system. Nevertheless bigger chances, such as adaptation of the grid by increasing capacity and nodes with foreign grids to accommodate the exponential increase of renewables. Yet, as Germany is phasing out coal, gas and nuclear powered plants, these centralized plants will be necessary for the the operation reserve and more flexible spinning reserve.

Dependency electricity (self-sufficiency)

As opposed to Amsterdam, Hamburg Germany has an in-export surplus of -7.36%. The surplus leads to the export of large quantities of electrical energy to neighboring countries as The Netherlands, that in turn import green energy.
Because of the large amount of surplus Germany is able to sell electricity against a fairly low tariff per kWh. Exact tariff numbers lack in reports and are thus unknown. However, an analysis by (Fraunhofer ISE, 2016) Fraunhofer institute for Solar Energy systems displayed data of an surplus over 45 terawatt hours in 2014. And by selling a large proportion of this share, Germany has generated over €13 billion euros in the past 10 years. Because of Germany's surplus, consequently The Netherlands is thus able to import rather cheap electricity, assuming the electricity would be sold under the Dutch tariff of €0.15/kWh to compete with the Dutch market, meaning Germany, where the tariff is around €0.30/kWh is selling the electricity at dumping prices. An additional benefit of becoming more self-sufficient in electricity energy is the variation of electricity tariff market. Surplus lead to reduction of electricity tariffs, deficiency leads to an increase of electricity tariffs.

4.2.4. Regime

Renewable energy investments (R&D)

The R&D trends in Germany are interesting for a couple of reasons. First, Germany is the pioneer in renewable energy deployment. Second, Germany is phasing out conventional sources rapidly including nuclear thereby adequate replacements in the form of renewables need to be deployed to meet energy demand. To substitute conventional sources by renewables large amount of research and development in the renewable sector is necessary. The IEA emphasizes that a transition to supersede fossil fuels within its prospected timeframe (2030) far more investment is required and only continued R&D investments will lead to technical progress. As a response, Germany has increased its yearly renewable deployment budget from €4.6 billion (2000) to nearly €19 billion (2014) (Federal Ministery for Economic Affairs and Energy, 2016). However, German investment peaked in 2010 at 27 billion and have fallen sharply to the investment level of 2014. The sudden lack of investment may be due a couple of reasons. First, renewable energy targets were met on time in 2012, therefor investment declined for the time period between 2012 and 2014. Second, the amount of energy generated from renewable sources have increased yearly from 2000 (10.391 GWh) to 2014 (136.061GWh) (Federal Ministery for Economic Affairs and Energy, 2016). And third, governmental investment brackets may be released once new targets are set and previous targets have been met, because if initial targets have not been met, new financial impulses and The most investment went to the deployment of wind-turbines accounting for €12.3 billion in 2014. Followed by solar energy €3.1. billion and bioenergy €2.4. billion, other renewable such as hydro energy and geothermal energy accounted combined investment of €1.1 (Federal Ministery for Economic Affairs and Energy, 2016).

Wind energy is by far the most interesting renewable investment sector in Germany, on- and offshore investments increased 85% and this share is expected to increase in the following years. Solar energy investments declined sharply between 2007 and 2012. In this time period, the total amount of solar energy investments accounted up to 70% to a corresponding €2.3 billion. Other sectors as geothermal and biomass remained largely equal in % of investment throughout the period 2002-2014. Hydro energy investments stagnated because of the natural capacity of hydro energy possibilities in Germany.

Revenues in the renewable energy sector have risen steadily in tandem with the deployment of renewables in Germany. Renewables offers chance on economic and manufacturing market, consequently Hamburg has been heavily investing in becoming Europe's leading wind management, engineering and innovation services centre for renewable energy.

Level of ambition renewable energy policies

The German government currently has a wide pallet of 9 active national policies focused on renewables to reach their target in 2040. The first national policy is the Green Power policy aiming for better regulations and economical means for operators to handle " the new product" green electricity that changed the tariff to their customers. It also enabled costumes to make a decision whether they want to consume energy generated by conventional or green sources. In the following year the policy of Federal Building Codes for Renewable Energy Production was enforced. This policy describes how renewable plans cannot be contested on the municipal level if plans are not in place. The government enforced this policy because municipalities were able to overrule privileged areas initially aimed for renewable installations and thus renewable energy generation. In addition to these two regulatory policies, Germany decided it needed a supporting financial policy to stimulate the private and non-private sector by offering *soft* loans on all renewable technological frontiers. The Market Incentive policy was introduced in 1999 and was the first major incentive programme. The policy described supporting renewable energy and heat generation with an initial budget of 100 million allocated over 5 years mainly for R&D and the deployment of solar and bioenergy as biomass for heat and biomass for electrical energy.

From 1997 till 2010 no policies in the sector of electricity were enforced. Here, the German government realized the importance of energy transition, because, during this period, nuclear energy was rapidly declining in popularity across the country. As a response, the government enforced the Energy Concept 2010 to support regulatory instruments and policy implementation. The Energy Concept draws together several goals of securing supply and protecting the climate while at the same time promoting the growth and competitiveness of the German industry (International Energy Agency, 2016a). First goal; include achievement of 40% cut in greenhouse gas emissions by 2020, 55% cut by 2030 and 70% by 2040, with the ultimate target of 80 to 95% (almost carbon neutral) in 2050 (International Energy Agency, 2016a). The second goal is to generate up to 60% of renewable electrical energy by 2050. The third goal includes 20% reduction in primary energy consumption by 2020, and a 50% reduction by 2050 compared to 2008 levels. The fourth goal includes the annual rate of building renovation to upgrade energy performance is to be doubled from current levels, from 1% to 2% per year (International Energy Agency, 2016a). In all, a comprehensive policy that has set the standard to achieve the ambiguity goals and targets that stipulates the path and projected towards superseding fossil fuels.

Table 7 Inforce policies electricity sector - type RE source Germany

All active national (macro) policies	Policy type						Support of renewable source					
Year. Name of policy	Economic instrument	Information and Education	Policy Support	Regulatory Instruments	Research, development and Deployment	Voluntary Approaches	Wind	Solar	Bioenergy	Geothermal	Hydro	Other
1996. Green Power				■			■		■	■	■	
1997. Federal Building Codes for Renewable Energy Production				■			■		■			
2010. National Energy Action Plan (NREAP)			■				■	■	■	■	■	■
2010. Energy Concept			■	■			■	■	■	■		
2011. KfW Programme Offshore Wind Energy	■						■					
2014. Amendment of the Renewable Energy Sources Act	■		■				■	■	■	■		
2015. Ground-mounted PV Auction Ordinance	■							■				
2016. Subsidy for solar PV with storage installations	■							■				
2017. Amendment of the Renewable Energy Sources	■		■				■	■	■	■	■	■

kFW programme Offshore Wind Energy is a supporting policy to the Energy Concept, enforced in 2010 to accelerate the expansion of offshore wind energy in Germany. This policy also gives financial tools to expand the possibilities for the construction of wind farms.

The Amendment of the Renewable Energy Sources Act is enforced to support expected targets set forward in The Energy Concept. An increasing share of green energy in the grid demands tools to support an integrated renewable energy market.

In 2015, Ground-Mounted PV Auction Ordinance was enforced as part of the reform of the German Renewable Energy Law. This policy aims to implement auction system for PV-installations in a cost-effective manner while maintaining a high level of public acceptance and stakeholder diversity (BMWi, 2014). The practical effectuation exists by yearly planned auctions according to a fixed schedule thereby selling PV-capacities between 100kW and 10MW year(International Energy Agency, 2016a). As joint policy for the Ground Mounted PV Auction Ordinance, the Subsidy for solar PV with storage installations (2016) was enforced. Battery storage of highly volatile generated electricity by PV's from residential installations in order to strengthen grid services and management. The policy provides soft loans for PV installations (PV panels and storage, the complete package). It further grants up to 25% of the eligible solar PV panel.

Lastly, the recently enforced policy Amendment of Renewable Energy Sources provides support for small and large scale installations by offering economic instruments and policy support. Economic instruments consist of public tender procedures for mainly onshore wind, offshore wind, solar and biomass projects. This policy supports renewable energy targets, similarly to the Energy Concept 2010 by stipulating capacity corridors for technology deployment in order to control capacity volumes (International Energy Agency, 2016a).

4.2.5. Summary results Hamburg

Technology

From the technological perspective, the primary renewable energy source applied in the municipality is bioenergy and comprises the largest amount to the total share. The reason for this is the redevelopment of former coal and gas-fired plants transformed to large centralized bioenergy plants. Similar as the municipality of Amsterdam, bioenergy is followed by wind energy accounting for almost a quarter of the generated energy.

If the current path of developments will be achieved the target of generating 60% of renewable energy by 2040 is theoretically manageable because the municipality would need to increase the annual renewable generation capacity to approximately 1.76%. The transition pathway: S-Curvature, is described as a slow development at first, characterized by rapid growth as the transition progresses. Thus one would expect that the generation capacity exponentially increases over time, the effect of this that the grid requires non-spinning and spinning reserve to absorb the 'highs and lows'.

Function

While the energy transition has indirectly increased the electrical energy tariff to one of the highest tariffs in the European Union, Germany, and its underlying municipalities remain in favor of the renewable transition. The expectation exists that the electrical energy consumption declines in the next decades due to efficiency measures. Nevertheless, an increasing tariff bears consequences in the energy market, the switch of consumers from one energy provider to another is a noticeable effect on the German market. This effect could be fortuitous development as renewable energy startups compete on the regular energy market to become most cost-efficient and attract consumers, hopefully with the expectation that tariffs remain stable.

With regard to the electrical energy consumption, two main incentives constitute the current annual consumption of figure 6920 kW compared to Amsterdam and Copenhagen: a significant amount of industry at the Port of Hamburg and urban morphology. Indirectly the urban morphology affects the consumption figure of the of the households which was measured at 2325 kW/household because of terraced housing stock consuming less energy. Furthermore, it should also be noted that the municipality has a considerably larger surface compared to other cases, therefore containing a more substantial amount of rural areas contributing to the RAP potential since it is here that wind turbines can be situated.

Infrastructure

Despite the fact that the German grid is the best-performing grid regarding functionality and reliability (14.9min of interruption annually), the rapid pace of renewable energy transition still requires changes in the near future to maintain its current standard. Chances include the market frameworks adaptation due to the increase in electricity tariffs. Balanced operational and spinning reserve to absorb the 'highs and lows.'

The dependency figures display a self-sufficient Germany, mainly due to the surplus of fossils fuels -and renewables. The excess of fossil fueled energy should be regarded as negative because the consumption of unused fossil energy is undesirable even if the excess energy is exported. However, it should be noted that excess of electrical energy leads to a reduction of electricity tariffs by selling it at dumping prices making electricity more accessible for the greater audience.

Regime

Private and non-private investments in R&D accounted for approximately 0.48% of the national GDP resulting in a standardized score of 0.16. One would expect a greater share of investments; Germany has effectively decreased investments because of meeting several targets in the past. However, as the IEA emphasized, continued R&D is inherently valuable to lead to technical progress. The expectation exists that private and non-private investments will gradually increase once new targets have been set, and previous targets are met. The most attractive renewable pathway is the on and offshore wind energy sector. There may be a couple of reasons for this, 1) windy geographical characteristics of the northern regions in Germany enable wind turbines to generate a viable amount of energy, 2) the government prioritized wind energy as Hamburg, as the wind energy hub is contributes to this pathway by providing services. Hamburg may be profiting because the investments in renewables offers the municipality a chance by actively engaging in this market.

When looking at the level of ambition renewable energy policies in the sector of electrical energy, the notable development is the early enforcement of the Green Power policy that aimed for better regulations and economic means to adapt to energy generated by renewables. Allowing the market to shape its current economic form for renewable energy sources and ensure parties to decide on consuming ‘green energy.' Another important enforced policy that pushed the transition forward is the Renewable Energy Source Act, promoting renewables by stipulating feed-in-tariffs, enabling private renewable generation to sell excessive electrical energy at fixed prices, ensuring their investments and proving an economic basis against variable (none)renewable energy.

Table 8 Overview standardized results Hamburg

K1	Technology			
K1.1	Share renewable sources	Meso	13%	0.65
K1.2	Future share renewable sources (2040 or 2050)	Meso	60%	0.60
K2	Function			
K2.1	Electricity tariff households	Macro	0.30 €/kWh	0.49
K2.2	Electricity consumption inhabitant	Meso	6920 kW/inhabitant	0.62
K2.3	Electricity consumption household	Meso	2325 kW/household	0.44
K2.5	Renewable area potential (RAP)	Meso	77.9 m2/inhabitant	0.78
K3	Infrastructure			
K3.1	Security electricity supply	Macro	14.9 Mins/interruption	0.98
K3.3	Dependency electricity (self-sufficiency)	Macro	-7.36% in-export	0.65
K4	Regime			
K4.1	Renewable energy investments (R&D)	Macro	0.48% of GDP	0.16
K4.2	Level of ambition renewable energy policies	Macro	9 active policies	0.82

4.3. Results Copenhagen

4.3.1. Technology

Share of renewable sources

The Municipality of Copenhagen, as defined in Appendix 11, generates 16% of renewable electrical energy in 2014, over half less compared to national level of renewable energy generation 39% (EnergiNet DK, 2016). The 16% consist of bioenergy 62% followed by wind energy 38% (Municipality of Copenhagen, 2015). Solar and geothermal energy are practically non-existent because Denmark and Copenhagen do not have the solar and geothermal resources as seen in Appendix 4 Solar radiation and photovoltaic electricity potential and Appendix 5 Geothermal energy potential. The municipality aims primarily to deploy wind energy sources because of the geographical windy-position as seen in Appendix 3 Wind energy resource potential, wind energy is one of the viable and feasible options. Evidently, bioenergy is the primary renewable energy source. Denmark and the region of Copenhagen has an abundance of natural waste that can thus be useful for bioenergy generation. Additional bioenergy plants are planned in the future, the currently coal-fired Avedøreværket plant will be converted to bioenergy CHP plant for combined heat and energy (Municipality of Copenhagen, 2015). EnergiNet, an energy statistics bureau stresses that bioenergy plants play an important role in the electricity supply and in the transition from fossil to renewable in Denmark and Copenhagen. Because conventional techniques may be used when The bioenergy plants also play a strategic role in the grid distribution by offering the flexibility to generate electrical energy in periods with low production of solar or wind.

