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Methodology and Tools

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Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Thellufsen, J. Z. (2017). *Contextual Aspects of Smart City Energy Systems Analysis: Methodology and Tools*. Aalborg Universitetsforlag. PhD Series, Technical Faculty of IT and Design, Aalborg University

CONTEXTUAL ASPECTS OF SMART CITY ENERGY SYSTEMS ANALYSIS

METHODOLOGY AND TOOLS

BY
JAKOB ZINCK THELLUFSEN

DISSERTATION SUBMITTED 2017

AALBORG UNIVERSITY
DENMARK

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Dissertation submitted

7 April 2017

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Dissertation submitted: 7 April 2017

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PhD Series: Technical Faculty of IT and Design, Aalborg University

ISSN (online): 2446-1628
ISBN (online): 978-87-7112-941-0

Published by:
Aalborg University Press
Skjernvej 4A, 2nd floor
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2017

ENGLISH SUMMARY

Cities around the globe, are in the process of taking on the challenge of a renewable and sustainable transition. They create local plans for becoming a *resilient city*, *smart city*, *CO2 neutral city*, or *sustainable city*, to name a few concepts for sustainable urban development. These concepts all, at some level, include the energy system of the city as a focal point in the development of cities, but do not have a common basis for understanding the energy system of a city.

Based on the concepts of *smart cities* and *smart energy systems*, the thesis defines the concept of *smart city energy systems*. These are urban energy systems where the integration of electric, thermal, and gas grids is essential to achieving the most efficient energy systems for the city. These *smart city energy systems* focus on improving the individual sectors, but also on increasing the flexibility of the urban energy system through the integration of the sectors. *Smart city energy systems* do not necessarily require energy production, but they must utilise the energy required by the residents efficiently based on the concepts of system integration.

Thus, a vital part of *smart city energy systems* is the acknowledgement of the importance of two contextual aspects: the system integration context of *smart cities* and the geographical context of *smart cities*.

The thesis investigates the system integration context of *smart city energy systems*. Since *smart city energy systems* rely on the concept of system integration, this context impacts both decision-making and the design of the surrounding energy system. To discuss decision-making, the thesis suggests an approach by which system integration is measured against traditional energy systems. The impact on the system design, and the implementation of a single technology, are assessed through energy systems analysis of a systematic implementation of the given technology. With a continuous measure of the performance of the energy system, the consequences of the implementation of the given technology in a *smart city energy system* can be identified.

Sustainability is often a target in the development of future cities, but many existing plans consider only the specific development of the local urban area. Thus, even if they achieve local sustainability targets, the plan developed potentially hinders other cities in making the same transition to a sustainable or renewable energy system. Thus, a sustainable energy system, or a sustainable city, must consider its resource use so it does not limit the opportunities of other cities, for it to be considered sustainable.

The *geographical context* is therefore important to assess in the development of *smart city energy systems*. The thesis stresses that the resource use of the urban energy system must be considered from the perspective of the plans for the development of national energy systems. This can to a large extent be achieved with already-existing tools for energy systems analysis, but to gain the full perspective, the interaction between the *smart city energy system* and the national energy system must be assessed. The thesis therefore develops a tool and a methodology to link urban energy systems with national energy systems, the MultiNODE tool for EnergyPLAN.

The MultiNODE tool enables EnergyPLAN to assess the interaction between urban energy systems and the surrounding national energy systems, from which the user can identify impacts on total resource use and electricity exchange. This is something EnergyPLAN in its stand-alone version is not capable of doing. These assessments are necessary when the *smart city energy system* does not require energy production.

The final element investigated is the interplay between a *smart city energy system*, the geographical context, and the system integration context. Through this two-dimensional approach, the total relationships among the individual elements can be assessed to determine the operation of the energy system.

These elements are all tested on concrete cases. The system integration context is first investigated through the assessment of implementing system integration in a 2050 scenario for the Irish energy system, currently relying on individual heating. With the implementation of combined heat and power, thermal storage and district heating, a more efficient scenario is achieved. The second aspect of the system integration context assessed is the implementation of a single technology in an integrated energy system. Here, the results of the analysis of the implementation of energy savings in a Danish district heating system show that system integration potentially can influence the performance of a single technology.

The concept of *smart city energy systems* is compared with concrete plans for Sønderborg and Copenhagen and assessed in relation to the geographical context of the development of a renewable Danish energy system. The study shows that an uncoordinated plan that does not take the geographical context into account can result in sub-optimisation in terms of resource use and integration between the local and national energy system.

To combine and discuss the two aspects, the thesis investigates the benefit of system integration in relation to system interconnection – a two-dimensional approach – in the case of two archetypical energy systems, a northern and a southern system. From this, the study shows that when investigating *smart energy systems*, this approach helps identify how variable renewable energy is best utilised, since it can either be used through system integration or exported to the surrounding energy system.

DANSK RESUMÉ

Byer over hele verden er i gang med at omstille sig til et mere vedvarende og bæredygtigt samfund. I den forbindelse udarbejdes der lokale planer med målsætningen om resiliente byer, smarte byer, CO2 neutrale byer og bæredygtige byer. Disse koncepter forsøger alle til et vist niveau at inkludere energisystemet i byen som et vigtigt element i udviklingen af byen. Koncepterne har dog ikke en fælles forståelse for byens energisystem.

Baseret på konceptet smarte byer og smarte energisystemer, definerer denne afhandling konceptet smarte urbane energisystemer. Disse er byens energisystemer, hvor integrationen af el-, varme- og gasnettet er essentielt for at opnå det mest effektive energisystem for byen. Energisystemerne skal fokusere på at optimere de individuelle sektorer, men igennem integrationen af sektorerne kan et mere fleksibelt urbant energisystem opnås. Smarte urbane energisystemer kræver ikke nødvendigvis lokal energiproduktion, men de skal have en effektiv udnyttelse af den energi, der kræves af beboerne i byen, baseret på systemintegration.

Det er derfor nødvendigt i analyserne af smarte urbane energisystemer at acceptere vigtigheden i to kontekstuelle aspekter. Systemintegrationens kontekst af smarte byer og den geografiske kontekst af smarte byer.

Afhandlingen undersøger systemintegrationskonteksten baseret på to perspektiver. Smarte urbane energisystemer er afhængige af systemintegration. Systemintegrationen påvirker både beslutningsprocessen vedrørende udviklingen af energisystemet og systemdesignet af hele energisystemet. For at diskutere beslutningsprocessen, foreslår denne afhandling en analyse, hvor systemintegration måles imod et allerede defineret energisystem uden systemintegration for at påvise fordelen ved systemintegration. Systemintegration påvirker systemdesignet, og effekten af implementering af én ny teknologi i energisystemet. For at vurdere dette samspil mellem den enkelte teknologi og systemintegration, foreslås en metode, hvor der ved hjælp af energisystemanalyse, analyseres en kontinuerlig øget implementering af teknologien. Ved at måle kontinuerligt på energisystemets performance kan konsekvensen ved implementeringen af teknologien i et smart urbant energisystem identificeres.

Bæredygtighed ses ofte som et mål i udviklingen af fremtidige byer, men mange af de eksisterende planer forholder sig kun til den lokale udvikling af deres specifikke by. Derfor kan den lokale plan, selvom de skulle opnå de

lokale mål for bæredygtig udvikling, potentielt forhindre andre byer eller lande i også at lave bæredygtig omstilling eller et bæredygtigt energisystem. Det er derfor nødvendigt, at et bæredygtigt energisystem, eller en bæredygtig by, forholder sig kritisk til det lokale ressourceforbrug, så andre byer også efterlades muligheder for en bæredygtig omstilling.

Den geografiske kontekst er derfor nødvendig i vurderingen af smarte urbane energisystemer. Afhandlingen understreger, at ressourceforbruget lokalt skal ses i relation til den fremtidige udvikling af det nationale energisystem. Dette kan til et vist omfang håndteres i allerede eksisterende energisystemanalysemodeller og -værktøjer, men for at opnå det fulde perspektiv skal samspillet mellem smarte urbane energisystemer og det omkringliggende nationale energisystem kunne vurderes. I forbindelse med afhandlingen udvikles der dermed en metode og et værktøj til at linke urbane energisystemer med nationale energisystemer. MultiNODE til energisystemanalyseværktøjet EnergyPLAN.

MultiNODE gør EnergyPLAN i stand til at vurdere interaktionen mellem byens energisystem og omkringliggende nationale energisystem, hvorfra brugeren kan vurdere, blandt andet ressourceforbruget og el-udvekslingen. Dette er EnergyPLAN ikke i stand til i stand-alone versionen. Disse analyser er nødvendige, når de smarte urbane energisystemer ikke er afhængige af lokal energiproduktion.

Det sidste element, der undersøges i denne afhandling, er samspillet mellem det smarte urbane energisystem, systemintegrationskonteksten og den geografiske kontekst. Igennem denne todimensionelle tilgang, kan relationen mellem de individuelle elementer undersøges, for at detaljere hvordan energisystemet skal fungere.

De tre elementer analyseres alle på konkrete cases. Systemintegrationskonteksten analyseres først i forbindelse med implementeringen, af et Irisk energisystem for 2050 baseret på individuel opvarmning. Med implementeringen af kraftvarme, varmelager og fjernvarme opnås et mere effektivt scenarie. Det andet aspekt af systemintegrationskonteksten undersøges ved implementeringen af en enkelt teknologi i et integreret energisystem. Specifikt viser resultaterne fra implementeringen af energibesparelser i et dansk system baseret på fjernvarme, at systemintegrationen påvirker, hvordan den enkelte teknologi performer.

Konceptet smarte urbane energisystemer sammenlignes med konkrete planer for Sønderborg og København i Danmark og undersøges i relation til den geografiske kontekst, i dette tilfælde udviklingen af det danske energisystem. Analyserne viser, at en ukoordineret plan, der ikke tager den geografiske kontekst i betragtning, kan resultere i suboptimering i forhold til ressourceforbrug og utilstrækkeligt samspil mellem det lokale energisystem og det nationale energisystem.

For at kombinere og diskutere systemintegrationskonteksten med den geografiske kontekst undersøger afhandlingen samspillet igennem en todimensionel tilgang, to arketypiske energisystemer – et nordligt og et sydligt energisystem. Den analyse viser, at når smarte energisystemer undersøges, kan en todimensionel tilgang vise, hvordan den vedvarende energi kan udnyttes enten igennem systemintegration eller ved import/eksport til omkringliggende energisystemer.

ACKNOWLEDGEMENTS

The PhD project and thesis is part of the Centre for IT-Intelligent Energy Systems in Cities (CITIES) research project funded by Innovation Fund Denmark. The author would like to extend a thank you to the involved partners.