While solar irradiation is similar to Hamburg and Amsterdam, the deployment of solar energy lacks behind. Similarly as Amsterdam bioenergy is one of the spearheads to meet Copenhagen's future renewable energy targets. However, the organic materials that will provide usable energy is a combination of MSW and biodegradable materials such as tree-trunks (Municipality of Copenhagen, 2015). Denmark reportedly generated over 39% renewable energy in 2014, a world-record, the majority being generated by off-shore wind farms (EnergiNet DK, 2016). Thus Denmark, as a country, generates considerably more renewable energy compared to Copenhagen as municipality.

Future share of renewable sources (2035)

As one of the frontrunners of renewable deployment. Denmark and the municipality of Copenhagen have set the ambitious target of generating 100% renewable electrical energy by 2050. To achieve this long-term goal the city of Copenhagen requires a long-term smart energy system. This includes complete electrification of transport sectors as well as energy saving measures in the built environment and heating and cooling techniques. A couple of sub-targets is set leading to the 2050 target. Interesting about these sub-targets is that they address specific sectors or effects forward so to accelerate a transition. As such, strategic energy planning is called into existence to specify the sectors that need policy support or require change, a couple of broad political agreement have been made for 2020.

The first target is a 12% reduction of in the primary energy supply compared to 2006, currently (2014) Denmark and Copenhagen achieved a reduction of approximately 8% (EnergiNet DK, 2016).

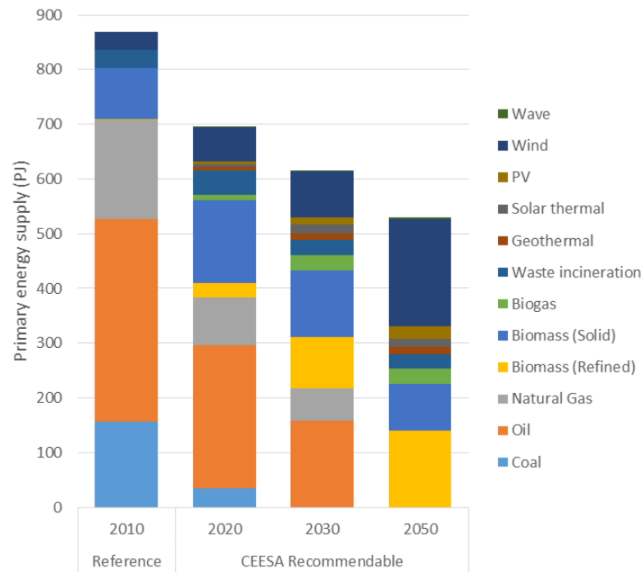


Figure 12 CEESA (2010) Primary energy supply sources

The second target addresses 35% renewable energy by 2020 of the entire energy system in Denmark and thus Copenhagen. From this share it is expected that at least 50% will be generated by wind turbines. Additionally to the 2020 targets, Denmark expects to generate around 10% of biofuels or renewable energy in the transport sector.

Furthermore, the government's goal in 2020 is the reduction of CO2 emissions by 40%. By 2030 it is expected that the energy system is completely coal free and no oil is consumed for heating purposes. In 2035 the government aims to generate 100% renewable energy in the electricity and heating sector. By 2050 the sector of transport and industry are 100% renewable. In all, several targets addressing particular sectors such as the transport sector and building sector, in which energy generation- and energy saving measures are introduced. Together, on the one hand energy generation and the other energy saving should lead to Copenhagen's and Denmark's target of 100% renewable electrical energy by 2035.

4.3.2. Function

Electricity tariff households

The electricity tariff for a household in Denmark is one of the most expensive in the European Union. The Danish grid tariff composes three settlements: grid tariff, system tariff and PSO tariff (EnergiNet DK, 2016), all together form the 0,30€/kWh (2014). Grid tariff includes settlements for transmission of energy. System tariff includes costs related to the reserve capacity and system operations. Finally, PSO tariff the highest component covers cost related to public service obligations as intended by the Danish Electricity Supply Act (EnergiNet DK, 2016). The Danish electricity tariff surely is a lot more expensive than anywhere else in the European Union. Closer examination of the Danish household tariff displays a continuous increase since the 1960s but has remained stable until the 2000s.

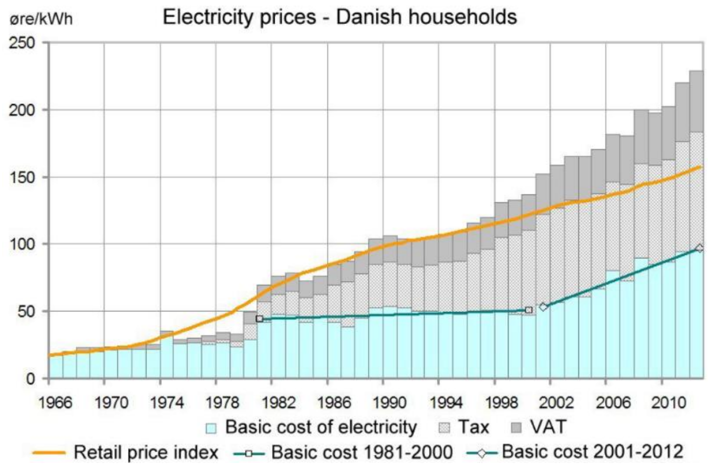


Figure 13 Electricity Tariff Denmark (Source Energinet statistics, 2016)

From 2000 onwards there is a sharp increase in the electricity tariff. From 2001 to 2012 the tariff increased by 83% (EnergiNet DK, 2016). It has been debated that the increasing deployment of renewables is the root cause of the increasing electricity tariff. This might be true, however, there are a couple of developments that has led the tariff to increase, some of which related to the renewable energy deployment.

First; expensive decisions were made in the past, the Danish grid operator invested over €15 billion since 2005. Mostly new assets to prepare the grid for renewable energy such as interconnectors, feeders for offshore wind parks and new transmission lines for in-export purposes. These investments are related to the renewable transition, most of these expenses were allocated to the electricity tariff. Additionally, the operator decided to replace several miles of 400kV over-headlines to underground cables, the Danish government suspended the project due to high cost. Lastly, taxes increased 60% throughout the period 1998-2013 (EnergiNet DK, 2016). It also has been argued that Denmark is exporting their electrical energy surplus at no cost while investment increased (Bach, 2014). Surely, renewable energy deployment equals investment into a new technology has to be compensated. Although in the case of the Danish tariff there are multiple non-renewables variables that might have influenced the tariff to record high.

Electricity consumption inhabitant and household

With regard to the electricity consumption per inhabitant, which includes commercial and non-commercial sector, a 20% reduction is targeted compared to 2010 levels (Municipality of Copenhagen, 2015). With the current consumption of 4017 kW/inhabitant annually, a 20 % reduction should lead to an annual estimated consumption of 3214 kW/inhabitant in 2025.

Copenhagen has a relatively old building stock and faces similar issues as Amsterdam in terms of energy efficiency. Because of the old building stock, improvements are much harder to implemented, however the potential of saving up to 53% of the heat in buildings is promising. Energy savings indirectly results in less energy consumption of fossil and non-fossil energy sources (Mathiesen et al., 2015). Currently, the electricity consumption per inhabitant/household is 2000kW (Municipality of Copenhagen, 2015). While the electricity consumption of households have been on steady levels since yearly 2000s to 2013 the municipality aims to reduce electricity consumption by 10% by 2025.

Renewable area potential (RAP)

There is limited available space for local wind and solar energy generation. The amount of RAP for these sources in the municipal Copenhagen area is estimated at 27.4 m2/inhabitant. Information as to where the municipality plans to locate local renewable energy sources and what sources will be deployed is not widely publically available. A couple of projects seem to be catching attention.

4.3.3. Infrastructure

Security electricity supply

The Danish electricity grid is the best performing grid in the European Union. The time of power outage annually is 17 minutes (2014), thereby guaranteed supply of electrical energy. According to the (Danish Energy Agency, 2015 p23) the Danish grid capacity is sufficient and consistent in that few electricity shortages have been observed. It has been concluded that wind energy contributes to security of energy supply (Danish Energy Agency, 2015 p24).

Furthermore, The electricity system is in transition with the number of interconnector, so to balance the grid for the share of highly volatile energy input as solar and wind source deployment increases. Denmark is expected to grow capacity by increasing the number of interconnectors in 2020 thereby contributing to a more strengthened capacity adequacy and thus robustness of the grid(Danish Energy Agency, 2015). Aspects that affect the capacity adequacy of the grid that might increase frequency of failures on interconnector is the increased probability of neighboring countries not being able to supply electricity to Denmark and meet demand peaks. However, as put forward in the next section of dependency, Denmark according to 2014 figures is relatively independent of electricity supply. Closing neighboring electricity sources as the Swedish nuclear power plants do not appear to have any significant effects to the Danish capacity adequacy (Danish Energy Agency, 2015). In fact, the Great Belt connection, the highvoltage link between Denmark – Norway – Germany increases security of electricity supply by exporting the surplus. Another Great Belt connection to the United Kingdom and The Netherlands would increase further capacity adequacy.

Dependency electricity (self-sufficiency)

While the dependency of the German and Dutch grid is relatively high, Danish import only 2.28% of the total consumption in 2014. While the in-export figure varies annually, the general generation deficit in 2014 led to import of energy mainly from Germany and Norway and Sweden. The Danish in- and export direction of the interchange of electricity is determined by differences in capacity between countries and limitations to capacity on the international connections (EnergiNet DK, 2016). Beside the variable of natural resources determine renewable energy generation capacity is interlinked with winter and summer months. Typically Denmark has a generation surplus in the winter months and deficit in the summer months, also seen in the figure displaying the amount of energy in-and exported to Sweden, Norway and Germany.

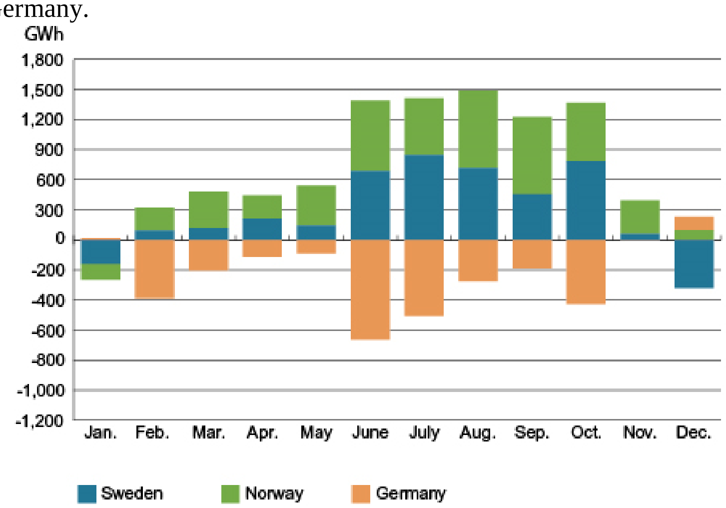


Figure 14 In- and exports electrical energy to and from Denmark (Energinet - Energy Denmark, 2016)

The reason for this is attributable to the fact that electricity in the Danish grid is heat bound (EnergiNet DK, 2016) there is more wind in the winter than summer. While dependency is almost negligible in the Danish grid, dealing with season fluctuations poses a threat to the security of energy supply. Because a deficit in surrounding countries with an annually increasing renewable share is expected to encounter similar season fluctuations.

4.3.4. Regime

Renewable energy investments (R&D)

In 2014, Denmark invested a total of 10.1 billion in research and development of renewables, almost five times the investment in fossil fuels amounting the 2.96% of the Danish GDP. Half of the investments were allocated from pension funds. To highlight the pension and allocation of funds to project several examples have been studied. PensionDanmark invested heavily in sustainable energy plants (wind, solar and bioenergy) amounting to a total capacity of 2500mW annually (State of Green, 2016). PensionDanmark is a non-profit market pension fund managing pensions under collective and corporate agreements and health care product. It further invests in direct infrastructure projects to support the renewable transition (State of Green, 2016).
The following example is PKA, the largest pension fund in Denmark. PKA invested over 2,3 billion in climate-related projects. PKA invested in multiple off shore wind parks and invested heavily in foreign renewable energy projects in The Netherlands, Germany and England (State of Green, 2016).

Here we have two large pension funds, investing more in renewable energy than fossil fuels. So why it is that Danish pension funds take the risk of investing in renewable energy projects. According to CEO of PensionDanmark as reported in (State of Green, 2016 p10) *"The Danish Climate Investment Fund and the Danish Agribusiness Fund are good example of how public and private capital can work together to address global societal challenges in a way that benefits both Danish companies and investors".* Thus blended finance can make risky investment bankable through public-private financial models. To minimize investment risk, collaboration between public and private market is essential. Especially the investment of wind energy has a proven record of positive financial output. These models can thus be applied in various countries, as is currently happening in The Netherlands, were the Danish pension fund PKA financed the construction of Dutch offshore project Gemini in the North Sea.

Level of ambition renewable energy policies

The following policies define the Danish electricity network in the quest to become more renewable in the sector of electricity. In 1976 Denmark enforced the Electricity Supply Act, which provided a framework for the control of the electricity sector where only licensed companies were allowed to produce, transmit and distribute electricity through the public grids (International Energy Agency, 2016a). This policy resembled regulatory instruments for small and large scale plants that enabled the government to use security of supply justifications to oblige electricity supply companies to include specific types of energy in their supply mix (renewable and non-renewable) in order to improve the energy efficiency of supply (International Energy Agency, 2016a). Thus, the 1976 Electricity Supply Act ensured governing the development and structuring of the electricity sector. In the same year, the Energy Research Programme was enforced, the programme supports the implenmentation of the Danish energy policy in the sense that it support wide range of energy related projects supply (International Energy Agency, 2016a)All renewable sources are included in this programme with the exception of nuclear energy, besides the conventional renewables, also fuel cells, hydrogen technologies and even wave-energy technologies are included. The Energy Research Programme enabled private and non-private companies to access financial support more easily for deployment and starting R&D programmes.

Table 9 Inforce policies electricity sector- type RE source Denmark

All active national (macro) policies	Policy type							Support of renewable source					
Year. Name of policy	Economic instrument	Information and Education	Policy Support	Regulatory Instruments	Research, development and Deployment	Voluntary Approaches		Wind	Solar	Bioenergy	Geothermal	Hydro	Other
1976. Electricity Supply Act				■									
1976. Energy Research Programme	■							■	■	■	■	■	■
2004. Replacement Scheme for Wind Turbines on Land	■							■					
2009. Feed-In-Premium Tariffs for Renewable Power	■							■	■	■	■	■	

2009. Promotion of Renewable Energy Act													
2010. National Renewable Energy Action Plan (NREAP)													
2011. Energy Strategy 2050													
2012. Danish Energy Agreement for 2012-2020													
2012. Regulation on Net-metering For the Producers													

In 2004 the policy Replacement Scheme for Wind Turbines on land was enforced and provided economic instruments for the deployment and more importantly the replacement of inefficient outdated wind turbines, this meant a complete overhaul of existing in-place wind technologies and enabled the Danish government to push newly set renewable targets.

Because of the increasing contribution of renewable energy in the Danish grid, the enforced Feed-in premium tariff for renewable power in 2009 enabled for a more balanced cost structure of onshore and offshore wind energy (International Energy Agency, 2016a)Also in 2009 the Promotion of Renewable Energy Act was enforced so to provide regulatory and economic instruments to establish a "loss of value scheme" that provides clarification regarding payment in case of loss of value to real property due to deployment of for example wind turbines, but also other renewable installations (International Energy Agency, 2016a).

In 2010 the National Renewable Energy Action Plan (NREAP) required members of the European Union to be obligated to draft and submit their plans outlining the pathway to meet their 2020 renewable energy, efficiency and GHG cut targets. As such, Denmark set the energy targets. Measures in the policy to meet the targets includes; Governmental investment in research, development and demonstration projects, efforts for increase of energy efficiency in buildings, energy savings efforts on national and local levels, price subsidies for energy generation from RES, Financial support for mini and micro installations; Biofuel blending obligations and tax reliefs (International Energy Agency, 2016a).

The goal of the Danish government is to become independent of fossil fuels. Shortly after the creation of the National Renewable Energy Action Plan the government prepared a new policy: Energy Strategy 2050, adopted in 2011. This plan, similar to the NREAP policy includes a more detailed plan achieving 100% independence from fossil fuels. The policy support includes the following aspects for the target to be achieved: the deployment of large scale offshore wind parks, research and development for solar and wave energy technologies, district heating by biomass/gas and geothermal energy. The Energy Strategy is in essence a generic policy addressing the latitude of renewable energy deployment and measures to meet targets, it is the framework in which the Danish government enabled last couple of years to actively address targets involved.

Approximately a year later, the Danish Energy Agreement 2012-2020 outlined the path towards 2020. According to this agreement more than half of the energy demand has to come from wind energy, while simultaneously decreasing electrical energy demand by 12%. The agreement secures expansion of wind energy parks by defining exactly the location of parks and the amount of wind energy to be generated (International Energy Agency, 2016a).

Lastly, the in 2012 enforced policy Regulation on Net-metering for the Producers of Electricity for Own Needs, enables producers of electricity to exempt self-produced electricity from paying tariffs for the amount of exported electricity. This includes self-producers generating all renewable sources excluding geothermal energy installations.

4.3.5. Summary results Copenhagen

Technology

The Municipality of Copenhagen generates 16% of renewable electrical energy in 2014, considerably less than renewable energy deployment on national level and generates more compared to Amsterdam and Hamburg, an expected result. The leading renewable source is bioenergy followed by wind energy. To meet future targets the municipality aims to deploy additional wind combined with solar energy. The deployment of solar lacks behind, this is due Copenhagen extensive natural resource wind and bio degradable substances in Denmark. The usability of bioenergy stagnates due to the limited biodegradable substances available for fuel consumption, wind is limited due to the urban environment of Copenhagen. Therefore other renewable technologies have to be deployed in order for Copenhagen to meet future target of 100% renewable, which is the highest set target of all cases and is therefore also scored the highest standardized result.

Function

The electrical energy tariff for household consumption is considered high with the average value of 0.30€/kWh. The three settlements involved in the tariff have been increasing since the extensive deployment of renewable energy. Even though there is no direct indication that indeed, the deployment of renewable energy is the root cause of the increased tariff. It may be coincidence that from the moment renewable were actively deployed, the tariff increased but it were clear that costly decisions affected the tariff as well. Both, the deployment of renewables and costly decisions may have contributed to the tariff peak. A high tariff consequently means lower electrical energy accessibility.

The current consumption of 4017kW/inhabitant annually is considered average in the European Union. The municipality aims to reduction consumption of commercial and non-commercial sector by 20% compared to 2010 levels. Household consumption is around 2000 kW/householder/per person annually. Similarly to Amsterdam, quite low household consumption.

The municipality would have to be innovative to meet future renewable energy targets. The RAP of 27.4 Ha/inhabitant is severely limited making conventional renewable energy deployment as wind and bioenergy hard to implement. Furthermore, solar energy might be the sole solution to meet targets, that is, during the summer months. Technical and geographical limitations pose an additional problem in that covering the entire roof area of Copenhagen with solar arrays may not be sufficient to meet targets during winter and thus the average renewable generation annually could be insufficient.

Infrastructure

Without doubt, the Danish electricity grid is a well performing grid with only 17mins of interruption annually. As the other cases, which have equally high scores with regard to the security electricity supply, providing the next step in the transition process should not face issues. Even more, the Danish have simultaneously upgraded the grid for the expected high volatile energy input by renewables. An increasing number of high voltage cables together with interconnectors throughout the country enables the highly volatile energy to be easily distributed from one part of the grid, to another.

Furthermore, Denmark imports 2.28% of their electrical energy from Germany, Norway and Sweden. It is positive that the country is almost independent from neighboring countries, however, with an increasing renewable sources deployment, nationally and internationally, an interconnected grid and thus in-and export is highly required to top-off peak electrical energy generation. Beside this, the Danish generation capacity is closely linked to seasons, thus expectations and trends can be modelled, so to minimize peakload and thus balance the grid.

Regime

The Danish research and development expenditure is measured at 10.1 billion or approximately 3% of the national GDP in 2014, considerably higher compared to other cases. There are a couple of reasons for the success of the Danish investment trend. Firstly, pension funds appear to be willingly invest in renewable energy while ditching fossil fuel investments in recent decades. Pension funds see the potential gains of investing in renewable energy, since there is less(financial) risk involved due to collaboration of companies and investors as well as the fact that renewable energy is more sustainable in the long term. Secondly, the Danish investigated the renewable area potential extensively and invested in primarily wind energy due to the windy geographical nature of Denmark. Thirdly, financial and regulatory support in the electrical energy sector were enforced as early as 1976, investing heavily in the beginning of 2000s, taking a considerable advantage and thus headstart compared to other countries.

With regard to the level of ambition, the current policy implementation is not really distinctive compared to other cases in terms of quantitative measurement. Nevertheless, the current score of the circularity of electrical energy metabolism in general is significant. This may indicate that the current Danish market has reached a threshold of continuous development, thereby effectively penetrating lock-ins and thus establishing technologies in the regime is able to breakthrough without the necessity of a wide range of supporting policies.

In any sense, the Danish government enforced policies supporting the transition to a post-carbon society as early as the 1976s. Economic instruments as grants and subsidies and regulatory instruments enforced R&D.

Table 10 Overview standardized results Copenhagen

K1	Technology			
K1.1	Share renewable sources	Meso	16 %	0.80
K1.2	Future share renewable sources (2040)	Meso	100 %	1.00
K2	Function			
K2.1	Electricity tariff households	Macro	0.30 €/kWh	0.49
K2.2	Electricity consumption inhabitant	Meso	4017 kW/inhabitant	0.84
K2.3	Electricity consumption household	Meso	2000 kW/household	0.60
K2.5	Renewable area potential (RAP)	Meso	27.4 Ha/inhabitant	0.27
K3	Infrastructure			
K3.1	Security electricity supply	Macro	17 Mins/interruption	0.97
K3.3	Dependency electricity (self-sufficiency)	Macro	2.28% in-export	0.45
K4	Regime			
K4.1	Renewable energy investments in R&D	Macro	2.96 % of GDP	0.99
K4.2	Level of ambition renewable energy policies	Macro	9 active policies	0.82

Discussion

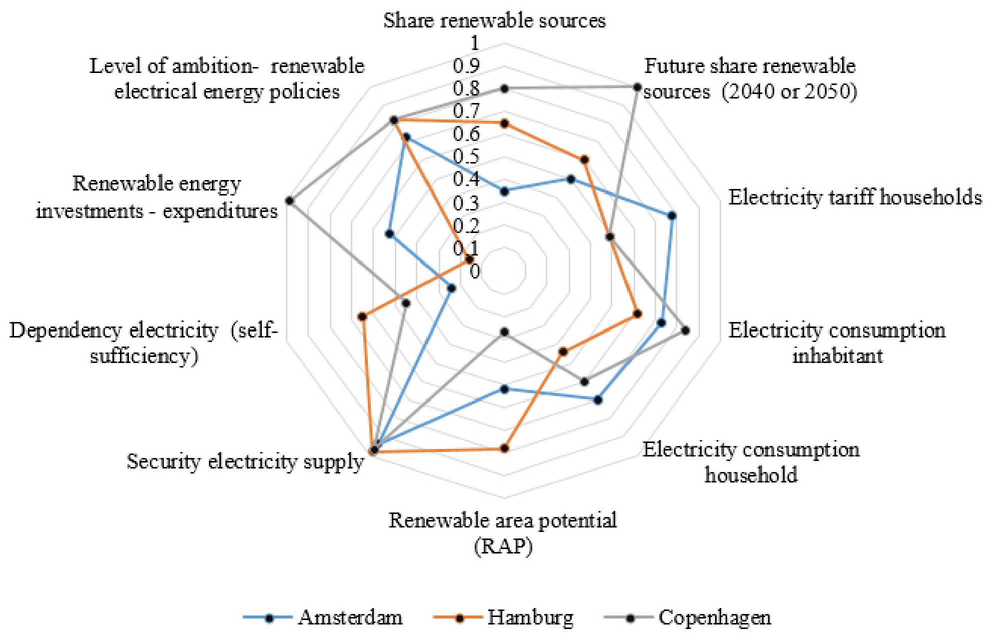
The discussion is structured around the main outline of this thesis. Results in the domains of technology, function, infrastructure and regime are elaborated including the alignment of the domains for each municipality. This is followed some discussion points in the methodology, that further comprises uncertainties and limitation and vital assumptions in this study. And finally the recommended areas for future research is highlighted.

5.1. Results

Table 11 Overview of collective results

Level of measurement – Indicators for the degree of renewable energy implementation				
No	Dimension with related indicator	A	H	C
K1	Technology	0.42	0.62	0.90
K1.1	Share renewable sources	0.35	0.65	0.80
K1.2	Future share renewable sources (2040 or 2050)	0.50	0.60	1.00
K2	Function	0.68	0.58	0.55
K2.1	Electricity tariff households	0.78	0.49	0.49
K2.2	Electricity consumption inhabitant	0.73	0.62	0.84
K2.3	Electricity consumption household	0.70	0.44	0.60
K2.5	Renewable area potential (RAP)	0.52	0.78	0.27
K3	Infrastructure	0.59	0.81	0.71
K3.1	Security electricity supply	0.94	0.98	0.97
K3.3	Dependency electricity (self-sufficiency)	0.24	0.65	0.45
K4	Regime	0.63	0.49	0.91
K4.1	Renewable energy investments - expenditures	0.53	0.16	0.99
K4.2	Level of ambition- renewable electrical energy policies	0.73	0.82	0.82
		0.57	0.59	0.76

Figure 15 Overview of results in a radar diagram



Technology

From a technological perspective, as seen in Figure 16, Copenhagen has the highest share (currently 16%) and future share of renewables (100%) relative to Hamburg and Amsterdam, consisting currently of 62% bioenergy and 38% wind energy. Hamburg current share of renewables is 13%, consisting of 62% bioenergy, 29% wind and 9% photovoltaic. Followed by Amsterdam with a current share of renewables of 7, consisting of 77% bioenergy, 21% wind energy and 2% photovoltaic energy.

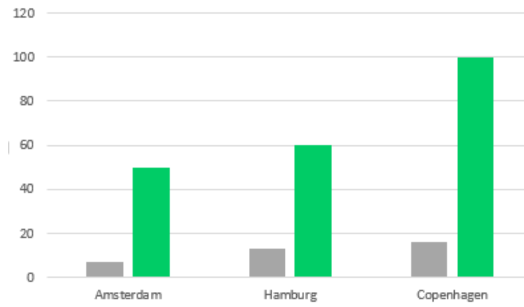


Figure 16 share and future share renewables in %.