In relation to the studies carried out in relation to the PhD project, the author would furthermore like to extend a thank you to:

- Daniel Møller and Ebbe Münster at PlanEnergi for providing discussions regarding the MultiNODE tool and the EnergyPLAN model for Sønderborg.
- Anders N. Andersen and Henning Mæng at EMD International A/S for assisting in the development of the MultiNODE tool.
- Loui Algren and Mette Gamst at Energinet.dk for assisting with understanding Sifre.
- John Paul Deane, James Glynn and Brian Ó Gallachóir at University College Cork for hosting my external research stay and assisting with Irish TIMES Modelling

Also, many thanks to my supervisor Henrik Lund and all my colleagues at Aalborg University.

The front-page picture has been provided by Amalie Zinck Thellufsen.

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CHAPTER 1. INTRODUCTION

The concept of s*mart cities* [1–3] is one of several concepts that discuss the role of the city in a more sustainable future [4]; others include resilient cities and sustainable cities [4]. The concept of smart cities is not strictly defined [5], but in overall terms it includes the increasing use of information technology and communication (ICT) solutions [6–8], the design of energy systems to supply the demands of the system [8–11], and the goal of making the city more sustainable [12,13]. The different definitions place emphasis on different aspects, and some have a sole focus on the city itself [12,13], while others include aspects of the surrounding country [9,10].

With this focus on energy and information technology and communication solutions, in combination with sustainability, the two main ways to approach the energy system for smart cities are smart grids [14–16] or smart energy systems [14,17–19]. Smart grids primarily focus on the electricity grid and technologies related to the use of electricity and converting energy into electricity. Cities contain not only electricity demands, but also heating demands, transport demands and industrial demands. The smart energy system approach is more applicable as it focuses on the individual grids and the connection between them while also considering not only the electricity sector, but also smart solutions for heating, transportation and industry. These *smart energy systems* in relation to smart cities are defined as *smart city energy system*.

The *smart city* concept includes the ambitions of sustainability and sustainable cities; however, it should strive towards more than creating individual sustainable cities. The cities should be sustainable in context [10]. This means that the *smart city* energy system should be sustainable in a way that enables other cities to achieve sustainability including enabling the remainder of the country to have the possibility of sustainability. Thus, a smart city energy system does not necessarily mean the self-sufficiency of renewable energy sources. Instead, the smart city energy system must identify renewable energy solutions within the context of the surrounding country. To this end, a smart city energy systems analysis is needed.

A *smart city energy systems* analysis cannot only focus on the city itself—rather, it must investigate the context of the solutions for the smart city energy system. This requires a set of tools and methodologies [10] that can handle the investigation into both the city and the surrounding context. These tools and methodologies should enable planners to investigate several questions that are necessary to identify the sustainability not just of the city, but also in relation to the surroundings. For instance, how much available biomass can one city use while leaving enough for the remaining national energy system, or what amount of wind turbines should the municipality erect?

This highlights a need to focus on the g*eographical context* of smart city energy systems and smart city energy systems analysis. Such context could be provided through national plans, such as those researchers have suggested for Denmark [20,21], Ireland [22,23], Germany [24], Portugal [25,26], the USA [27], Brazil [25,28] and China [29]. These plans do, however, tend to focus only on the country and do not provide guidelines for the development of cities. Thus, the geographical context is not only how the city reacts to the country, but also how countries as a whole should enable cities to act.

To leave room for the development of other cities and the remaining country, the smart city energy system should strive towards efficiency. Through the use of integrated energy systems [30], the utilisation of resources can increase with the benefit of the integration of the different energy sectors in the city [11,31]. Thus, it is necessary to investigate the *system integration context.* This means the principal evaluation of how system integration benefits the smart city energy system, but also the fact that several technologies should be implemented in smart city energy systems. It is necessary to evaluate these technologies based not on their standalone performance, but in the context of the integrated energy system. Thus, the choice of technologies must be evaluated as a part of the smart city energy systems analysis and the system integration context.

There are contextual aspects in determining the system design of the smart city and the smart city energy system as well as how the smart city energy system should relate to the surrounding country. Therefore, looking at how much the smart city energy system should rely on an interconnection with the surrounding country and cities, in addition to how much the city should utilise system integration, becomes relevant. It is also relevant to analyse a part of the smart city energy system to discuss the possibility of system integration in relation to interconnectors.

These two contextual aspects need to be investigated with a well-defined set of methodologies and tools. By including the contextual aspects in the analysis of smart city energy systems it is possible, during decision-making, to explain how well they fit together. Energy planners in Sønderborg or Copenhagen need to know whether their plan actually fits into the context of an energy plan for the whole of Denmark.

The focus of this PhD thesis is therefore to provide tools and methodologies for the investigation into the context between smart cities and national energy system development. It does this from a point of departure in cities and municipalities. It is vital that urban areas develop in relation to the remaining national energy system and leave room for the development of other cities. With a steady increase in the global urban population [32], a focus on efficient smart cities is necessary.

1.1. PROBLEM STATEMENT

Based on the issues highlighted, the thesis will revolve around the following research question:

What methodologies and tools are suitable to analyse smart city energy systems? And how should they be able to assess the smart city energy system and its contextual aspects?

From the scope of *smart cities*, this PhD thesis delves into two contextual aspects:

1) *System integration context.* Designing smart city energy systems requires a number of technologies; thus, there exists a contextual aspect that links the changes in energy system design. This applies to the implementation of technologies that lead to system integration, and how other technologies and solutions interplay with this system integration. This can, for instance, be district heating, the benefit of a new technology such as a heat pump, or the implementation of large amounts of heat savings in an integrated energy system.
2) *The geographical context* that relates the smart city energy system to the surrounding country and cities. Smart cities draw on resources from rural areas, such as land and biomass, and must share these available resources with other cities and towns. Therefore, the *geographical context* is an important aspect to analyse in the identification of sustainable smart city energy system solutions.

Figure 1.1 illustrates the overall concept of this thesis, with the smart city energy system as the offset and the two main points of investigation as axes. Through the discussion of these axes, the author hopes to come close to defining tools and methods for investigating not only smart cities but also the context of these and how they play together. The puzzle piece form indicates that the smart city is only one part of the solution, both in terms of the need for several smart cities and also because other solutions towards 100% renewable energy systems are needed.

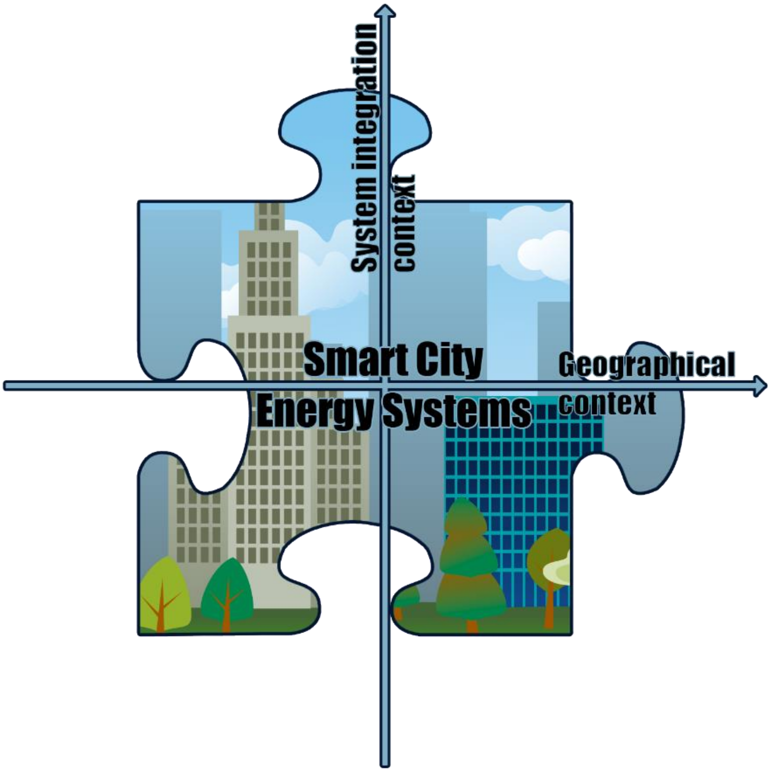

Figure 1.1. Conceptual drawing of the theme of the thesis. The smart city energy systems analysed with the two contextual aspects, the system integration context and the geographical context.

To develop tools and methodologies for investigating the context of smart city energy systems, the thesis first discusses the smart city energy system and the overall trends existing for national energy systems.

After this, the tools and methodologies are developed and are applied to the investigation of the two aspects. The three aspects are investigated in separate chapters. Finally, the thesis discusses the three axes in relation to smart city energy systems, and concludes with the research question. Figure 1.2 shows the structure of the thesis and indicates the use of the four papers that create the scientific foundation for the thesis.

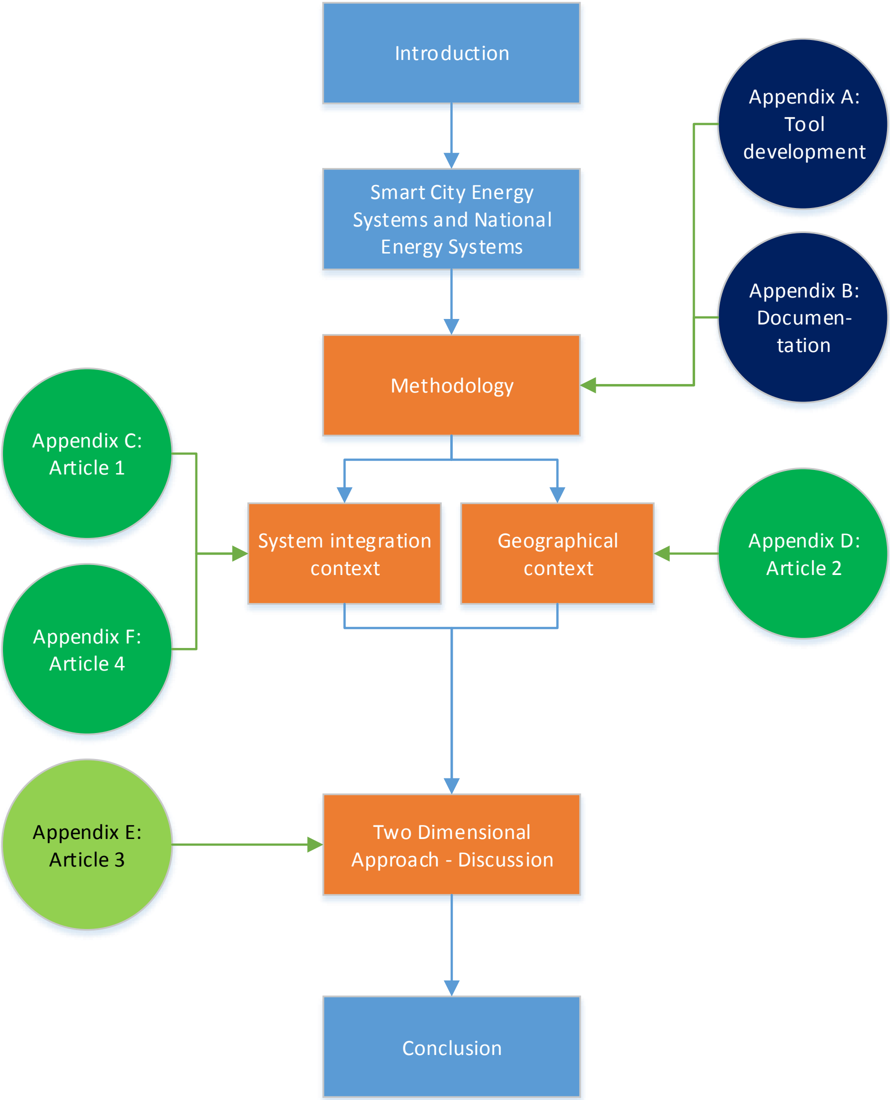

Figure 1.2. Structure of PhD thesis and how the appendices relates to the chapters.