Two factors can be attribute to Copenhagen's highest rank in share of renewables relative to Hamburg and Amsterdam. First, Copenhagen initiated the energy transition as early as the 1980s. Second, continues governmental support existed from that point onwards. When this technological development is envisioned in the transition S-curvature, as elaborated by Geels, one could argue that Copenhagen has surpassed the predevelopment phase. This indicates that Copenhagen is in the take-off or in the acceleration phase, while Hamburg and Amsterdam are still in the take-off phase.

An important finding is that the total energy share of the three municipalities is dominated by bioenergy. An explanation for this development may be, as (Faaij, 2006) elaborates: bioenergy plants utilize large parts of already existing fossil fuel power plants. Thus, coal and gas-fired plants are relatively cheap to overhaul and transform to bioenergy plants processing MSW. Hence in 2014, the majority of European nations utilized bioenergy for electrical energy generation (Eurostat, 2016.). However, the key problem with bioenergy consist in the consumption rate being limited to physical input of resources (Faaij, 2006). Achieving future targets with bioenergy is thus unrealistic, unethical, and, as mentioned in the theoretical framework, therefore excluded as possibility to increase the renewable energy share. However, bioenergy is key in the energy transition as it serves the cautious shift from full carbon emission to partly carbon emission to fulfil energy demand.

The future share of renewables are ambitious in all cases. Amsterdam intends to increase the deployment of renewables from 7% to 50%. Hamburg aims to increase the deployment from 13% to 60%. Copenhagen has set their target to a full transition from 16% to 100% by 2040. As seen in Figure 16, the gap between the current and future share of renewable energy generation is significant in all municipalities. Given the time perspective (2014 -2040) the biggest gap between present and future share exist in the Copenhagen case. Evidently, the greater the current renewable energy share, the higher the municipals ambition. All municipalities ambition is to meet targets by the deployment of wind and photovoltaic energy generation.

Function

Inhabitants of Copenhagen and Hamburg pay the highest tariffs, approximately 0,30€/kWh, followed by Amsterdam with €0.18/kWh. This can be explained by a couple of reasons. First, the pricing structure of taxes and surcharge is composed differently in referenced countries due to different macrolevel decisions and legislation. Second, as TenneT has put forward, significant in-export of electrical energy may affect the tariff due to electrical energy surplus. Third, (EnergiNet DK, 2016) elaborates that the tariff of Copenhagen has increased significantly due to investments and technological progress in the renewable energy sector. Scholars (Rotmans et al., 2001) explained that especially at meso level, alternative technologies, and social practices may be subjected to variations, most often these are supported by public subsidies. Thus, tariff increase, in for example Amsterdam, will accommodate a more profitable return for renewable operators, since they are largely dependent on subsidies.

The electrical energy consumption per household constitute of 1800 kWh in Amsterdam, 2325kWh in Hamburg and 2000kWh in Copenhagen. These overall results suggest that the municipality of Amsterdam is the most 'efficient' in terms of energy consumption. This is in line with the expectation, because effective measures prompted the Amsterdam municipality to implement municipal-wide household efficiency measures. Both Hamburg and Copenhagen perform well below the European average of 3500 kWh (Eurostat, 2016a).

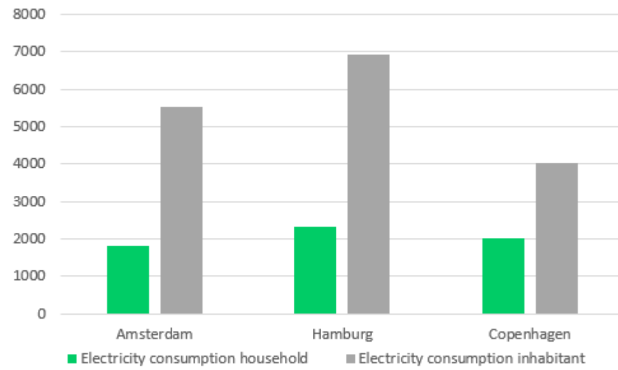


Figure 17 Comparison electrical energy consumption household and inhabitant - in kWh

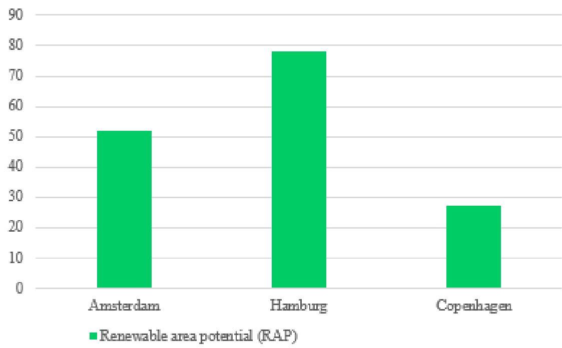


Figure 18 Comparison renewable area potential – in m2

Furthermore, a comparison of results of the average electrical energy consumption reveal that Copenhagen (4017 kWh) consumes the least amount of electrical energy a year per inhabitant, followed by Amsterdam (5522 kWh) and Hamburg (6920 kWh). The average consumption of Hamburg is around 1500kWh higher compared to Amsterdam and almost 3000kWh compared to Copenhagen. A reason for Copenhagen's low consumption rate is the exclusion of industrial activities. Copenhagen thereby effectively consumes less electrical energy per inhabitant. Whereas Amsterdam, and in particular Hamburg, includes large part of their harbor and industrial activities; consuming more per inhabitant. Additionally, another reasons could be the high urban morphology of Amsterdam and Copenhagen compared to Hamburg. This has been underlined by the RAP potential differences. Therefore, the housing stock of both cities probably consumes less energy on average due to terraced housing. Terraced housing is more efficient by design in terms of electrical energy consumption for heating. Additionally, Copenhagen and Amsterdam initiated efficiency measures in the private and non-private sector.

The renewable area potential in Amsterdam and Copenhagen is severely limited. Innovative renewable energy deployment, such as fixated or integrated solarpanels onto/into roofs and (more or less silent) wind turbines situated in industrial areas, are the sole possible solutions to increase the deployment of renewables in all cases. Amsterdam plans to increase solar by 1000MW and wind capacity by 400MW.

Infrastructure

From an infrastructural perspective, the equally well-performing grid stands out immediately. However, there are underlying differences in the performance of the grid. TenneT (2014), the Dutch-German grid operator, ensures that the grid and its performance will not be affected on the short-term. The report *'To a future-proof energy system in The Netherlands'* by TNO denotes that the grid has to undergo several significant adjustments to deal with large amounts of highly volatile wind and solar energy (TNO, 2010). Regarding the Danish grid, (Ropenus, 2015) explicates that the grid accommodates the existing renewable energy feed-in very well. Though, the (Danish Energy Agency, 2015) denotes that growth of capacity will have to be supported by increasing application of interconnectors in 2020, to strengthen the grid for volatile energy. The traditional infrastructure network is meeting its expectations considering the current development such as the highly volatile feed-in. Investments are necessary so to maintain its infrastructural reliability.

Concerning dependency on electricity, The Netherlands imports the largest amount of electrical energy (12.75%). The reason is its cheaper electricity tariffs, and the fact that green energy can be used to compensate grey energy to meet renewable targets. Germany has an in-export surplus of (-7.36%), thus, in turn, they sell bulk of electrical energy to The Netherlands, e.g., contrariwise the primary incentive to export more energy remains unclear. Denmark has a very stabilized in-export regime in the sense that in-export surplus is (2.28%) that implies: a well-matched energy generation – consumption pattern, and slightly over-generation of energy and thus a small percentage of energy is exported.

Regime

Compared to other cases, The Netherlands seem to be making additional investments in their quest to transition by spending 1.5% of its GDP on the energy transition. However, the RES investments are focused on biomass and waste-to-energy because these appear to be most successful in the R&D sector, and have probably minimal financial risks. Even though The Netherlands is categorized as a low-risk investment country for renewable energy (Noothout et al., 2016), investments are mainly focused on 'safe' and low risk investments. The Netherlands and specifically Amsterdam have the lowest renewable energy share (see Figure 16 share and future share renewables). One would expect at least investment levels compared to that of Denmark to increase the deployment of renewables.

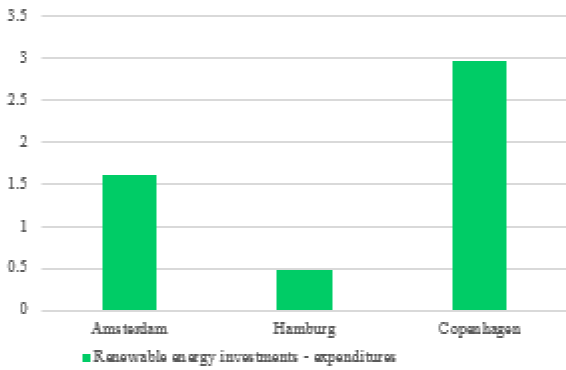


Figure 19 Comparison renewable energy investments – expenditures – in % of GDP

The same holds for Hamburg. The actual investments in renewables is relatively low. Mutual reasons exist between the Netherlands and Germany for rather 'small investments'. These include the closings of subsidies on renewables, and governmental investment brackets are depleted until new targets are set. The depletion of funds may indicate that the regime assumes that the current subsidies are sufficient to establish a stable transition.

Denmark invests almost 3% of its GDP in renewables. This almost twice the amount of investment of The Netherlands. This relatively large share, shows Denmarks' dedication to pursuing the energy transition.

However, the RES policy analysis in the electricity sector showed that there is a similar level of ambition amongst the three selected municipalities. In depth analysis showed differences in policy targets, type, support for renewable source and date of enforcement.

Alignment of domains

As (Geels, 2002) elaborates, the alignment of domains is important to a certain level of socio-technological acceptance in which the alignment and acceptance contributes significantly to the shift from one phase to another to ensure stability. The results presented in Figure 20 Cumulative results domains can be interpreted as the 'alignment' by taking into account the differences between domains. An optimal situation resembles equal cumulative results. Here we see that none of the analyzed cases has an equal alignment between domains. It has been argued by (Geels, 2002) that technology and overarching domain regime both play important role in transition. Technology is important because it enables socio-

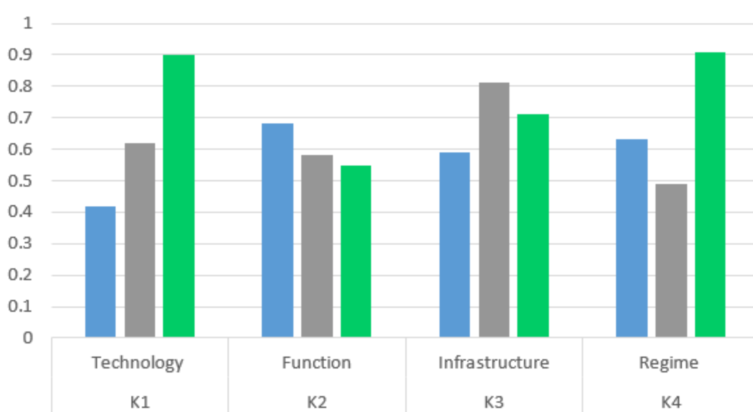


Figure 20 Cumulative results domains. A: Amsterdam, H: Hamburg, C: Copenhagen.

technical developments. And regimes enable the technological innovations to be adopted by economic and/or policy measures.

Looking at the relative importance of the domains, a relatively low alignment exists in Copenhagen (Figure 21). Despite being a frontrunner in renewable energy, function and infrastructure are lacking behind on the domains of technology and regime. Copenhagen is more advanced in the transition process, but the domains are more aligned in Amsterdam and Hamburg.

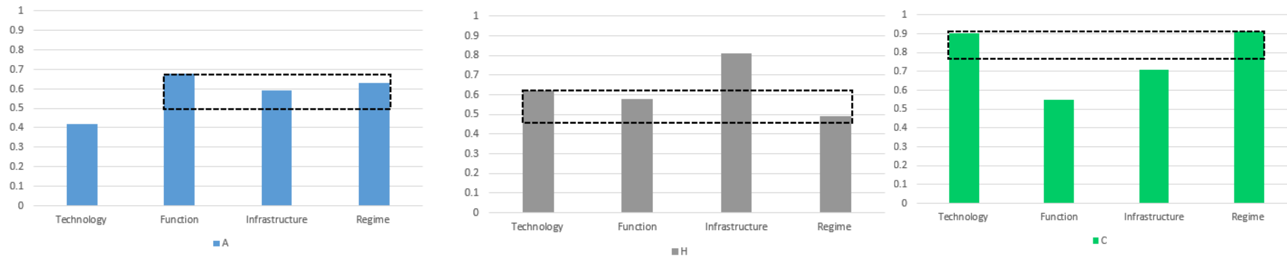


Figure 21 Cumulative results alignment domains case

One observation that could be made from Figure 21 is that technology lacks behind the other domains in Amsterdam. Reasons may be obvious: low deployment of renewable sources due to regime pathways, and more emphasize on energy efficiency measures (function) rather than technological measures. Hamburg enjoys firm alignment between the domains of technology, function and regime. The domain of infrastructure is more advanced compared to the other domains which indicates the readiness for energy transition towards more circular and thus renewable sources.

5.2. Methodology

Retrieved data is used for further case study analysis. This case study is a one-year measurement of energy circularity in the selected municipalities. This snapshot analysis might not be completely representative because it could be possible that the referenced year of 2014 might not be the optimal year for renewable energy generation, e.g. due to the variation of weather conditions. Additionally, weather conditions may vary due to geographical location thereby contributing more to the renewable energy generation and thus to the indicator. Case studies are intended to be used as descriptive tools, and do not determine cause and effect. As prospected future research, cause and effect can be measured by performing a longitudinal study with a multiple-shot analysis approach (Kumar, 2011).