CHAPTER 2. SMART CITY ENERGY SYSTEMS

To approach the analysis of *smart city energy systems*, the knowledge required to understand the concept as well as a definition of the term must be presented. This chapter does this by investigating the concept of first smart energy systems and then smart cities before combining these into an understanding of both a smart city energy system and its context.

2.1. SMART ENERGY SYSTEMS

A smart energy system [14,17,31,33] is a specific approach to the idea of integrated energy systems. This thesis recognises integrated energy systems as an overall concept that identifies energy system solutions that rely on the integration of the different parts of the energy sector, such as heat and electricity. What a smart energy system specifies is that the system should be set up to accommodate 100% renewable energy systems and that the integration of IT should coordinate the different parts of the energy system.

To set up a smart energy system, the concept of smart grids is expanded. Instead of only focusing on electrical grids [14], the smart energy system identifies the implementation of three smart grids: smart electricity grids, smart thermal grids and smart gas grids.

> *"Smart electricity grids are defined as electricity infrastructures that can intelligently integrate the actions of all users connected to them – generators, consumers, and those that do both – in order to efficiently deliver sustainable, economic, and secure electricity supplies."* [18]
>
> *"Smart thermal grids are defined as a network of pipes connecting the buildings in a neighbourhood, town centre, or whole city, so that they can be served from centralized plants as well as from a number of distributed heating and cooling production units, including individual contributions from connected buildings."* [18]
>
> *"Smart gas grids are defined as gas infrastructures that can intelligently integrate the actions of all users connected to it –*

> *suppliers, consumers, and those that to do both – in order to efficiently deliver sustainable, economic, and secure gas supplies and storages.”* [18]

These three grids and the interconnection between them are the main infrastructure in smart energy systems. The smart energy system seeks to identify and coordinate synergies between these three grids to achieve the best solutions for both the individual grids and the total energy system. Figure 2.1 illustrates the concept of a smart energy system.

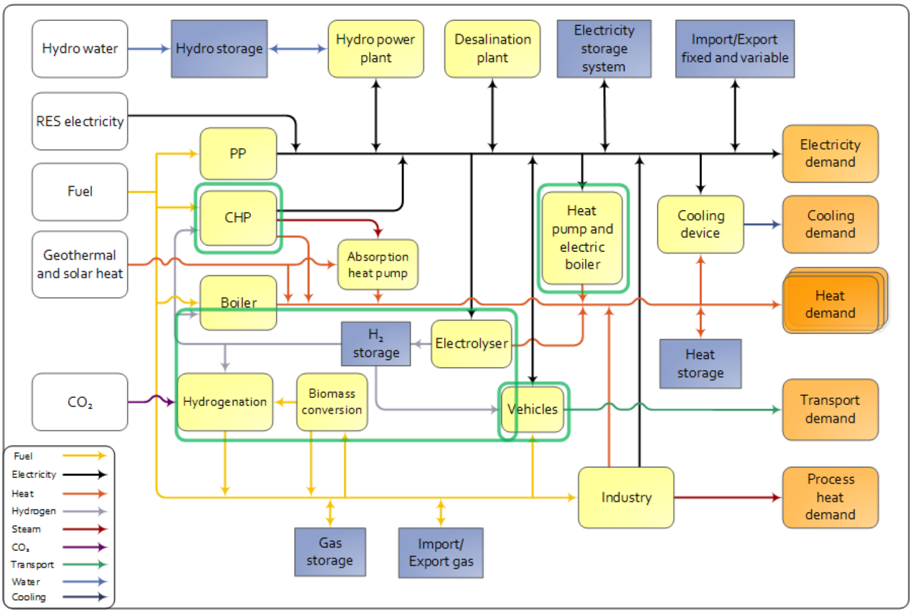

Figure 2.1 Conceptual layout of a smart energy system [34]. *The green boxes indicate integration technologies between the sectors.*

Smart energy systems require the utilisation of information and communication technology (ICT) to establish co-ordination between the different parts of the energy system. This integration of ICT should enable the necessary automatic responses to run an efficient and flexible system.

This flexibility is necessary to achieve the goal of 100% renewable energy systems, which is one of the main drivers for the development of the smart energy system concept.

The smart energy system approach seeks to utilise the flexibility of the energy system to integrate renewable energy. This can, for instance, be through power to heat solutions that enable the use of excess electricity from variable renewable energy to be stored as heat. Heat storage is significantly cheaper than electricity storage, especially when used in district heating systems [17]. By utilising this flexibility, the combined heat and power plants can operate only during the necessary hours of electricity demand when there is no heat demand. The smart energy system also suggests fuel storage through the use of electro-fuels, as this type of storage is cheap in comparison to storing electricity. Figure 2.2 illustrates these differences in cost.

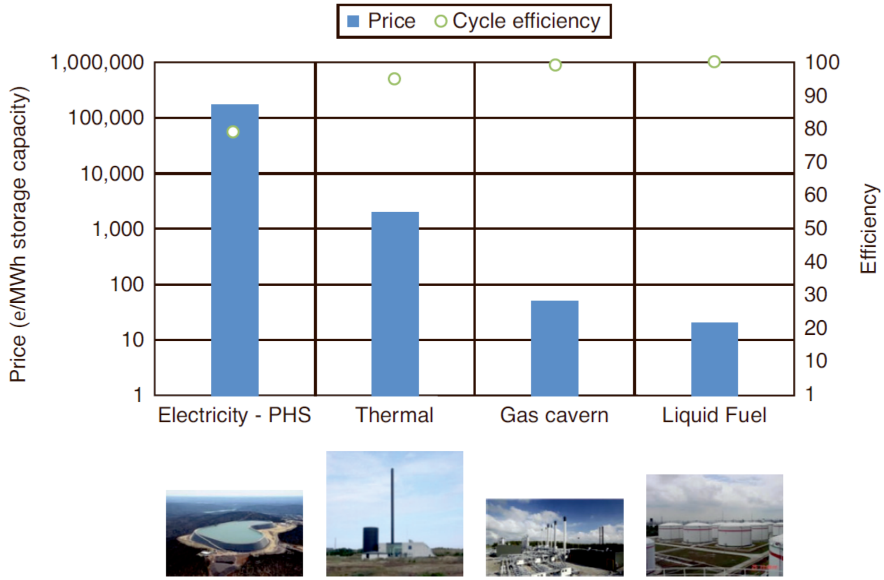

Figure 2.2 Comparison in investment costs and cycle efficiency of different types of storage. [17]

The smart energy system can, of course, also utilise electricity storage, but since the use of pumped hydro storage is geographically restricted, a general smart energy system would rely on electric vehicles with smart charge [35] and vehicle-to-grid technology [36,37]. Thus, it becomes integrated in the systems task of fulfilling a transport demand.

As Figure 2.1 illustrates, electricity becomes a primary element of a smart energy system, as a large amount of energy is delivered through variable renewable energy, such as wind and solar power. However, it integrates this electrical system with a necessary thermal system that fulfils heating and cooling demands. The interconnection point between electricity and heat is the use of heat pumps and electrical boilers. The gas grid is necessary as fuel storage that enables the system to fulfil all transport demands, but also offers flexibility in the production of electricity. The link between the gas and electricity system is represented by the electrolysers. Finally, the smart energy system will demand some fuel for critical situations, but also to produce the electro-fuels.

The smart energy system offers concrete solutions for the development of the entire energy system, not just the power sector.

2.2. SMART CITIES

The concept of *smart cities* is widely used both in urban planning and research; however, currently, as previously explained, there exists no clear and consistent understanding of the concept [5]. A smart city typically includes a focus on energy, transportation and the use of computer and modern technologies to create automated and flexible urban solutions [1,4,7,10]. These are often looked at with an overall target of improving the sustainable urban development in a given city.

Therefore, this thesis uses the following definition:

> *Smart cities are cities that utilise ICT in relation to their energy system to achieve the goal of 100% renewable energy systems.*

This is in line with the definition for smart cities used in the CITIES research project:

> *The smart city is where quality of life for residents are [sic] maximized using urban informatics and technologies to improve efficiency of services, to meet residents' needs effectively and in a predictive fashion. We contribute to the future of smart cities with*

> *fully integrated energy systems powered by the intelligent use of data.* [38]

While smart cities might expand beyond a focus on the energy system, this focus remains. This is a critical infrastructural part of the city and thus a key point of emphasis in achieving sustainability, which is commonly the target of smart cities.

Even though much research into smart cities has focused on the energy system, there is no clear definition of what an energy system is in the context of a smart city. When discussing the energy supply in a smart city, research tends to focus on individual technological solutions that utilise ICT solutions within the field of energy [6,7,10]. While this research is relevant, it can be difficult to identify coherent solutions that apply to the total energy system in a city.

Some researchers have looked into possible ways of supplying the whole energy system of a city [11,39–41]; however, not many link to the specific smart city solution. These solutions do, however, point to the implementation of renewable energy, such as solar power, and also to the role of different heating solutions. However, it is ambiguous whether the city system should be based on, for instance, district heating [42], as is the case of cities like Copenhagen [11] and Aalborg [41], or electric heating in the form of individual heat pumps [43], as is highlighted as a solution in the EU Energy Roadmap 2050 [44].

Aside from research, there exist a number of city and municipal plans that try to apply the concepts of CO2-neutral cities, resilient cities, and smart cities [4]. This is the case with, for instance, Copenhagen [45], Sønderborg [39] and Vejle [46] in Denmark, and Seattle [47], New York [48] and Oakland [49] in the USA. Several other examples can be found in the Carbon Neutral City Alliance [50].

While not all of these are designed as energy systems for smart cities, to a large extent they fit within the definition used in this thesis. Thus, the point is that there is no clear way of designing these energy systems for smart cities. This lack of design and guidelines for planners could potentially create issues, as all these cities should co-exist within the same future. It is therefore important to look not only at the individual city itself, but also at all the other cities and countries planning future energy systems.

2.3. SMART CITY ENERGY SYSTEMS

Since there are many different approaches for renewable energy systems in future smart cities, it becomes difficult to identify common solutions. This thesis combines the ideas of smart energy systems and smart cities to describe the concept of smart city energy systems.

A smart city energy system combines the goal of smart cities by identifying ICT solutions in the process of achieving renewable energy systems with the specifications of a smart energy system. Thus, a smart city energy system is defined using the following parameters.

The smart city energy system seeks solutions for the energy system of the whole city as well as the individual sectors. This results in the utilisation of smart electricity grids, smart thermal grids and smart gas grids. Through this utilisation, the smart city energy system has to have the flexibility to enable it to integrate variable renewable energy into its energy system. The smart city energy system cannot be designed to rely only on combustible fuels.

Thus, it becomes important for the smart city energy system to enable the flexible use of electricity in the form of, for instance, heat pumps, electric vehicles and the production of electro-fuels. Furthermore, the planning of a smart city energy system should also focus on the utilisation of suitable storage, such as through the application of district heating and cooling systems.

The smart city energy system focuses on the layout of the energy system, especially surrounding the concept of integrating solutions that fulfil the demands illustrated in Figure 2.1. In that case, the smart city energy system can be seen as comprising certain parts of the smart energy system. This is illustrated in Figure 2.3.

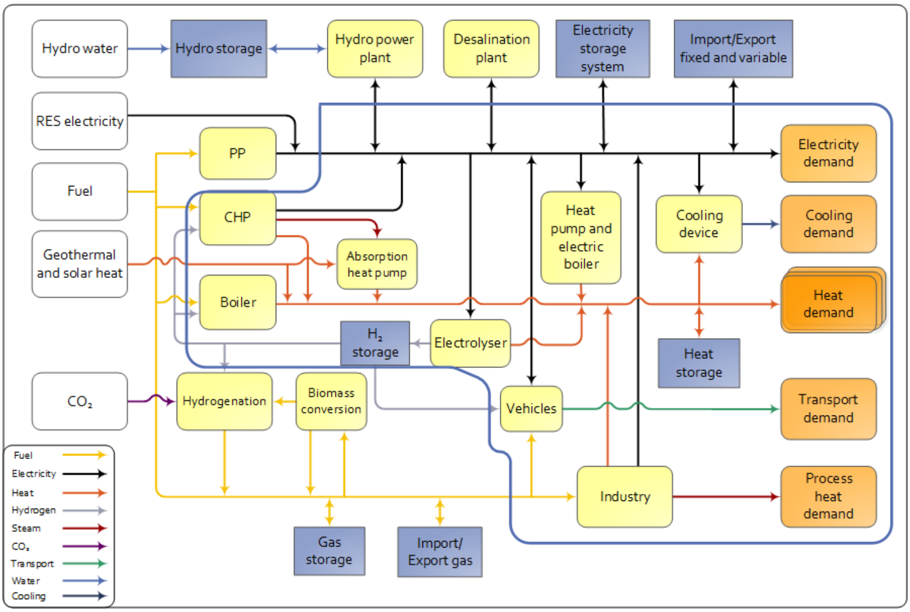

Figure 2.3 Conceptual layout of a smart energy system [34]. *The blue box defines a potential split between what parts can be seen as part of the energy system within the city and what potentially belongs to areas outside the city.*

Figure 2.3 illustrates that certain parts of the smart energy system might not be part of the smart city energy system, such as the available resources necessary to sustain the energy demands of the city. Not all cities have sufficient access to fluctuating renewable energy or fuels to be self-sufficient. Instead, the smart city energy system will in many cases have to be reliant upon its surroundings. This means that while it is important to see smart city energy systems as a solution for the planning of energy systems in cities, this planning has to be seen in relation to the context of the given city.

These contextual aspects can be broken into the two main types already mentioned in Chapter 1.

1) System integration context.
   Smart city energy systems rely on system integration between the grids to establish the flexibility to implement renewable energy in the energy system. It is therefore necessary to look at the context of how crucial system integration is to a smart city energy system—that is,

the *system integration benefit*. Since smart city energy systems rely on system integration, the implementation of technologies is dependent on this specific system design. That means the implementation of other solutions has to function within the system integration. This is labelled as the *single technology integration context.* This integration reflects the interaction between the smart electricity grid, smart thermal grid and smart gas grid. An example could be how energy savings work in the setting of a system with integrated heat and electricity supply.

2) Geographical context.
   The smart city energy system only reflects the city itself, but it is necessary to identify the amount of resources available as well as how the system will affect other cities and the remaining country in order to make the transition to a 100% renewable energy system. A smart city cannot be sustainable at the cost of other cities not being able to achieve sustainability as well.
   It is therefore necessary to take into account the assumed development of the remaining cities and the surrounding country. This also highlights the need for an overall co-ordination between cities, perhaps aiming for the same perspective on their energy systems.

While tools are already in place for analysing the performance of a given energy system [14,51,52], such as a smart city energy system, it is necessary to identify how these energy systems relate to the given contexts described above. Chapter 3 therefore identifies and discusses methods and tools to analyse smart city energy systems to arrive at solutions that can take the contextual aspects into account.

CHAPTER 3. ANALYSING SMART CITY ENERGY SYSTEMS

To analyse smart city energy systems, it is necessary to identify a methodology and a set of tools that allow for both the analysis of the energy system in the city and how that energy system relates to its contextual aspects. This chapter therefore covers the choice and development of methodologies and tools for analysing smart city energy systems and the contextual aspects. It also discusses the application of different energy system analysis frameworks to the case of the smart city energy systems analysis to identify how the set of thoughts behind a given tool impacts the way the tool will approach smart city energy systems.

3.1. IDENTIFYING METHODOLOGIES AND TOOLS FOR SMART CITY ENERGY SYSTEMS ANALYSIS

To identify the methodologies and tools for analysing the smart city energy system, it is therefore necessary to consider the following points: the ability to investigate the entire energy system, the options for modelling various storage technologies, how the system includes variable renewable energy sources and the flexibility in modelling smaller and bigger cities.

The tool used for the smart city energy system analysis has to be based on a methodology that includes the entire energy system. This is necessary to allow for the fundamental aspects of smart energy systems [14,31]; that is, to seek the optimal solutions for both the individual grids and the entire energy system. The tool therefore also has to have the ability to analyse the electricity, thermal and gas grids. A few tools focus on the electricity grid and might be sufficient to model smart electricity grids [53–55]. These tools are, however, insufficient since their methodology does not allow for district heating. The methodology behind the tool also has to include the principle of linking the different grids. The tool therefore has to include the power-to-gas and power-to-heat technologies as well as the other relevant energy conversion technologies necessary to build a smart energy system that can create flexibility and optimal solutions by utilising the co-ordination of the different parts of the energy system.

The *smart city energy systems* rely on creating flexibility through the smart co-ordination of various storage technologies. Thermal storage in particular is relevant in its potential to be situated in the city as part of a district heating (and cooling) grid. The tool used for modelling the smart city energy system should therefore include the possibility of modelling storage in a meaningful way. First, it should include various types of storage, but more importantly, it must be based on a methodology that allows for the charging and discharging of stored energy over a period of time. Therefore, it comes down to what temporal scale the tool uses and to what extent it works with continuity. The model can, for instance, work in yearly, monthly, daily or hourly scales, or it can be flexible, with the user being able to determine the temporal scale. In the cases where the user determines temporal scale, it can sometimes influence the time continuity. In order to model storage, it is necessary to acknowledge that a charge comes before a possible discharge. Hence, it is important to have a tool that includes time continuity.

The temporal scale also becomes important when the system has to model variable renewable energy. The variable renewable energy sources fluctuate with weather patterns and are, as such, not a stable source of energy that can be used on demand. There will be situations where there is a low supply of energy and a high demand, as well as low demands when there is an excessive supply of energy. The tool therefore has to consider this behaviour in its methodology. One way is to use a high temporal resolution, as that requires the smart city energy systems to react to the fluctuating behaviour of, for instance, wind energy. Thus, the tool can test the flexibility of the smart city energy system and to what extent it can accommodate variable renewable energy. It is possible to have tools that work on other methodologies to assess variable renewable energy; however, these tools have to analyse the different scenarios that can occur in terms of demand and supply as well as how sensitive a system is to the frequency of these scenarios occurring.

Finally, urban regions can vary in size; thus, the tool has to be flexible in modelling different sizes of energy systems as well as what technologies are accessible for the city. A demand model would not be relevant on its own, as some cities might have access to energy production units. The methodology has to be flexible.

3.2. MODELLING SMART CITY ENERGY SYSTEMS IN DIFFERENT ENERGY SYSTEMS ANALYSIS TOOLS

The field of energy systems modelling is filled with many different types of tools, all based on various methodologies. Connolly et al. [52] conducted a thorough review of available computer tools for energy systems analysis and identified seven types of tools, depending on the overall operation:

1) Simulation tool. Seeks to operate the energy system to fulfil a set of demands.
2) Scenario tool. Seeks to create scenarios for energy system development in the future.
3) Equilibrium tool. Seeks to generate an economic equilibrium based on information on supply, demand and prices.
4) Top-down tool. Identifies changes to the energy system and prices based on general macro-economic data.
5) Bottom-up tool. Constructs the energy system based on demands and technologies available to find investment alternatives.
6) Operation optimisation. Optimises the operation of an energy system based on a given parameter. Typically linked to simulation models.
7) Investment optimisation. The tool identifies the optimal investment choices over a given period of time. This normally links to scenario tools.
   [52]

This does an excellent job of illustrating the very different types of tools available and hence also the very different sets of underlying methodologies. In addition to these seven types, the available tools might not be able to analyse the whole energy sector, as do tools like WASP [55] and HOMER [53].

That provides a quite substantial number of available tools. Some work on lower-resolution temporal scales over a long period of time, such as MARKAL/TIMES [56] and RETScreen [57], while others, such as EnergyPRO [58], EnergyPLAN [34] and Sifre [59], focus on hourly simulations. Some have specific technical foci, such as EnergyPRO [58], while others simulate the total energy system, for instance EnergyPLAN, Sifre and TIMES [34,56,59].

It is not within the scope of this thesis to assess whether all these tools are applicable for a smart city energy systems analysis. However, it is necessary to discuss how different tools could be applied, as this serves to help identify how methodologies and tools can be developed to analyse the contextual aspects of smart city energy systems.

The tools investigated should be able to model the whole energy system; they should also have the ability to provide a sensible degree of temporal resolution to model storage and renewable energy. This rules out the top-down tool and many of the scenario tools as being suitable for smart city energy systems analysis. To cover the different tools, the thesis discusses: 1) TIMES, which is a tool focusing on investment optimisation by building scenarios from a bottom-up approach; 2) Sifre, an operation optimisation tool developed by Energinet.dk that simulates a user-built energy system based on least marginal costs; and 3) EnergyPLAN, a tool that seeks to simulate a user-built energy system based on an analytically programmed understanding of the operation of an energy system.

From [52], it is clear that not all tools focus on city energy systems, and of those that do, Homer [53] and TrnSYS [54] do not cover the whole energy system. The three chosen tools, Sifre [59], EnergyPLAN [34] and MARKAL/TIMES [56], can all work on a national, state or regional level. The discussion then highlights to what extent they can be applied to a smart city energy systems analysis.