Uncertainties and limitations

Various uncertainties and limitations exist mainly in relation to data. First in relation to meso-level data, data inconsistencies, and limitations in indicators/factors involved. The meso-level data was used to gain insights in the performance of the city in question. Due to a lack of uniform meso-level data, macro-level data was included as well. The inclusion of macro-level data resulted in more dynamic and robust results, because a municipal pathway in energy transition is largely defined by its overarching macro-level entity. However, macro level data is only a rough indication of meso-level functioning. As (Dóci et al., 2006) elaborates, the macro or landscape level represents external processes and factors that influence the regime on meso-level, and (F. W. Geels, 2005) the macro-level is formed by the sociotechnical landscape.

Second, could be the urban environment. An urban metabolism is measured preferably within specific boundaries operating at meso-level. The selected municipalities within this study differ in e.g. size and population. It was expected that even though differences exist between municipalities relevant and homogeneous information at both meso and macro level could easily be gathered by accessing a databank with homogenous datasets similar to Worldbank and Eurostat. Obtaining consistent homogenous data appeared to be challenging. To circumvent this limitation, the definition based on Eurostat data for GDP/population and selected predetermined municipal boundaries based on Eurostat and ArcGis was used.

Third, the potential area for renewables can only be measured for the renewable sources solar and wind energy. Because bioenergy and geothermal are largely centralized installations and not similarly translatable to the potential area sizes in km^2 or m^2. Hydro energy is excluded because this is not implemented within municipal borders. Likewise, the level of ambition of each municipality to increase its share renewables is restricted to the electrical energy sector and includes only enforced policies. Thereby, previous enforced policies and perhaps other (non-electrical energy sector) policies that may contributed to the transition process might be excluded.

Assumptions

Several assumptions were made based theory. Some of these coincide with the findings, others are in contradiction to the findings. First, the urban electrical energy metabolism of the investigated cases are assumed to be linear. As research progressed it became evident that defining a linear electrical energy metabolism is not as straightforward as other flows in an urban metabolism because of data inconsistency. Nevertheless, the assumption that all cases are linear corroborates with the empirical and theoretical findings. In no case, the renewable energy generation capacity exceeded >50%. Therefore, it can be concluded that the municipalities are linear, indicating that the assumption is justified.

Second, it was assumed that accumulated municipal electrical energy generation of source X was generated within municipal borders. However, some renewables, were located outside the municipal boundaries. These were excluded, based on the primary objective and scope of this study.

Third, it was assumed that Copenhagen is further developed in its energy transition than Amsterdam and Hamburg. The results underline this assumption. Copenhagen indeed obtained higher standardized scores and is therefore, more transitioned towards a circular energy metabolism.

6. Conclusions

6.1. Transition towards a more circular electrical energy metabolism

Various theoretical and empirical insights are derived that are used to answer the **GRQ**. Insights involve the differences in domains between the selected cases, the differences in the alignment of these domains, and the progression of domains. As an example, the case of Copenhagen provides theoretical and empirical insights into the 'desired' configuration needed for a more circular electrical energy metabolism and how this configuration is achieved. Understanding the differences between domains is key to determine the extent to which selected cities will be able to transition towards a more circular energy metabolism by 2040.

This study shows that the differences between domains may be attributed to multiple developments. For example, the geolocation of a municipality that leads to different adoption of suitable technologies. Technology has shown to be the 'most' important domain in energy transition of the selected cases. This can be explained by the fact that technology affects the rate of adoption of, amongst others, alternative energy sources, and thus enhances energy transition.

The empirics in this study have shown that the domain of technology enhanced Copenhagen's energy transition with an above average score in the MCA. This could primarily be explained by the support of the domain regime, where it finds continuous support. Copenhagen demonstrates that even though the fact that the domains of infrastructure and function are less progressed, the well progressed domains of technology and regime exert more influential power in the transition process. Regime and technology are thus mutually supporting domains. This means that progression of the domain technology can be attributed to concurrent progression by the domain regime. In fact, it might be argued that the regime plays an important, if not an indispensable role to allow technology factors to be exponentially adopted.

Theoretically, it has been elaborated that the first phases of energy transition are characterized by a slow adoption rate of technology in which regime support in the form of policies and investments is heavily required to disrupt existing lock-ins. As such, continuous regime support during the first phases of transitions is required, leading to a change of configuration of the domains. This suggests that it is important to offer low production cost, low selling prices to enhance niche penetrations to break existing lock-ins, change configurations, and positively affect the adoption rate during the first phases (predevelopment and take-off phase). Copenhagen proved that 'early' accessibility and applicability of technological innovations had to be supported by regime measures.

Copenhagen may optimize its current energy system by improving the function and infrastructure domain. Optimizations for affordable electricity prices to increase the consumption of circular (renewable) urban energy. And grid optimizations: centralized towards decentralized grid to mitigate high volatile electrical energy by (local-international) interconnectors and energy storage solutions. Both measures can potentially enable the municipality to achieve an alignment across all domains and prevent future bottlenecks.

Amsterdam is arguably in the pre-development phase of the energy transition. Technology wise the municipality lacks behind due to very slow adaptation rate of renewable sources. The local regime has successfully implemented municipal-wide efficiency measures while less successfully supported renewable sources. The theory suggests that macro-level regime decisions affect the meso-level technology development. Existing regime lock-ins: traditional energy generation methods, continue to persist this day. Optimizing the energy system in Amsterdam requires careful collaboration and mutual macro-meso level support.

Hamburg, is also arguably in the pre-development phase. Its domains are relatively aligned in which domain of regime underperforms. This can form a potential bottleneck in the energy transition as regime support is essential for the technology domain to improve the adoption rate of renewable technologies.

6.2. Contributing factors energy transition

The factors contributing to a successful sustainable energy transition in the selected cases are identified (**SRQ1**), based on theoretical and empirical analysis. It could be concluded that alignment of the domains of technology, infrastructure, function, and regime on itself is an important factor of success. Alignment of these domains is fundamentally important for a 'stable' transition. Additionally, the following underlying factors of importance for sustainable energy transitions are identified: the current share and future share of renewables, electrical energy tariff, consumption of inhabitants and households, the renewable area potential, security of electrical energy supply, self-sufficiency, renewable energy investments, and renewable energy policies. Furthermore, as explained in the GRQ, dynamic factors in the form of historic (oil-crisis) events may affect domains direct or indirectly.

Moreover, additional dynamic factors could influence the pathway of a transition, e.g. historic events as the 1970s oil crisis. The oil crisis of the 1970s resulted in an increase of Copenhagen's awareness of the negative side effects of the dependence on fossil fuels. This led to a demarcated configurable change by implementation of policies and increasing expenditures on renewables. Demarcated configurations are difficult to change, but can (more easily) be changed by implementing policies, increasing level of expenditures in renewables, and consequently sustaining these factors (policy and expenditure) on relatively high levels over long periods of time. Consistency and determination of these changes are key for a successful transition. Policies and expenditures are factors that could be categorized into the domain of regime. This suggests that the regime plays an important and possibly vital role in the (beginning) of sustainable energy transition.

6.3. Differences in factors

Important differences exist in terms of selected domains between the selected cases (**SRQ2**). The following differences are addressed: differences in empirical analysis of factors, differences in the alignment of domains, and other more comprehensive dynamic differences.

The following factors display the most notable differences among the selected cases: current- and future share of renewable sources, electricity tariff and renewable area potential (domain of function), and renewable energy investments (domain of regime). The difference in these factors can be attributed to a couple of dynamics. First, the factor of *current- and future share of renewable sources* is dependent on differences in transition initiation. For instance, Copenhagen ensured increased deployment of renewables. Second, difference in meso-macro pathways lead to different positions of the selected cases. For example, the domains are more aligned in Copenhagen compared to Amsterdam and Hamburg. Third, future share is attuned to a realistic probability scenario in which the current amount of renewables determines future targets. The factor of *Electricity tariff household* is correlated to investments to ensure a continues deployment of renewable sources, management and improvements to the grid. This explains the differences between Copenhagen and Hamburg/Amsterdam. The factor of *renewable area potential* unveils differences in the morphological situation of Amsterdam and Copenhagen. Innovative solutions in terms of renewable energy technology, location of energy sources, and energy utilization are required in limited RAP cities. Last, a notable difference in *Renewable energy investments* is recognized. This includes the risk profile of renewable energy investments. Fossil fuel supporting policies on national and/or municipal level contribute to a higher investment risk-profile.

6.4. Differences in alignment domains

The empirical analysis showed differences in alignment of domains between the selected cases as well. The largest differences are between the domains of technology, function and regime. The domain infrastructure is relatively equally aligned to the other domains between the cases. Reason for this equality in the domain of infrastructure may be found in the fact that the investigated indicators serve as top priority to be maintained in the European Union. This suggests that high standards are expected in all cases and thus high MCA scores are achieved.

In addition to the difference in the domain of technology, function and regime, municipalities and national policies enable specific measures to kickstart the transition in which prosperous development and alignment of domains triangulate. For instance, Copenhagen allocated large private and non-private investment funds to post-carbon developments. This enabled R&D to push the transition more rapidly in the technology domain. Hamburg initiated their own wind-energy manufacturing hub that attracted global wind energy businesses. And Amsterdam is effectively aiming at large-scale energy efficiency measures throughout the municipality. The selected municipalities have thus specific measures to build upon.

In answering **SRQ3,** it has been learned that there is a complex dynamic meso-macro playground that affects the transition pathway. Decisions made on macro level have direct consequences at meso level. and enforced policies and public funds are a direct result of decisions made on macro level. The energy transition pathway is partly dependent on geographical location and morphological urban geography because these poses opportunities (RAP) restrictions and limitations regarding renewable deployment. Furthermore, it can be concluded that the domains of technology and regime should be aligned in the first phases of transitions to make 'rapid' progression.

6.5. Recommended areas for future research

Altogether, the derived insights encourage further empirical research and a broader understanding of transition theory in urban environments. The findings of the four most relevant domains in transitions that distinguishes different configurations helps to further determine the transition pathway. This study also corroborates the finding that technology is indeed an important domain.

The extent to which the mentioned municipalities may be able to transition towards a more circular energy metabolism should be studied in further research. A suggestion could be to determine differences in configurations of domains as proposed by Rip and Kemp (1998). This is traditionally known as a multi-layered approach. It could provide the necessary additional information to decipher municipal configurations, since the underlying domain factors are rarely bound to the meso-level exclusively, because the majority of meso-level factors originate from top-down - macro-level decisions.

Furthermore, the study measured the current state of affairs to evaluate actual change. This suggests that the path of transition, additional (yearly) points of measurements (longitudinal study), will have to be carried out. By this method, the path of transition can be mapped out including a detailed pattern and probabilistic determination of the steepness of the typical S-curvature in transition studies.

To provide a more accurate and reliable study within the MCA constrains. The most optimal and least optimal cases should be examined. By doing so, the quantified values can be used to more accurately define the range of ideal- and least ideal world of energy transition and therefore more accurately derive standardized quantified results.

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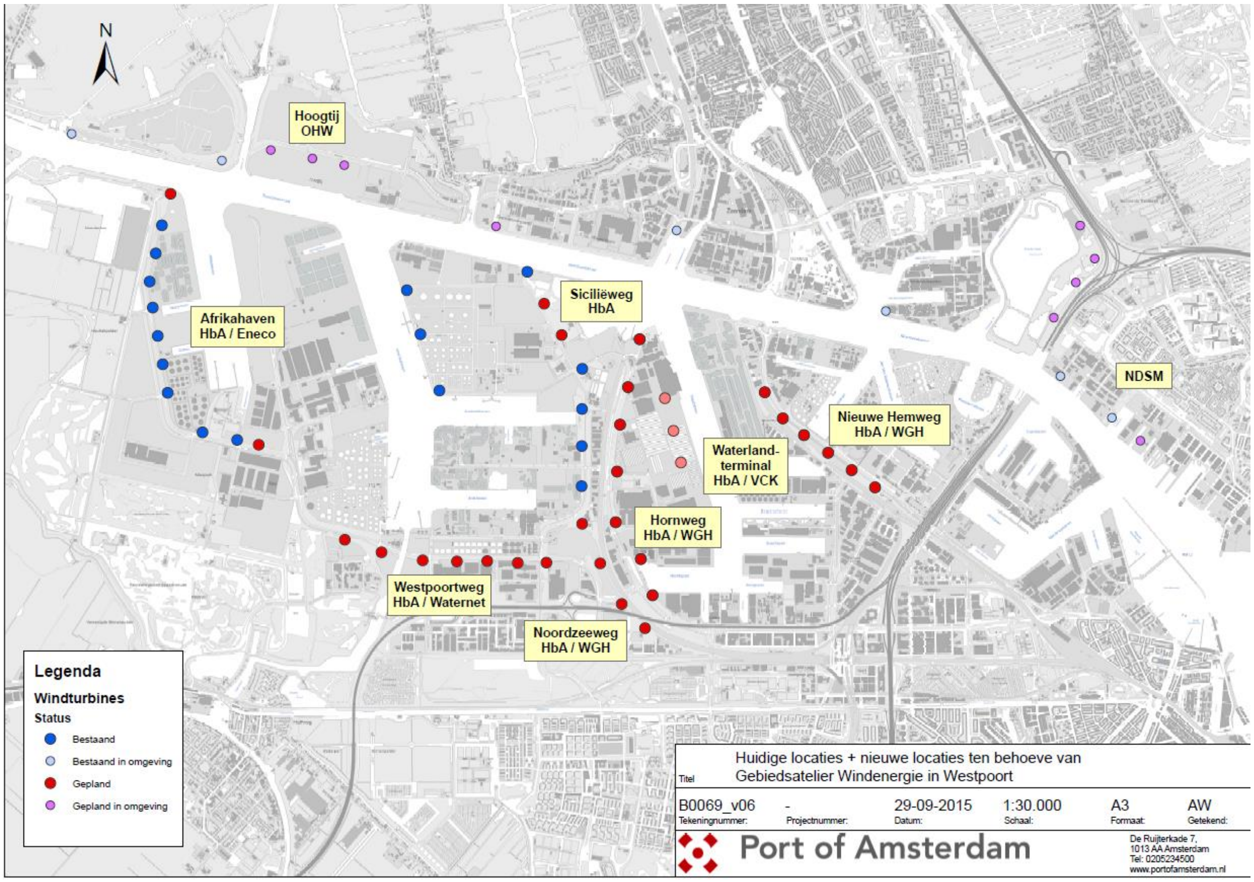
7. Appendices