3.2.1. TIMES FOR SMART CITY ENERGY SYSTEMS ANALYSIS

TIMES (The Integrated MARKAL-EFOM System) is an energy system analysis model developed by the International Energy Agency (IEA) [60]. The TIMES model is based on linear programming that enables the tool to choose least-cost energy systems [61]. It does this based on user-defined input regarding technologies and costs-to-construct scenario, with user-defined constraints to identify a partial equilibrium [56]. The overall principle is shown in Figure 3.1.

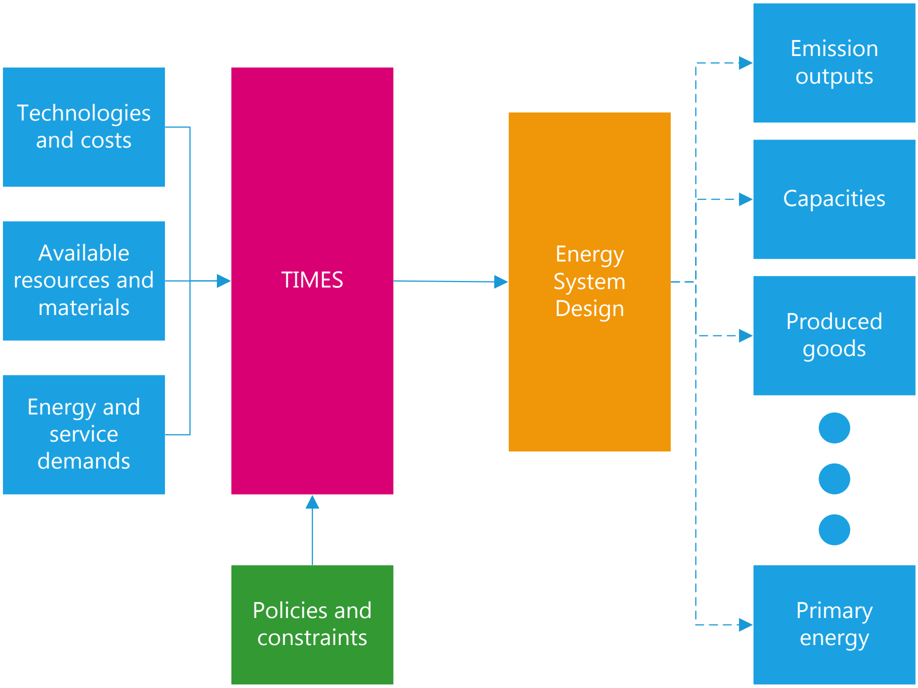

Figure 3.1 Basic principles of TIMES. Based on certain types of input, the TIMES model designs an energy system that develops over time. From this it is possible to extract output such as capacities, final energy and emissions.

To conduct a TIMES analysis, the user has to define the energy demands in the system as well as potential development in these demands based on identified drivers, such as GDP and population growth [56]. The user also has to identify the available supply of primary energy and potential materials for industry. These have to be associated with a cost. It is possible to constrain the growth of demands and the supply of resources to restrict the output [56].

The third element of a TIMES analysis is that, through inputs of techno-economic solutions, it determines the most efficient way to cover the demands. These solutions can rely on the available resources but can also be demand-reducing solutions such as energy savings. By providing a large amount of available solutions, TIMES is able to choose the least-cost solutions [56].

The user can also define constraints to the system through the modelling of policies: for example, 100% renewable energy systems or no carbon capture and storage of coal. This then limits the technologies or fuels from which TIMES can choose [56].

TIMES works over a user-defined time frame, but a normal setup is to build scenarios for energy system development over a period of several years. Thus, the time resolutions are typically split into periods, like, years, seasons, weeks and days [56]. While the model can work hourly, it seldom does due to the vast amount of computation this requires. Since TIMES is mostly applied to building scenarios over a 30-year time span, optimising in each hour over this time span will slow the calculations down. It is over this user-defined time frame that the model minimises net total costs. This is done based on net present values [56].

Thus, TIMES can create scenarios for energy systems based on bottom-up input. The discussion therefore moves on to whether it can be applied to smart city energy systems and whether it can encompass the main components in terms of smart grids, interconnection between grids, and storage. Thus, it is not the most suitable tool to investigate operation. It is, however, necessary for it to take the operation possibilities into account when making investments.

TIMES has been applied to investigate energy scenarios for cities and municipalities in a few cases [62–64], such as for Pesaro, Italy [63], and Madrid, Spain [62]. Both cases, however, restrict themselves to only investigating parts of the energy system; the Pesaro case looked at households, the public sector and transport, while the Madrid article focused on transportation using hydrogen. The Pesaro case did look at heating, but did not investigate district heating. It is therefore hard to identify cases where TIMES has had a chance to identify smart city energy systems as a suitable scenario.

Since the TIMES model, to a large extent, is an investment model that creates scenarios, the question is whether it can reasonably include smart city energy systems as a scenario. It is possible to set up a TIMES model to include gas grids, thermal grids and electricity grids; hence, it can include the grids present in a smart city energy system. However, due to the time resolution, TIMES simplifies the operation of the system so its calculation can be done without hourly resolution. TIMES regards energy as a single commodity, thus it inherently understands heating, electricity and gas to be the same unit. It therefore has difficulty handling energy as a waste product of a different energy product—for instance, heat as a waste product of electricity production in combined heat and power plants. There are work-arounds for this in

TIMES, but it can be difficult to model a system with co- or tri-generation where the main output changes over the course of the year [65].

It is possible for the user to define time slices in TIMES [56], but since it is set up to handle general principles, it is normally divided into 6 to 12 slices, with varying resolutions for yearly, seasonal and daily situations [56]. Thus, it has difficulty dealing with storage since it needs a certain time resolution. In order to model storage, it is also necessary to keep track of the chronology. If TIMES does not model all hours of a year in the right order, it is simply not able to keep track of how the amount of energy stored changes over time. TIMES might be able to identify that in certain times of the year it is possible to store energy while in other times it might be possible to use stored energy, but it does not know if the two situations of charging and de-charging the storage will be in line with the storage capacity.

Together, this makes it questionable whether a TIMES model will be able to consider smart city energy systems, since its technical setup cannot encompass the key characteristics of a smart energy system. The tool simply has issues in storing energy and connecting the different grids in the smart energy system. Similar problems exist in tools similar to TIMES that work on the same basic principles.

3.2.2. SIFRE FOR SMART CITY ENERGY SYSTEMS ANALYSIS

Sifre is an energy system analysis tool developed by the Danish transmission system operator Energinet.dk [59]. It is a linear programmed tool, but in contrast to TIMES, its goal is to simulate the operation of an energy system based on a sport market. It does this on an hourly level based on user-defined input regarding demands, distributions of demands and specifications of energy-producing units.

The tool is set up so that the user defines a number of areas [59,66]. These delimit all the demands the analysis looks at as well as the available fuel type. A distribution file is associated to each demand to disperse it out over the hourly differences over a year.

Within each area, the user can specify the production units available. This can either be done by aggregating similar units or by modelling each unit individually. The production units are specified with energy inputs, energy outputs and certain restrictions to the production profile. This can be hours without operation due to maintenance, production profiles for renewable energy whether a wind turbine can be curtailed or how fast a power plant can ramp up and down. The overall principle of the operation of Sifre is illustrated in Figure 3.2.

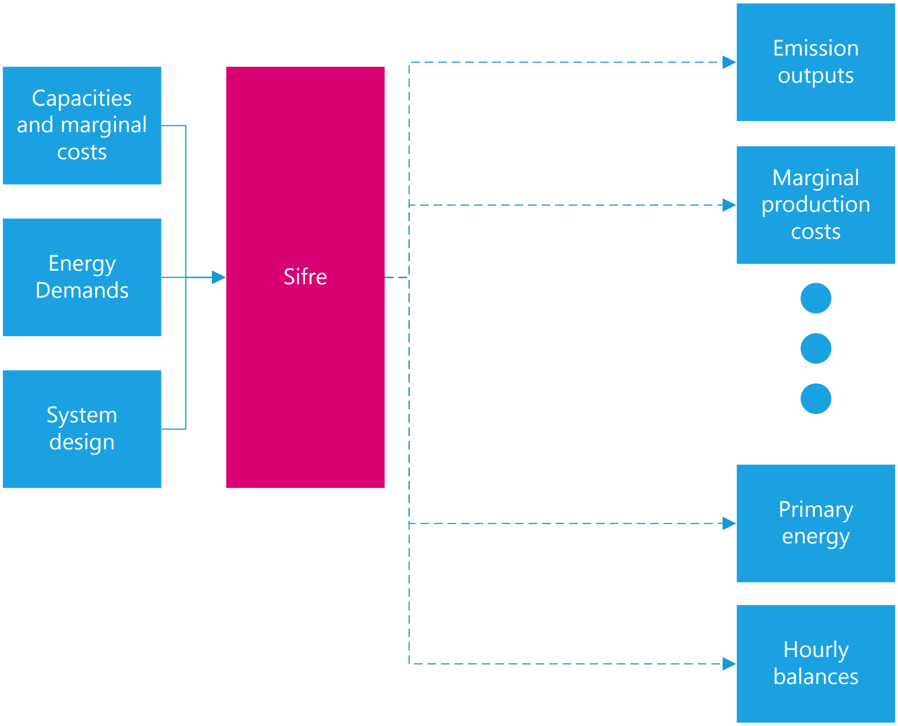

Figure 3.2 Basic principles of Sifre. Based on certain types of input, Sifre operates the energy system based on linear optimisation. It identifies the hourly operation over a year with the lowest marginal costs. The user defines the energy system. It provides outputs as primary energy, production costs and hourly balances.

Since Sifre uses a linear optimisation principle, all technologies must have associated operation costs. The model simply cannot run without cost data. It can be as simple as only the cost of the fuel, but can also be expanded to include maintenance cost, loss of income due to down time, CO2 emissions and so on [59]. Thus, Sifre falls into the category of an energy system analysis tool that simulates the yearly operation of a user-defined energy system based on an operation optimisation using several short-term marginal costs. Sifre does not include investment costs; the user should keep track of these consequences separately.

Since Sifre uses marginal costs to identify the optimal operation of an energy system, it is not always operating the most efficient energy system from other perspectives; for instance, the use of primary energy [59]. The Sifre model therefore becomes sensitive to the cost inputs, and the nature of how the cost of fuel and electricity fluctuates should be taken into consideration [67].

The energy production units used in Sifre are grouped into the following main categories:

1) Power and heat production
2) Variable renewable energy
3) Heat pumps
4) Electric vehicles
5) Storage

These main categories indicate a system in line with the smart energy system line of thought. It is also possible to be flexible within the categories, making Sifre capable of modelling power-to-gas technologies as well. Thus, it is a tool that could be suitable for smart city energy system analysis. It has for instance already been used on the case of Sønderborg [66]. Furthermore, the tool can model several energy systems as well as the interconnectors between them. This allows it to take some of the contextual aspects into account.

One of the main issues with Sifre is that the tool is not readily available for researchers and planners. Currently, it is mainly used within Energinet.dk, and while they are keen to expand the number of users, all users must access the databases and solvers through an Energinet.dk certified computer. I therefore believe that while the infrastructure of the program is sufficient for smart city energy systems analysis, it is not ideal for research or local energy planning on a city or municipal level. In the first case, this is due to the difficulty in easily replicating results, and in the second case it is due to the lack of accessibility making it hard to ensure that local energy planning is conducted in a concise way across different municipalities.

3.2.3. ENERGYPLAN FOR SMART CITY ENERGY SYSTEMS ANALYSIS

EnergyPLAN was developed at Aalborg University. It is an analytically programmed energy system analysis tool that simulates the hourly operation of an energy system over a year [34]. EnergyPLAN is primarily designed to assess national energy systems, as shown in examples for Denmark [21,68], China [29] and Ireland [22,23]. It has, however, also been applied to cases of cities [11], municipalities [40,41,69] and regions [70–72].

EnergyPLAN is set up for the user to determine several types of input. Based on this input, EnergyPLAN simulates the energy system based on both user-defined and predetermined criteria to identify the output of the energy system. The user input criteria are energy demands, capacities and efficiencies of plants, fuel usage, CO2 emissions from fuels and costs. Furthermore, the user has the option to choose the simulation strategy and how to handle excess electricity [73]. Based on this input, EnergyPLAN delivers outputs on the performance of the energy system. The most used are typically the total annual costs of the system, the primary energy use, CO2 emissions, hourly balances of energy demand and production and the amount of excess electricity in the system [51].

Energy demands are associated with a given distribution file to disperse the demand across all hours of the year. The same is true regarding the production of variable renewable energy. In terms of production units, the model is set up to aggregate the available plants within each sector. This means that EnergyPLAN needs an aggregated input for all wind turbines, for all power plants and for all power-to-gas facilities. Within district heating, EnergyPLAN differentiates between large-scale combined heat and power plants, small-scale combined heat and power plants and district heating networks with only boilers, providing three groups of district heating networks.

Figure 3.3 illustrates the overall operation of an EnergyPLAN analysis.

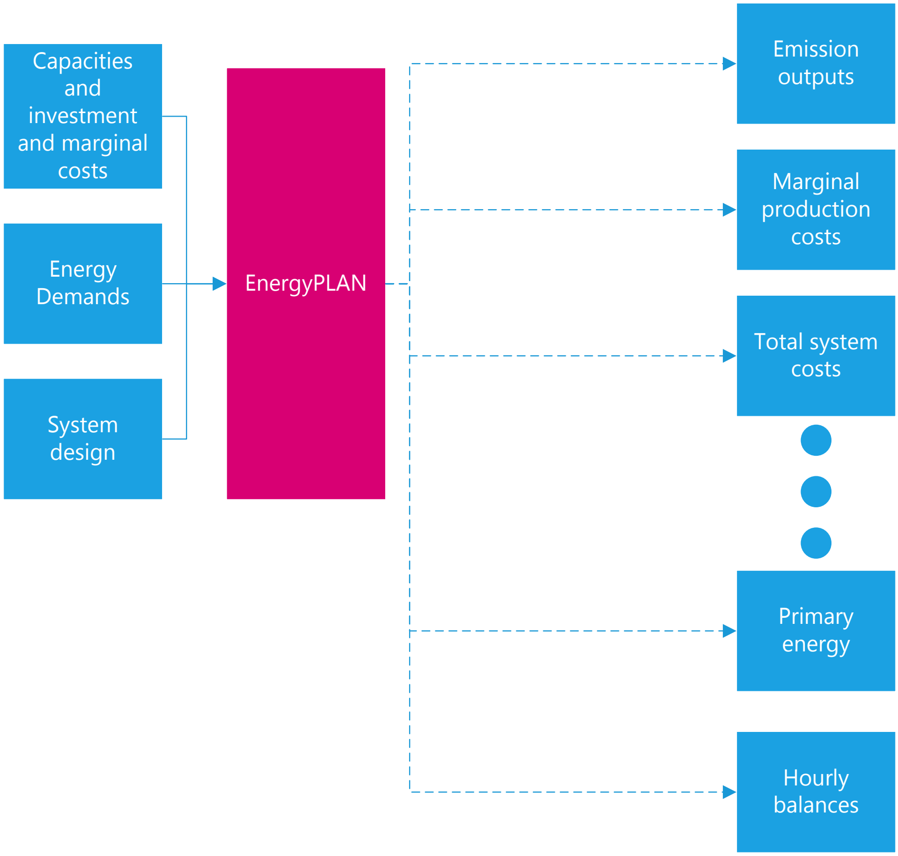

Figure 3.3 Basic principles of EnergyPLAN. Based on certain types of input, EnergyPLAN operates the energy system based on either marginal costs or by a pre.determined merit order. Respectively economic and technical operation strategy. The technical strategy is constructed to limit fuel usage. The user defines the energy system based on a pre-set layout. It provides outputs as primary energy, production costs and hourly balances.

One key feature in EnergyPLAN is that it is able to operate the energy system based on two different simulation strategies. The first is the technical simulation strategy. The main target is to reduce fuel consumption based on a predetermined order of operation. Besides this, the technical operation strategy has four different ways of operating the combined heat and power plants, whereby they can be operated to balance heat demands, to balance both heat and electricity demands and to balance the production based on the triple-tariff [34].

The predetermined order of operation in the technical strategy follows this basic principle:

1) Plants with no direct fuel usage; this means waste heat and variable renewable energy.
2) Utilisation of energy in storage.
3) Combined heat and power plants to produce electricity and utilise the waste heat.
4) Power plants and boilers; these are determined to be the most inefficient units, as they only have one purpose.
5) Import of electricity.

Overall, these five steps seek to minimise the total fuel consumption in the system.

The second simulation strategy is the market economic simulation. In this, EnergyPLAN simulates the energy system based on short-term marginal costs of a unit. This means that steps 2 to 5 from above become much more intertwined. In this strategy, EnergyPLAN will first use energy units with no short-term marginal costs. These are identified as waste heat plants and variable renewable energy units. Hereafter, based on user-defined inputs for marginal costs, EnergyPLAN identifies the least-cost unit in every given hour. It furthermore compares this to the external electricity market in order to import, export or store electricity. Overall, this simulates the energy system achieving the smallest marginal costs.

EnergyPLAN has been used in several cases to simulate smart energy systems. This is mostly regarding countries, such as Denmark and Ireland, but also in the case of the city of Copenhagen. EnergyPLAN has been updated over time and with the concept of smart energy systems in mind. The current version can therefore simulate the electricity grids, thermal grids and gas grids, and also the necessary technology to convert between the grids. Storage technology has furthermore also been integrated, with both electricity storage, gas storage and thermal storage available. This makes EnergyPLAN suitable for smart city energy systems analysis.

Furthermore, EnergyPLAN benefits from being freely available online, in addition to the fact that it can perform a technical analysis that can run without cost information. This makes it readily available to researchers and planners to conduct their own smart city energy systems analysis. Furthermore, EnergyPLAN is able to model storage while balancing the charge and discharge cycle over a year, and chronologically know the amount of energy available in storage.

One of EnergyPLAN’s strengths is its focus on one specific energy system. However, that does pose a challenge when looking at the context of a smart city energy system. As they are both based on solvers, TIMES and Sifre could just add surrounding energy systems, while EnergyPLAN does not simulate the surrounding energy system. The user has the option of adding a transmission cable and a price to the area, but it is not possible to model the specific layout of the surrounding energy system in EnergyPLAN. This poses a challenge in assessing how a smart city energy system influences the potentials of the surrounding country and cities that also want to make a renewable transition.

3.3. CHOICE OF PRIMARY TOOL

The description of the three possible tools highlights the importance of being able to do hourly simulations to assess the use of storage and renewable energy in a continuous matter over a given period, such as a year. This makes it hard to utilise TIMES as a tool for smart city energy systems analysis, since it might not be able to design an energy system for a smart city that fulfils the requirements defined in Chapter 2.

Both Sifre and EnergyPLAN can simulate the smart city energy system and are as such suitable for conducting analyses of smart city energy systems. This thesis chooses EnergyPLAN as the main tool for analysing smart city energy systems. There are two main arguments for that.

The first argument is the availability of the model. As mentioned, Sifre is currently not readily available to potential users, whereas EnergyPLAN is free to download, thus making it easier to both reproduce results and potentially implement the tool in local energy planning.

The second argument comes down to a discussion of the technical and economical operation of an energy system. When moving towards energy systems with high amounts of variable renewable energy, basing the operation on short-term marginal costs is in all cases not the most ideal way forward, as variable renewable energy will introduce many technologies with basically no short-term marginal costs [74]. These technologies instead have other associated costs related to their intermittency. These costs are not considered in an operation based on short-term marginal costs. Instead, a short-term marginal cost simulation of an energy system with a high share of renewables tends to produce as much electricity as possible and export it to the surrounding systems. This approach is highly sensitive to changes in price, but also sensitive to the overall development in all energy systems. With more systems that develop towards increasing variable renewable energy systems, the utilisation of cables and interconnectors will change compared to today's energy systems. Electricity production potentially would not come down to short-term marginal costs. Both the EnergyPLAN economic simulation and Sifre operate based on reaching the lowest short-term marginal costs.

The alternative is to approach the smart city energy system from a technical perspective. This is possible through EnergyPLAN. Here, the goal is to minimise fuel use. Like the simulation based on short-term marginal costs, this will result in a high use of variable renewable energy, but instead of marginally deciding between power plant production, import or export, it chooses technologies based on certain principles. The technical approach prioritises production units that utilise electricity and production units that result in co-production. This means that combined heat and power plants are specifically prioritised over power plants and that heat pumps are used specifically to handle excess electricity instead of exporting it. The technical simulation will furthermore seek to utilise storage in the thermal grid, gas grid and electricity grid in every situation where it can replace a power plant or a boiler. These basic principles focus on the investigation of the feasibility of smart energy systems. The economic simulation potentially does not prioritise storage or technologies that link the different grids. This thesis therefore analyses smart city energy systems using the technical simulations in EnergyPLAN.

CHAPTER 4. ANALYSING CONTEXTUAL ASPECTS OF SMART CITY ENERGY SYSTEMS

The goal of this thesis is not only to analyse smart city energy systems, but also to investigate the identified contextual aspects. Each section in this chapter identifies how EnergyPLAN can be applied to analyse the contextual aspects of smart city energy systems.

4.1. SYSTEM INTEGRATION CONTEXT

The first contextual aspect of smart city energy systems investigated in this thesis is the *system integration context*. This aspect seeks to investigate the importance of system integration and how the implementation of technologies is affected by this system integration.

To investigate this, the system integration must be modelled. Regarding the aspects of smart energy systems and smart city energy systems, this should follow the steps outlined in Chapter 3 for increasing system integration. This will enable the user to investigate the system integration context without the geographical aspect, which is in any case interesting in the implementation of smart city energy systems.