Appendix 1 Location renewables

Source: (Port of Amsterdam, 2015)

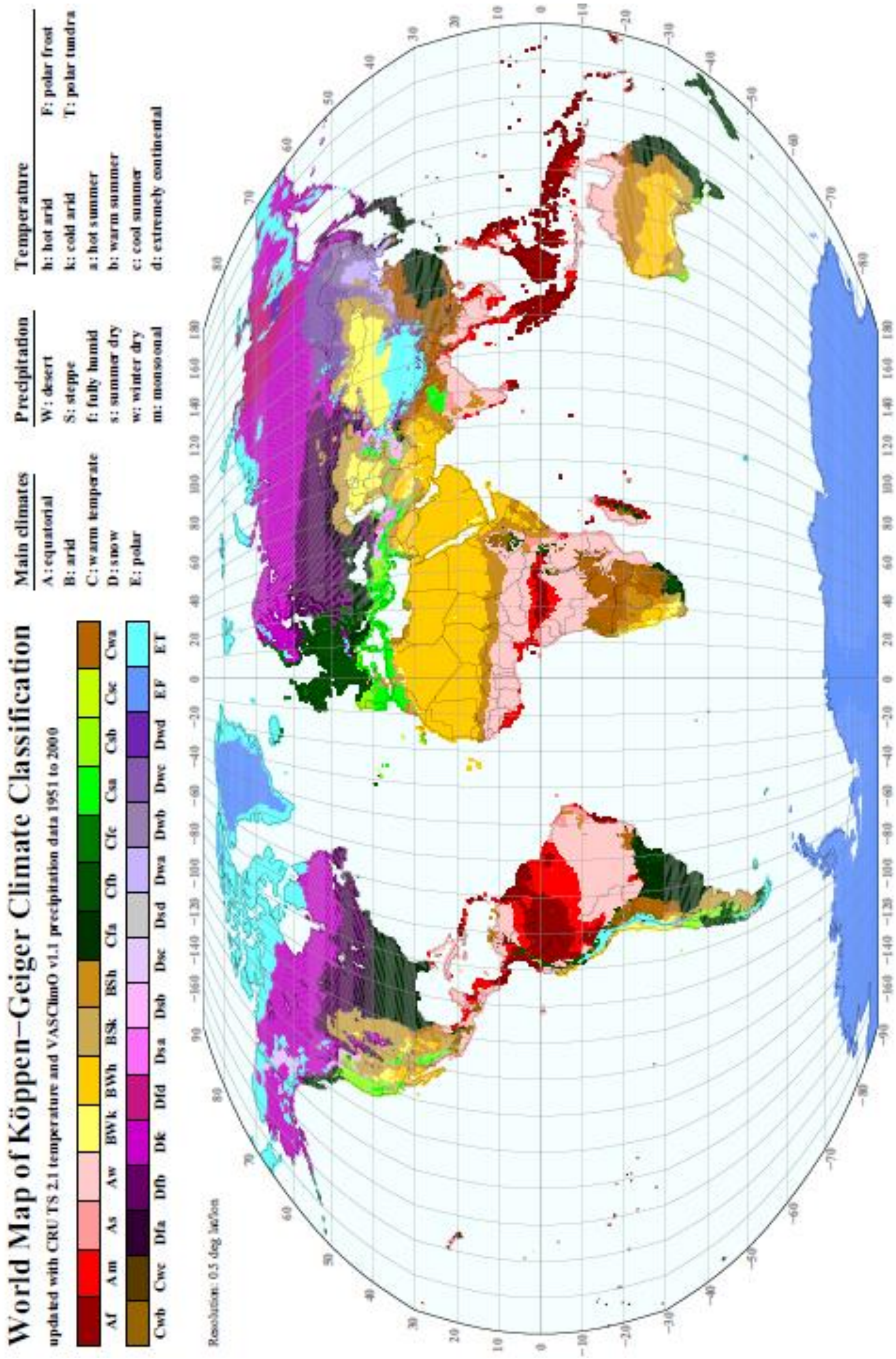


Appendix 2 Criteria case study selection

Comparability selected cases. Population, density and GDP via (Eurostat, 2016b). *Climate via* (Eurostat, Climate Data 2016)

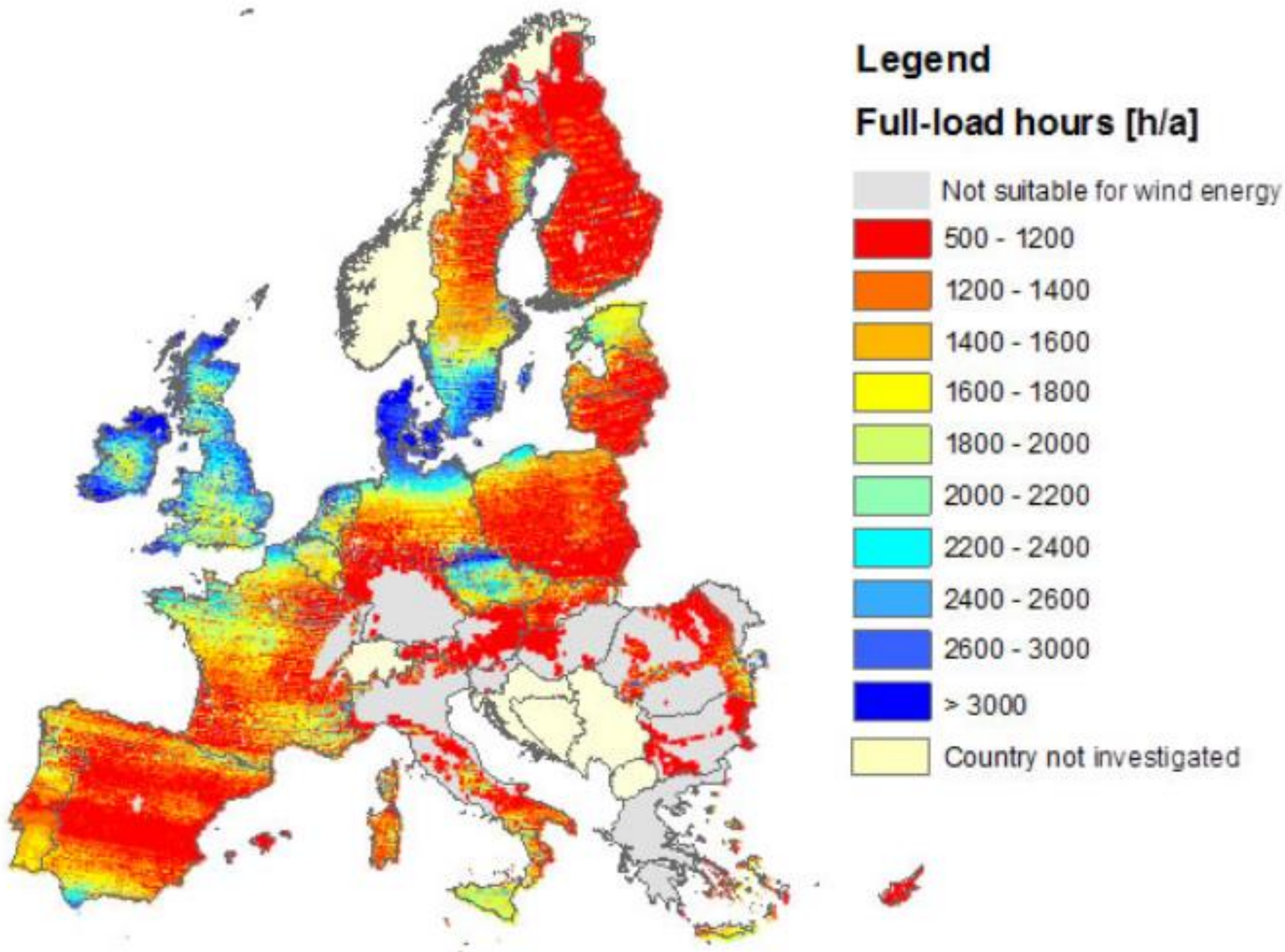
Criteria	*Amsterdam*	*Stockholm*	*Copenhagen*	*London*	*Hamburg*	*Oslo*	*Helsinki*	*Riga*	*Paris*
Population	838,338	847.073	591.481	8.538.689	1.780.329	658.390	629.512	641.007	2.240.621
Population density	4.987/km^2	3.597/km^2	2.052/km^2	5.432/km^2	2.300/km^2	1.400km^2	2.945/km^2	2.300/km^2	10.550.350km^2
GDP (metropolitan area- per capita)	€ 47,388 (2014)	€ 59,812 (2014)	€ 57,133 (2014)	€ 61.823 (2013)	€ 66.949 (2015)	€ 61.233 (2014)	€ 48.798 (2014)	€ 13.388 (2013)	€ 71.126 (2011)
Average yearly temperature	17 °C	16 °C	17 °C	16 °C	17 °C	14 °C	12 °C	14 °C	19 °C
Average yearly sun exposure	1662 hours	1821 hours	1540 hours	1460 hours	1652 hours	1632 hours	1802 hours	1812 hours	1840 hours
Irradiation kWh/m^2	Max-1300 Min-1000	Max-1000 Min-750	Max-1100 Min-800	Max-1200 Min-900	Max-1200 Min-900	Max-800 Min-600	Max-900 Min-700	Max-900 Min-700	Max-1400 Min-1050
Average yearly wind speed	5 m/s	3.5 m/s	4.5 m/s	4 m/s	4 m/s	3 m/s	3.5 m/s	3.5 m/s	4 m/s
Climate typology	Warm temperature	Warm temperature	Warm temperature	Warm temperature	Warm temperature	Warm temperature	Snow	Snow	Warm temperature
Precipitation	Fully humid	Fully humid	Fully humid	Fully humid	Fully humid	Fully humid	Fully humid	Fully humid	Fully humid
Temperature	Warm summer	Warm summer	Warm summer	Warm summer	Warm summer	Warm summer	Warm summer	Warm summer	Warm summer
River-based city	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sea-based city	✓	✓	✓	X	X	✓	✓	✓	X
Country EU-member	✓	✓	✓	✓	✓	X	✓	✓	✓
Number of active renewable energy policy types (per country)	13	8	10	12	8	8	7	6	8
Data availability and consistency	✓	X	✓	✓	✓	X	X	X	✓

Appendix 7 Climate classifications



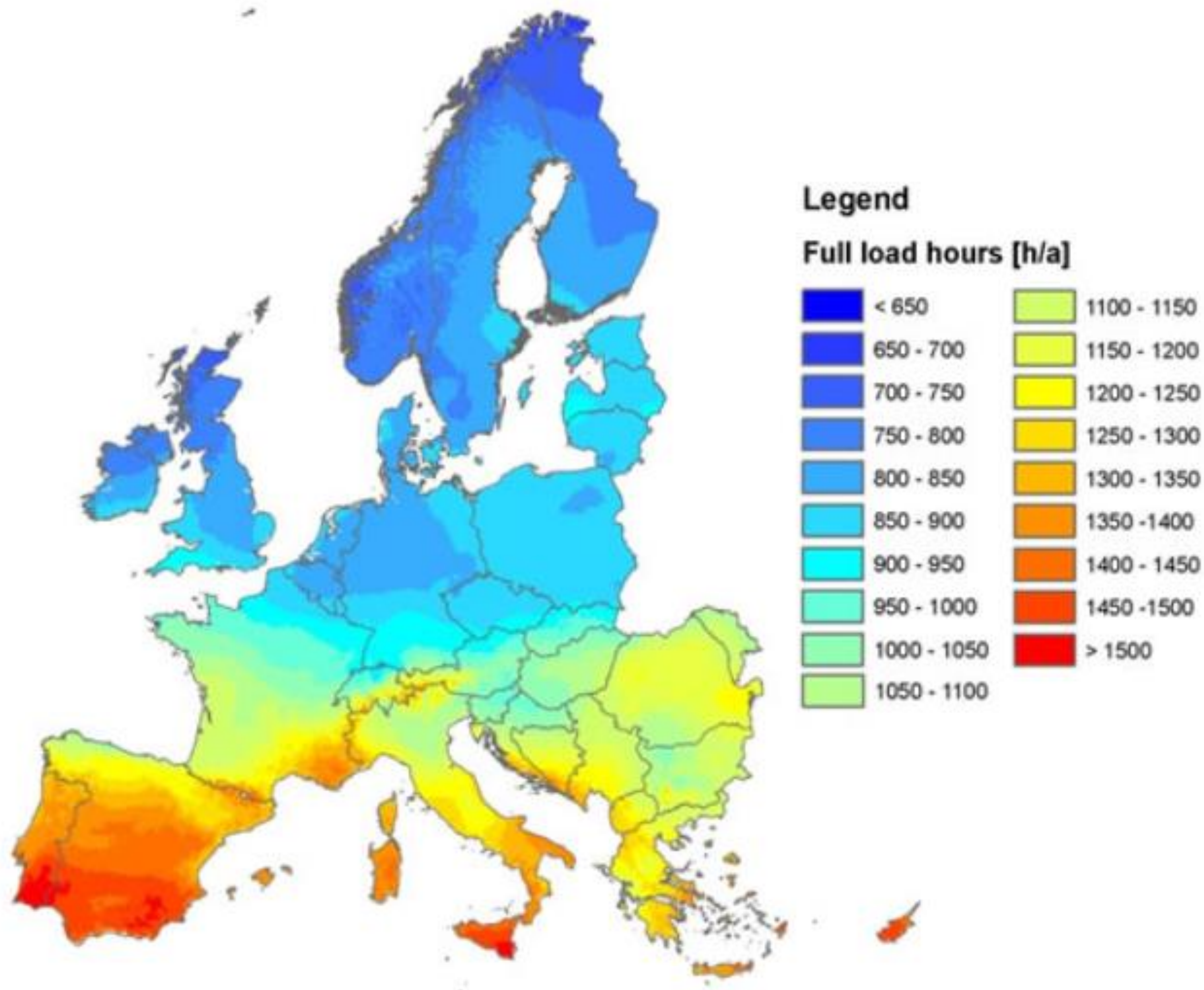
Source: (Kottek et al., 2006)