The importance of integration is identified in Chapter 3, but can be further investigated in relation to this thesis. The system integration benefit is therefore analysed by investigating outputs from optimisation models and investigating whether more efficient solutions can be found with a higher level of system integration. Specifically, the thesis links the use of TIMES with the use of EnergyPLAN to investigate heating scenarios. Furthermore, when investigating smart cities, not all resources are necessarily available. The system integration benefit should therefore be seen in this relation.

Another important aspect of the system integration context is that the technologies implemented in the smart city energy system interact with the principles of smart electricity, thermal and gas grids that are all interconnected. Thus, when implementing technologies, they should work within an environment that includes district heating and the utilisation of waste heat, for instance from combined heat and power plants [14]. This single technology integration context of smart city energy systems must be investigated. This is done through the study of implementing specific technologies in the system design of smart city energy systems. The goal is to see how well certain technologies integrate into a smart city energy system. Through the design of models of smart energy systems, it is possible to lay down the system integration context in which the technology should be implemented. In this context, the performance of a single technology and the different sizes of these technologies should be measured to identify how they depend on the design parameters of the smart city energy system. Since the thesis focuses on the technical aspects of the system, especially fuel usage, CO2 emissions and excess electricity are interesting to measure. The fuel use and CO2 emissions specify the degree by which the performance of the technology is affected by the smart city energy system design. Thus, they also work as parameters for tweaking the implementation of the technology to gain the highest level of performance. The excess electricity could be relevant to use in order to see how the implementation of the given technology potentially affects the geographical context of the smart city energy system.

EnergyPLAN has been used in several cases to test how different technologies affect the performance of energy systems. Examples are heat pumps, vehicle-to-grid, storage solutions, and energy savings [17,33,36,75]. EnergyPLAN enables the user to set up a model of an existing energy system, in this case of a smart city energy system, and within that model, rapidly introduce new technologies. Based on the output, users can analyse how the new technology works within the system integration context of the smart city energy system.

The goal of investigating the system integration context is both to analyse the palette of available technologies but also to see the specific performances so that the planners of smart city energy systems can make conscious choices in terms of determining what technologies to implement in the local energy system. It also shows the benefits of integrated energy systems. Chapter 5 discusses an example of the implementation of heat savings in a system with smart thermal grids and smart electric grids.

4.2. GEOGRAPHICAL CONTEXT

As mentioned in Chapter 3, EnergyPLAN in its basic form focuses on a single energy system in its approach. In other words, EnergyPLAN can be used to simulate the energy system of a country, a region or a city, but the tool cannot assess the link between two different energy systems.

EnergyPLAN can primarily model an external energy system by defining the transmission capacity to an external electricity market with a defined electricity price. In the economic simulation strategy, EnergyPLAN can exchange electricity with this external market based on the price levels. In the technical simulation strategy, EnergyPLAN will export electricity in hours with excess electricity production. Imports of electricity will only happen in hours with insufficient capacities. This approach is not quite sufficient to assess the geographical aspect of smart city energy systems. It does not take into account the layout of the surrounding energy system, as it assumes that sufficient capacity is available, and it is not possible to assess the overall impact on resources.

To assess this *geographical context*, other approaches have been used in city or municipal analyses made with EnergyPLAN.

The research revolving around the Aalborg Energy Plan tries to assess a 100% sustainable energy system for the municipality of Aalborg [41]. The study creates a system that is sustainable within the municipal borders, with the assumption that the system is connected with the remainder of Denmark in order to exchange electricity. This establishes a certain set of principles in terms of capacities and transmission. However, there is no assessment of the impacts on the remaining Danish energy system. The research does, however, discuss the role of industrial waste heat and the allocation of demands between a city and the remaining country. The discussion revolves around Aalborg Portland, a large cement factory located on the outskirts of the city of Aalborg. Should you allocate all the energy demands of the factory to the municipality of Aalborg, even though many of the products are shipped outside the city? And if you do not allocate all the energy demands to the city of Aalborg, can you then allocate all the excess heat to Aalborg?

The Aalborg Energy Plan study chose to assume that the industrial demands of Denmark were allocated evenly based on the population in all cities and municipalities [76]. This resulted in a lower energy demand for industry in the given model. However, it still utilised all the waste heat from Aalborg Portland in the city’s district heating grid, based on the fact that it cannot be utilised in other cities. This difference in allocation highlights some of the issues of this approach. While it is sound to allocate certain demands (or capacities) based on population averages, it becomes harder to justify a specific local usage of, for instance, waste heat. This approach to the problem is therefore not ideal when assessing the interplay between a local energy system and a national energy system.

In relation to the project Energy City Frederikshavn, an EnergyPLAN model was created for the municipality of Frederikshavn, Denmark [40,69]. Since Frederikshavn has no main power plant production, it is reliant on power from the surrounding remainder of Denmark during certain hours. To account for this, instead of using a transmission cable, a nationwide power plant was modelled in EnergyPLAN. That served as the backup capacity and illustrated the right fuel mix for the Danish energy system. While this approach illustrates the potential impact a plan can have on power plant production in a country, it still does not take into account how these power plants have to operate for the remainder of the country. The approach is furthermore limited in that it cannot take new renewable energy capacity in the remainder of Denmark into account. This approach is therefore also not suitable to assess the geographical context.

The Copenhagen Energy Vision [11], which modelled a future 2050 plan for Copenhagen, Denmark, in EnergyPLAN, approaches the geographical aspect qualitatively. Here, the researchers identified the energy system for Copenhagen based on a national Smart Energy System approach to Denmark [68]. The researchers assessed the city’s role in the energy system, then identified potential solutions that also took into account the fact that certain resources will be abundant while others will be scarce. While this approach most likely creates a sufficient split in resources between the city and the country, it cannot asses the specific impact of the smart city energy system on the surrounding country.

The plan for Aalborg, Frederikshavn and Copenhagen all stress the importance of not running these systems as islands. They emphasise that they should all be seen in relation to Denmark. However, it is not possible to analyse this in their current setup. Thus, based on this discussion and in relation to the PhD study, a new tool is developed instead. This tool should have the ability to enable the user to assess the geographical context between two geographical areas; for instance, a smart city energy system and the surrounding cities and rural areas. Appendix A describes the development of the tool, MultiNODE, and Appendix B contains the documentation of the current version of the MultiNODE tool that is bundled with the EnergyPLAN tool. The MultiNODE tool works as an add-on to EnergyPLAN and uses the EnergyPLAN framework to perform the system calculations. Thus, the MultiNODE tool can be seen as a tool that can link several EnergyPLAN analyses to each other.

The key principle of the current version of MultiNODE is that through a star network (see Appendix A) and with a user-defined merit order, the exchange of electricity between systems can be identified. This exchange relies on creating a balance between the excess electricity produced in some systems and the need to import electricity in other systems. The excess electricity comes from combined heat and power plants, waste incineration and variable renewable energy. The need for import is determined as either situations with insufficient power plant capacity or situations with production of electricity on power plants.

In the current version, the tool will only exchange electricity if both situations occur. Therefore, it will not ramp up a power plant in one system to fill under-production of electricity in another system. Thus, the tool examines how excess electricity can be used and does not guarantee the balancing of production and demand in all hours in all systems. In the long run, this feature can be implemented in the system, but it is not key to investigating how the smart city energy system interacts with the surrounding systems. The user just has to be aware that remaining excess electricity can result in the curtailment of wind power, and that a lack of capacity can result in an increase of power plant production. Both of these are related to the overall system operation and not to the interplay between the smart city energy system and the surrounding energy system.

The tool is not limited to the relations between cities and countries. The same situations and choices have to be analysed when discussing energy systems on a regional or cross-country scale. The tool is therefore designed to handle the general aspects of these issues. Countries do, for instance, have to investigate to what extent there is sufficient capacity in surrounding countries, or how much wind can actually be expected to be available at certain hours.

4.3. TWO-DIMENSIONAL APPROACH TO SMART CITY ENERGY SYSTEMS

The next part of the investigation is to combine the knowledge from the system integration context and the geographical context into a two-dimensional approach to smart city energy systems. Thus, the study investigates the combination of an increased system integration in the local smart city energy system and compares it to the surrounding country and an increase in the transmission between the surrounding country and the smart city energy system. The surrounding country can potentially go through the same integration steps at the same rate, but in specific cases it can be at a different rate. By doing this and using the MultiNODE tool, it is possible to see how the integration in the smart city energy system and surrounding energy system affect each other.

The final part makes it possible to analyse to what extent a large system integration in a smart city energy system affects the utilisation rate of renewable energy and to what extent it will increase or decrease the use of scarce biomass resources. Thus, it becomes possible to not only investigate to what extent a given energy system of a city can benefit from increased system integration, it is also possible to investigate how the context of system integration could potentially benefit the total national energy system or provide challenges for the national energy system.

This analysis provides the necessary offset to the main discussion of the thesis. Chapter 7 discusses and binds the thesis together based on this two-dimensional approach.

CHAPTER 5. SYSTEM INTEGRATION AND SYSTEM DESIGN

This chapter discusses the *system integration context* of smart city energy systems. The chapter reflects first on the necessity of system integration and why it is important to analyse system integration to be able to achieve the most efficient solutions. This is done based on the draft paper “Multi-model approach to analysing heating systems in low carbon energy systems: The case of Ireland” [77], found in Appendix F.

The second section of the chapter reflects on the consequences an integrated energy system has on the system design. With the choice of system integration, the energy planner should acknowledge that the introduction of new technology not only affects a single sector but can also potentially affect the entire energy system (the single technology integration context). This aspect is discussed based on the paper “Energy saving synergies in national energy systems” [78], found in Appendix C.

5.1. SYSTEM INTEGRATION BENEFITS

To reflect on the necessity of investigating the benefits of system integration and the fact that the choice of tool is crucial, this thesis looks at the results from the paper in Appendix F, “Multi-model approach to analysing heating systems in low carbon energy systems: The case of Ireland” [77].

The initial intent of the study in Appendix F is to apply both TIMES and EnergyPLAN to investigate potential heating scenarios for Ireland. This is with the acknowledgement that the Irish TIMES model is not set up to handle a large implementation of district heating, hence the Irish TIMES model is not ideal to investigate system integration [79]. Thus, EnergyPLAN provides insight into how system integration can improve a scenario.

The Irish TIMES model is suited to investigating different scenarios under the constraints and economic inputs provided by the user. The study here takes the CO2-80 scenario for Ireland identified by the researchers at University College Cork [79] as the point of reference. However, due to the limitations of the Irish TIMES model, the CO2-80 scenario does not investigate all heating solutions for the future energy system in 2050 in Ireland. The study utilises EnergyPLAN to convert individual heating in district heating and compares these results with the CO2-80 scenario, which primarily uses individual heating. The results from this study can be seen in Figure 5.1 and Figure 5.2.