Appendix 3 Wind energy resource potential



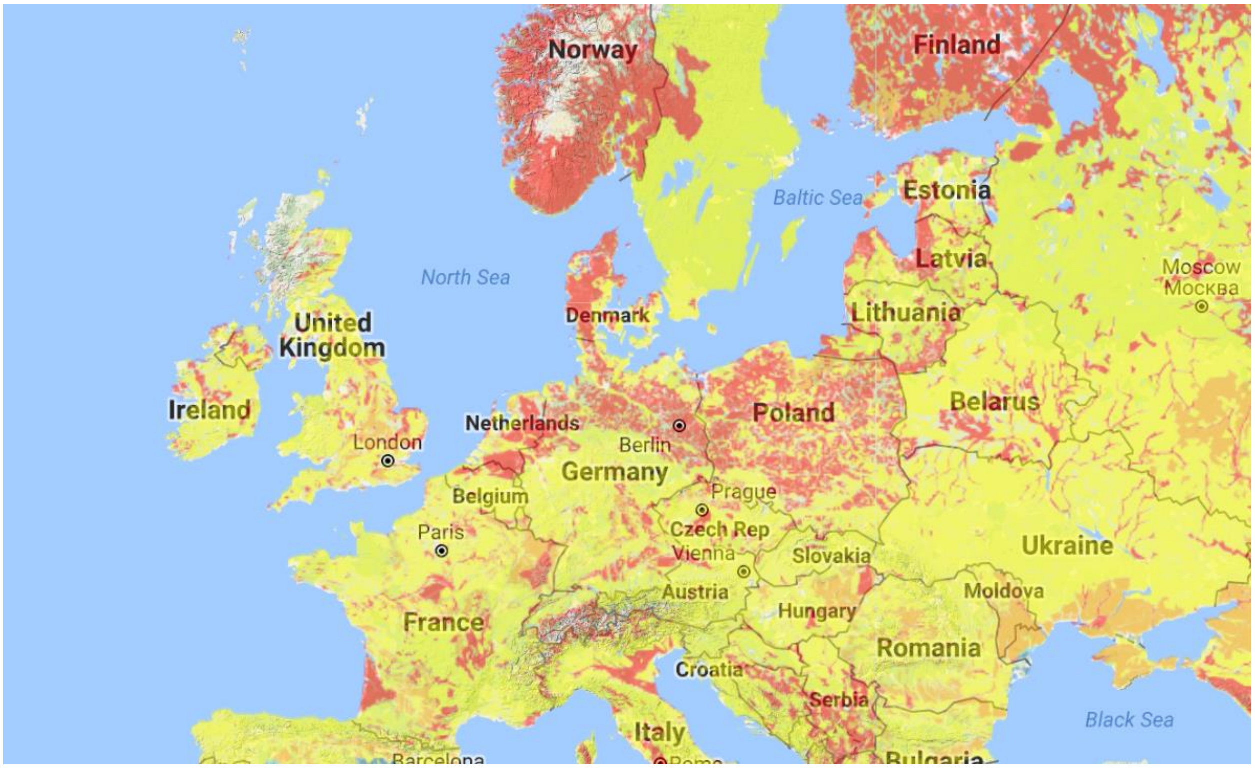
Source: (Hoefnagels et al., 2011)

Appendix 4 Solar radiation and photovoltaic electricity potential



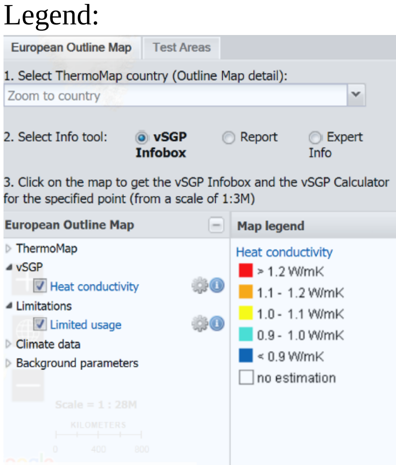
Source: (Hoefnagels et al., 2011)

Appendix 5 Geothermal energy potential



Source: (Thermomap, 2016)

Legend:



Appendix 6 Renewable electricity data per city

Amsterdam	2014	(estimation) 2040 target	**Description**	**Reference**
Renewable electricity generation:	GW/year	GW/year	Available data for year 2014 and 2040	(Municipality of Amsterdam, 2015)
Wind energy	132.5	806	Yearly wind electricity generated	(Municipality of Amsterdam, 2015)
Photovoltaic energy	10.8	833	Yearly photovoltaic electricity generated	(Municipality of Amsterdam, 2015)
Hydro - tidal energy	0	0	Yearly hydro electricity generated	(Municipality of Amsterdam, 2015)
Bio energy	542	490	Yearly biomass electricity generated	(Municipality of Amsterdam, 2015)
Geothermal energy	0	0	Yearly geothermal electricity generated	(Municipality of Amsterdam, 2015)
Total renewable electricity generation	685.3	2129	Sum of renewable electricity generation (within the municipality	Calculated
Total renewable electricity consumption	685.3	2129	Sum of renewable electricity consumption (within the municipality)	Calculated
Total non-renewable electricity generation	9329.4	9329.4	Sum of all conventional electricity sources	(Municipality of Amsterdam, 2015)
Total electricity generation	10014.7	11458.4	Sum of all electricity sources	Calculated
Total electricity consumption	4538.3	*No data*	Sum electricity consumption for the municipality	(Municipality of Amsterdam, 2015)
Total residential building electricity consumption	792.3	*No data*	Sum of electricity use residential buildings (number of households x average household consumption 3291 kWh)	(Energie In Beeld, 2016)and (World Energy Counsil, 2015)
% Non-renewable electricity generation	**93%**	**81%**		(Municipality of Amsterdam, 2015)
% Renewable electricity generation	**7%**	**19%**		(Municipality of Amsterdam, 2015)
% Electricity consumed by households	**17%**	**-**		

Hamburg	2014	2040 target	**Description**	**Reference**
Renewable electricity generation:	GW/year	GW/year	Available data for year 2014 and 2040	
Wind energy	114.7	*No data*	Yearly wind electricity generated	(Municipality Hamburg, 2016)
Photovoltaic energy	36.2	*No data*	Yearly photovoltaic electricity generated	(Municipality Hamburg, 2016)
Hydro - tidal energy	0.1	*No data*	Yearly hydro electricity generated	(Municipality Hamburg, 2016)
Bio energy	245.1	*No data*	Yearly biomass electricity generated	(Municipality Hamburg, 2016)
Geothermal energy	0	*No data*	Yearly geothermal electricity generated	(Municipality Hamburg, 2016)
Total renewable electricity generation	396.1	*No data*	Sum of renewable electricity generation (within the municipality	Calculated
Total renewable electricity consumption	369.1	*No data*	Sum of renewable electricity consumption (within the municipality)	Calculated
Total of other sources of electricity generation	2603.8	*No data*	Sum of all conventional electricity sources	(Municipality Hamburg, 2016)
Total electricity generation	3000	*No data*	Sum of all electricity sources	(Municipality Hamburg, 2016)
Total electricity consumption	12200	*No data*	Sum electricity consumption for the municipality	(Municipality Hamburg, 2016)

Total residential building electricity consumption	1691.1	*No data*	Sum of electricity use residential buildings (number of households x average household consumption 3079 kWh)	(Municipality Hamburg, 2016)
% Non-renewable electricity generation	**87%**	**40%**		(Municipality Hamburg, 2016)
% Renewable electricity generation	**13%**	**60%**		(Municipality Hamburg, 2016)
% Electricity consumed by households	**14%**	**-**		

Copenhagen			**Description**	**Reference**
Renewable electricity generation:	2014 GW/year	2015 GW/year	Available data for year 2014 and 2040	
Wind energy	178.9	*No data*	Yearly wind electricity generated	(Municipality of Copenhagen , 2015)
Photovoltaic energy	0.7	*No data*	Yearly photovoltaic electricity generated	(Municipality of Copenhagen , 2015)
Hydro - tidal energy	0	*No data*	Yearly hydro electricity generated	(Municipality of Copenhagen , 2015)
Bio energy	294.5	*No data*	Yearly biomass electricity generated	(Municipality of Copenhagen , 2015)
Geothermal energy	0.01	*No data*	Yearly geothermal electricity generated	(Municipality of Copenhagen , 2015)
Total renewable electricity generation	474.1	*No data*	Sum of renewable electricity generation (within the municipality	(Municipality of Copenhagen , 2015)
Total renewable electricity consumption	474.1	*No data*	Sum of renewable electricity consumption (within the municipality)	(Municipality of Copenhagen , 2015)
Total of other sources electricity generation	2528	*No data*	Sum of all conventional electricity sources	(European Green City Index, 2014)
Total electricity generation	3002.1	*No data*	Sum of all electricity sources	(European Green City Index, 2014)
Total electricity consumption	2288	*No data*	Sum electricity consumption for the municipality	(Municipality of Copenhagen , 2015)
Total residential building electricity consumption	1097	*No data*	Sum of electricity use residential buildings (number of households 283.000 x average household consumption 3878 kWh)	(Municipality of Copenhagen , 2015) and (World Energy Counsil , 2016)
% Non-renewable electricity generation	**84%**	**0%**		
% Renewable electricity generation	**16%**	**100%**		
% Electricity consumed by households	**48%**	**-**		

Appendix 7 Renewable Area Potential (RAP)

This section explores the renewable area potential in (km2-m2 per inhabitant) for the municipalities Amsterdam, Hamburg and Copenhagen.

Renewable application in cities is largely dependent geographical potential (Ramachandra and Shruthi, 2007). This includes;

1) the natural availability of resources: solar irradiation and wind speed.
2) the spatial availability – amount of area to implement renewable sources.

For calculating RAP, it is assumed that more available space mirrors a higher renewable area potential. It should be noted that these are theoretical estimations. Surely, not every km2 will be or can be made available for renewable applications because legal and jurisdictional restrictions.

The municipalities Amsterdam, Hamburg and Copenhagen have largely similar natural resources due to their close geographical location in the northern hemisphere, also seen in Appendix 3 Wind energy resource potential, Appendix 4 Solar radiation and photovoltaic electricity potential and Appendix 5 Geothermal energy potential meaning that the natural potential is more or less similar in all cases. Therefore only point 2), spatial availability – amount of available space to implement renewable sources will be further investigated. Furthermore, only "decentralized" sources as wind and solar will be taken into account because these are more easily expressed in the theoretical energy potential per m2.

Solar is calculated by measuring the available area for solar applications (roofs and fallow land e.g.), the available area mirrors the amount of m2 solar panels. Wind is calculated by measuring the available area for wind application in which maximum casting distance (585m) is taken into account as described by (KEMA - Ministry of Economic Affairs, 2013, p. 95). Casting distance is a virtual circle around the turbine for save distance to any residential building to be situated.

The total area and its spatial division in the municipality of Amsterdam is examined as seen in Table 12 Spatial potential for renewable applications in Amsterdam and Table 13 . Numbers are extracted from (Openbare Ruimte en Groen – Bodemgebruik 2014). The area for renewable sources application in urban environment is 11.5% solar and 3% wind.

Table 12 Spatial potential for renewable applications in Amsterdam

Division of space in km2 Municipality of Amsterdam	Solar	Wind
Parking area	0.1	0.01
Built area	0.2	0.02
Semi- built area	0.2	0.01
Recreation area	0.1	0.05
Agricultural area	0.15	0.2
Nature area	0.01	0
Water area	0.05	0.01
Average area for renewable sources in urban environments	*0.115*	*0.03*

This means that in urban environments the average area suitable for renewable applications is 11.5% for solar and 3% for wind respectively.

Table 13 Renewable area potential Amsterdam

Amsterdam	Area (km2)	Solar (km2) *Factor: 0.115*	Wind (km2) *Factor: 0.03*
Parking area	16.86	1.93	0.50
Built area	79.19	9.10	2.37
Semi- built area	11.89	1.36	0.35
Recreation area	25.57	2.94	0.76
Agricultural area	25.49	2.93	0.77
Nature area	5.6	0.64	0.17
Water area	54.82	6.30	1.64
Total km2	219.42	25.2	6.56
Total per inhabitant (821.752 inhabitants)	0.000267 km2 per inhabitant = 267m2	0.0000306 km2 per inhabitant = 30.6 m2	0.0000079 km2 per inhabitant = 7.9m2
Renewable area potential per inhabitant (2014)	30.6 + 7.9 = 38.5 RAP/inhabitant		

In table 7 the total area available per inhabitant is 267m2. For renewable area potential this is with the factor of 11.5% solar and 3% wind this is valued at 30.6m2 and 7.9m2 per inhabitant. For the cases Hamburg and Copenhagen identical area renewable potential factors are used.

Table 14 Renewable area potential Hamburg

Hamburg	Area (km2)	Solar (km2) *Factor: 0.115*	Wind (km2) *Factor: 0.03*
Total	755.3	86.85	22.65
Total per inhabitant (1,762,791 inhabitants)	0.000428km2 – 428 m2	0.0000492km2 49.2m2	0.0000128km2 12.8m2
Renewable area potential per inhabitant (2014)	49.2 + 12.8 = 62 RAP/inhabitant		

Table 15 Renewable area potential Copenhagen

Copenhagen	Area (km2)	Solar (km2) *Factor: 0.115*	Wind (km2) *Factor: 0.03*
Total	86.2	9.91	2.58
Total per inhabitant (569.557 inhabitants)	0.000104km2 – 104m2	0.0000173km2 – 17.3m2	0.00000452 km2 – 4.52m2
Renewable area potential per inhabitant (2014)	17.3 + 4.52 = 21.82 RAP/inhabitant		

Appendix 8 Dependency

Source: (Fraunhofer ISE, 2016)

Netherlands (Amsterdam). Data verified (CBS, 2015)

Import *(2014)*	TWh	Export *(2014)*	TWh
BE > NL	3	NL > BE	9.6
GB > NL	0.05	NL > GB	7.5
GER > NL	24.3	NL > GER	0.34
NO > NL	5.5	NL > NO	0.10
Total import	32.85	Total export	17.54
Net in-export	15.31 TWh import		
Total electricity consumption	Total: 120 TWh. 15.31TWh out of 120 TWh = 12.75%		

Germany (Hamburg). Data verified (Fraunhofer ISE, 2016)

Import *(2014)*	TWh	Export *(2014)*	TWh
NL > GER	0.34	GER > NL	24.3
AU > GER	5.5	GER > AU	14.5
CF > GER	4.6	GER > CF	11.5
PL > GER	0.05	GER > PL	9.2
DK > GER	4.5	GER > DK	8
LUX > GER	0.78	GER > LUX	4.2
CZ > GER	6.3	GER > CZ	3.8
SWE > GER	1.8	GER > SWE	0.77
FR > GER	14.8	GER > FR	0.83
Total import	38.67	Total export	77.1
Net in-export	38.43 TWh export		
Total electricity consumption	Total: 521.5 TWh 38.42TWh out of 521.5 total = -7.36%		

Denmark (Copenhagen). Data verified (EnergiNet DK, 2016)

Import *(2014)*	TWh	Export *(2014)*	TWh
GER > DK	8	DK > GER	4.5
SWE > DK	4.7	DK > SWE	3.8
NO > DK	4.1	DK > NO	1.5
Total import	16.8	Total export	9.8
Net in-export	7 TWh import		
Total electricity consumption	Total: 306 TWh. 7TWh out of 306 TWh= 2.28%		

Appendix 9 Indicators from literature

To measure the extend of (electrical) energy circularity in urban environments.		
Source	To measure	Indicator as referenced
(European Green Capital, 2016) and (International Atomic Energy Agency, 2005)	Energy performance	• The development and goals for renewable energy share of all energy (heat or electricity)(%) • Energy consumption and performance of buildings (kWh/m2)
(ICLEI-tools, 2016)	Greenhouse gas emissions	• Total CO2 equivalent emissions per capita (tones/cap/year). • Total electricity consumption per capita (kWh/cap/year) .
(IEA, 2008) (Yang, 2012)	Residential energy performance	• Energy consumption per occupied dwelling (kWh/cap/year) • Energy consumption total floor area (kWh/m2)
(International Atomic Energy Agency, 2005)	Energy accessibility	• Share of households without electricity or energy (%)
(International Atomic Energy Agency, 2005)	Energy affordability and prices	• Share of household income spent on electricity (%) • End-use energy prices by energy source and or by sector (kWh/$)
(International Atomic Energy Agency, 2005) and (International Energy Agency, 2008)	Use and production patterns: overall use	• Energy use per capita (kWh/cap/year)
(International Atomic Energy Agency, 2005) and (ICLEI-tools, 2016)	Use and production patterns: productivity:	• energy use per unit of GDP
(International Atomic Energy Agency, 2005) and (International Energy Agency, 2008)	Diversification: fuel shares and electricity	• Share of conventional energy sources to the total energy mix (MWh or GWh/year)
(International Atomic Energy Agency, 2005)	Diversification: renewable electricity shares	• Renewable energy share in energy and electricity (mWh/year)

Appendix 11 Urban environment of concern

Amsterdam

The capital city of the Netherlands founded in the late 12th century and situated in the west in the region also known as Holland. The city has quite unusual characteristics in that much of its land has been reclaimed, and the historic city center was builded around water and canals. Amsterdam is a dense and compact city inhabiting over 821.752 citizens (CBS, 2016) with a population density of 4.987 per square kilometer. The city is directly connected to the North-Sea (west) and IJsselmeer (east). The figure below displays the geographical location of the municipality of Amsterdam in The Netherlands.

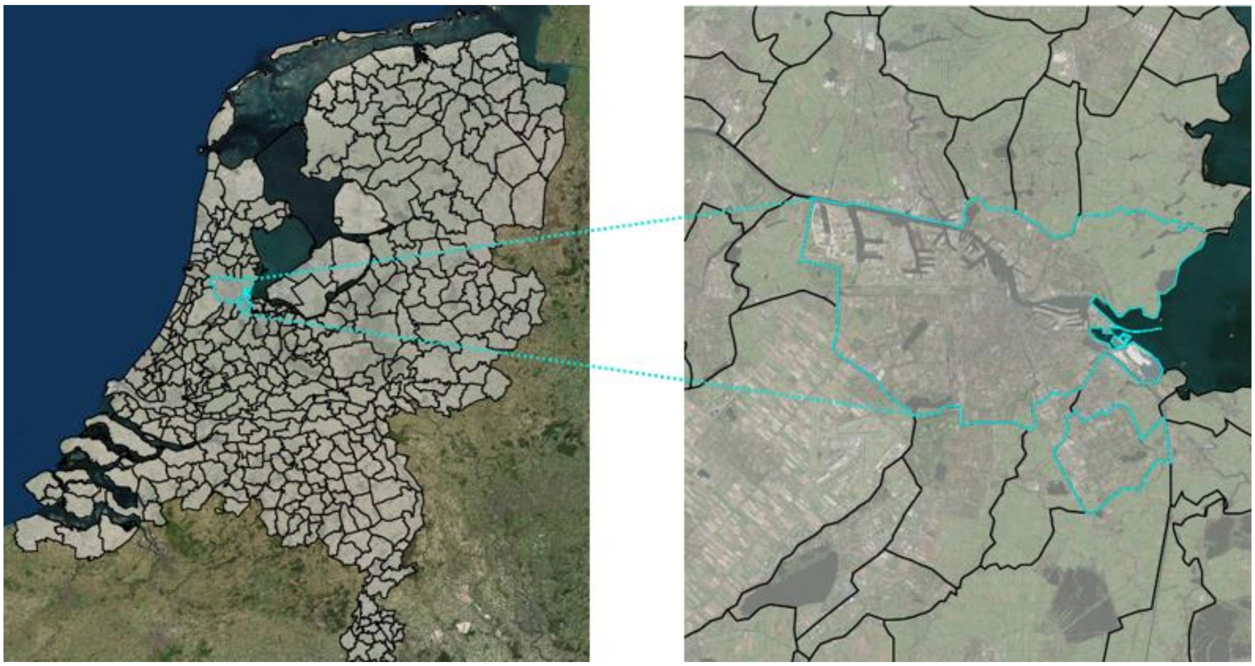


Figure 22 The Netherlands (left) and Municipality of Amsterdam (right) (ESRI ArcGis, 2016).

Hamburg

As one of the largest cities in Germany, Hamburg is a harbor city indirectly connected to the North-Sea. Compared to Amsterdam the municipality has a much larger surface and has a population of 1.754.567 (Municipality Hamburg und Schleswig-Holstein, 2016) and a density of 2,260.5 per square kilometer. The municipality is situated in the North-West of Germany as the figure below displays.

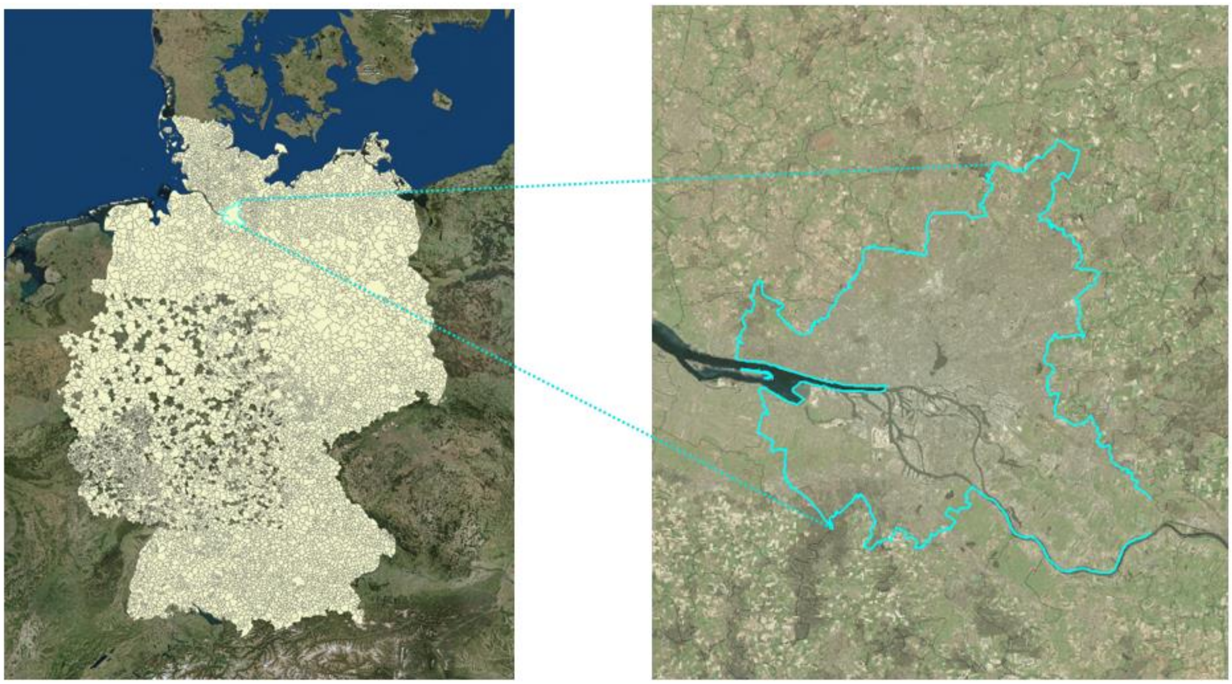


Figure 23 Germany (left) and Municipality of Hamburg (right) (ESRI ArcGis, 2016).

Copenhagen

The municipality of Copenhagen is situated on the most eastern side of Denmark. The city has similar geographical characteristics as Amsterdam and Hamburg in the fact that it is an harbor city of origin and mainly developed to its current form because of the trading route access to the North- and Baltic Sea. The city also is densely populated as has limited available space. In fact, the urban environment has extended outside the municipal border leaves little to no available space. The collective entity of the municipality including the surroundings is called Greater Copenhagen and inhabits over a million people. The study area is confined to the municipality of Copenhagen as defined in the figure below.

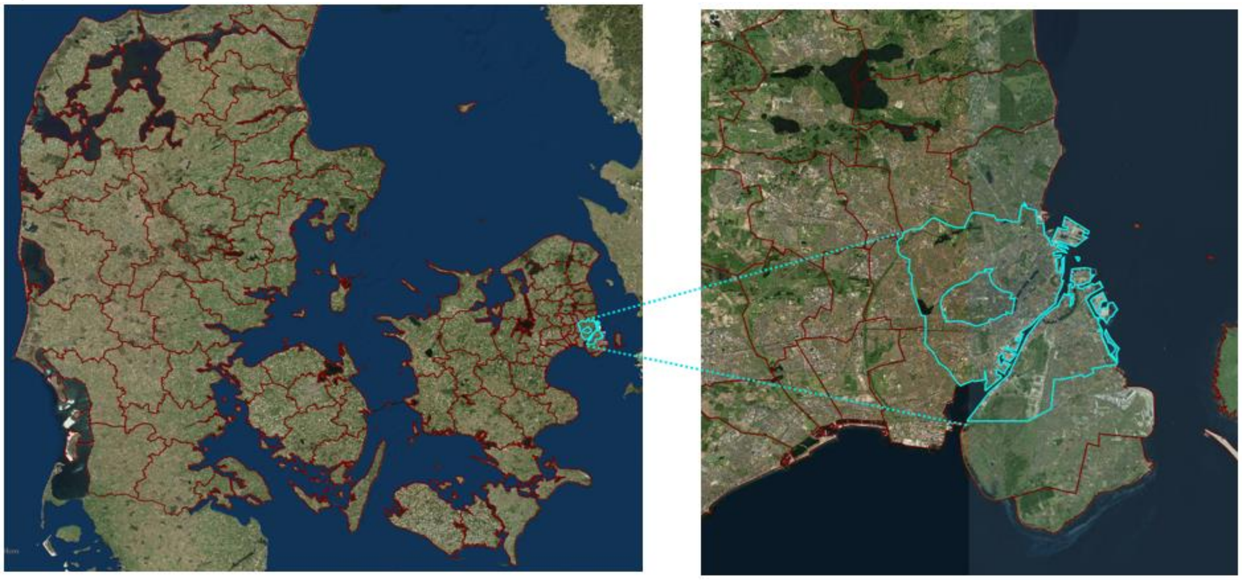


Figure 24 Denmark (left) and Municipality of Copenhagen (right) (ESRI ArcGis, 2016).

The confined area of the Municipality of Copenhagen inhabits approximately 591,485 citizens (Municipality of Copenhagen, 2015). The urban environment of Copenhagen extends outside the municipal borders, this area is called the Greater Copenhagen region.