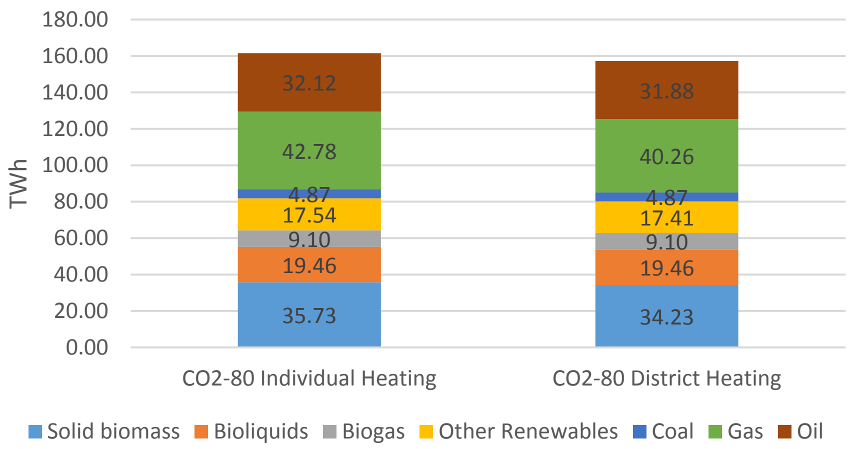

Figure 5.1 Comparison of fuel usage for the Irish CO2-80 scenario energy system based on either individual heating or district heating. [77]

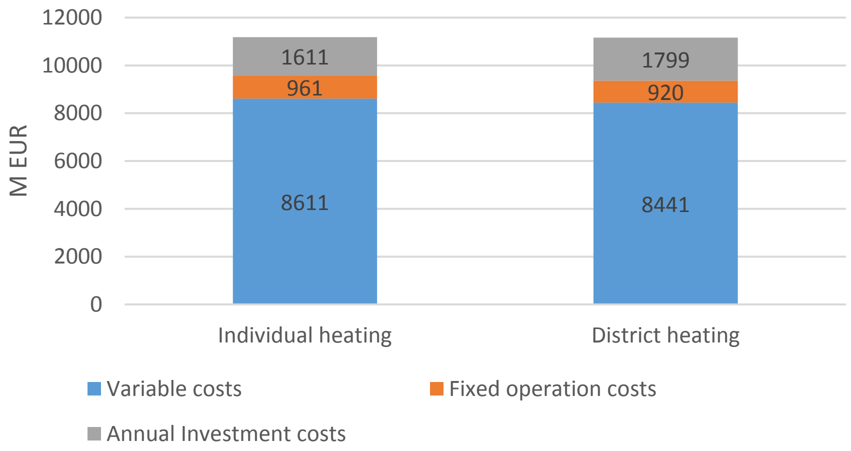

Figure 5.2. Comparison of annual costs for the Irish CO2-80 scenario energy system with individual heating and with district heating. [77]

Figure 5.2 shows that from a cost perspective it is possible to achieve a system with the same or lower total annual costs as in the case of the CO2-80 scenario, which is only with individual heating. Basically, this is achieved by reducing the variable costs for fuel and increasing investment costs due to the pipes of the district heating network.

What Figure 5.1 shows is that the CO2-80 scenario becomes more efficient with the implementation of district heating than it was with individual heating. The district heating grid reduces the use of biomass, natural gas and oil through the operation of a more fuel-efficient system.

Together, the study shows that the district heating system is not more expensive than the optimal system identified in the Irish TIMES model and it is in fact more fuel efficient. Together, these results show the importance of investigating the system integration context in smart city energy systems analysis and also of choosing the right tools for investigating the options. In cases where tools are used and they cannot investigate system integration, it is not certain that the most efficient system has been achieved. It must be the goal of smart city energy systems to be efficient, as this will allow for more options for the surrounding country and other cities wanting to transition to sustainable energy systems.

5.2. SINGLE TECHNOLOGY INTEGRATION CONTEXT

The paper in ref. [78] is in relation to the study carried out in [33], and both these studies discuss the implementation of energy savings in smart energy systems. The goal in ref. [33] is an investigation into the feasible amount of energy savings that can be implemented in a smart energy system that also utilises a large amount of waste energy. Ref. [78] specifically investigates the system consequences of performing energy savings. It tests how an energy system based on combined heat and power responds to the implementation of heat savings and electricity savings. This means it enables a discussion of how a key technology in the smart energy system responds to changes in the system design with changing energy demands. Thus, these are examples of how to investigate the single technology integration context when implementing a new technology in a smart energy system. In several cases, the energy system impact is not investigated for energy savings initiatives such as better appliances [80], lighting [81] and improved building stock [82].

The study in [78] is based on EnergyPLAN simulations of an energy system based on combined heat and power plants, with power plants and boilers to handle peak periods. The study then systematically changes the heat and electricity demands, respectively, and measures the performance of the energy system based on CO2 emissions and the primary energy supply. The study's main target was to investigate the potential synergies between electricity and heat savings in an integrated energy system. This reflection carries over to the system design context of smart city energy systems, as it relies on the integration of the heat and electricity sector.

Based on the methodology highlighted in [78], the study identifies that an integrated energy systems performance regarding energy savings is dependent on both the amount of savings but also on how savings are achieved across the different energy sectors. The results are highlighted in Figure 5.3.

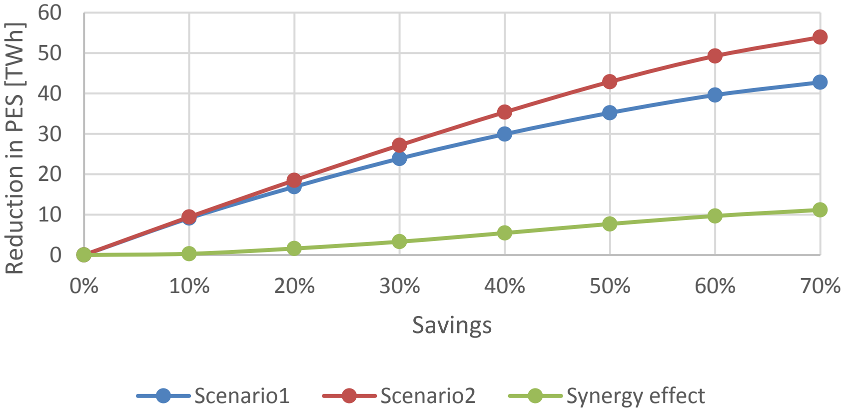

Figure 5.3 Comparison of reduction in primary energy supply, with respectively heat and electricity saving performed separately in two separate energy systems (scenario 1) and performed together in one energy system (scenario 2). The synergy effect reflects the influence of the system integration. [78]

The results in [78] conclude that in an integrated energy system it is beneficial to not only look at heat savings or electricity savings alone; when both are integrated at the same time, a better utilisation rate is achieved. What is, however, crucial to highlight is that the smart energy system performance can benefit from the integration of energy savings or other technologies. Ref. [83]

shows this for heat pumps and Ref. [33] identifies that for energy savings, the least-cost smart energy system is identified at approximately 40% heat savings. This result can be seen in Figure 5.4.

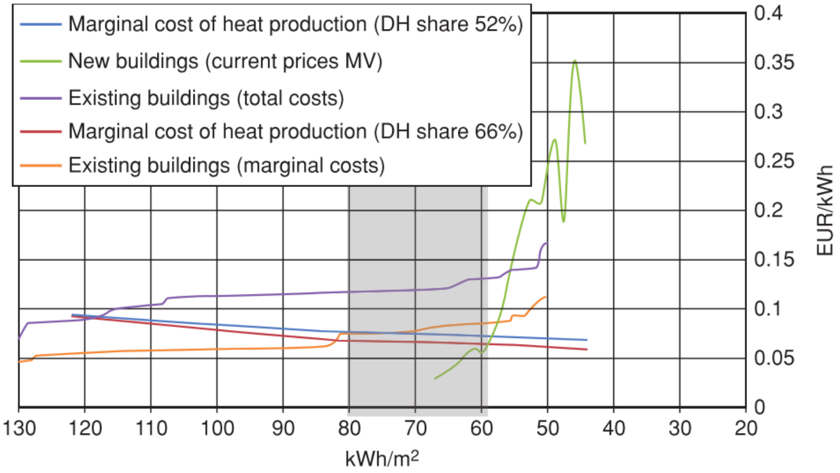

Figure 5.4. The marginal production costs of heating in a Danish 2050 smart energy system compared with the marginal costs of heat savings in the current Danish building stock and future Danish building stock. [33]

In relation to smart city energy systems, these studies identify that the system design of integrated energy systems can benefit from the implementation of technologies other than those emphasised in the core principles of smart energy systems. The specific studies regarding energy savings and heat pumps, however, also show that equilibrium occurs.

The smart city energy system relies on the interplay between the different sectors; that is, between the electricity, thermal and gas grids. Thus, the introduction of a new technology does not only affect one sector—it affects the whole energy system. For example, with the introduction of heat savings in a smart city energy system, the savings do not only affect the production of heat. Because of the integration between the sectors, a lower heat demand affects the production of, for instance, a combined heat and power plant, or how much excess electricity can be meaningfully converted to heat in a heat pump.

In such cases, it is important to note that the introduction of a technology might still make the energy system perform better to a certain extent, as illustrated in Figure 5.3. However, from the perspective of the system design context, the planner has to investigate how the introduction of a new technology relates to a smart city energy system and whether there are consequences from a system perspective. It is not sufficient to only look at potential heat savings; it is necessary to see to what extent the technology affects the overall performance of the energy system. When the whole energy system is taken into account, it is also possible to analyse possible measures that can improve the performance of the given technology. An example is shown in the results highlighted in Figure 5.3. Here, a system perspective makes it possible to see that the combination of heat and electricity savings improves the total benefit compared to the case where only one of the two occurred.

CHAPTER 6. LINKING A LOCAL ENERGY PLAN TO A NATIONAL ENERGY SYSTEM

This chapter highlights the *geographical contexts* of the smart city energy systems analysis. The reflections are based on the results of the paper “Roles of local and national energy systems in the integration of renewable energy” [84], also found in Appendix D.

The premise for the paper is that in the transition towards renewable energy systems and the reduction of CO2 emissions, there is a need for local and national energy planning [85,86]. Currently, the local energy planning in cities and municipalities emphasises specific targets within the city without relating these to the surrounding national energy system [39,45]. National planning, on the other hand, focuses on creating renewable energy systems for the country, and while they might indicate that local actions are important, they seldom create an action plan for different local regions [21,68,87].

The paper therefore uses the MultiNODE tool to link two local energy plans, one for Copenhagen [45] and for Sønderborg [39], with the case of national development in the CEESA energy system [68]. The Danish CEESA scenario is a national plan for Denmark based on the concept of smart energy systems. The goal of the paper is to see how the consequences of a specific local plan influence the national plan. In other words, the study investigates the consequences a local energy plan can have on the potential of the remainder of the country in terms of transitioning to smart city energy systems and smart energy systems. The study measures how well the systems connect by measuring how much excess electricity can be exchanged.

The results are shown in Figures 6.1 and 6.2, with 6.1 being between Sønderborg and Denmark and Figure 6.2 between Copenhagen and Denmark. The paper investigates a local system based on smart energy systems, a smart city energy system and as two locally designed plans.

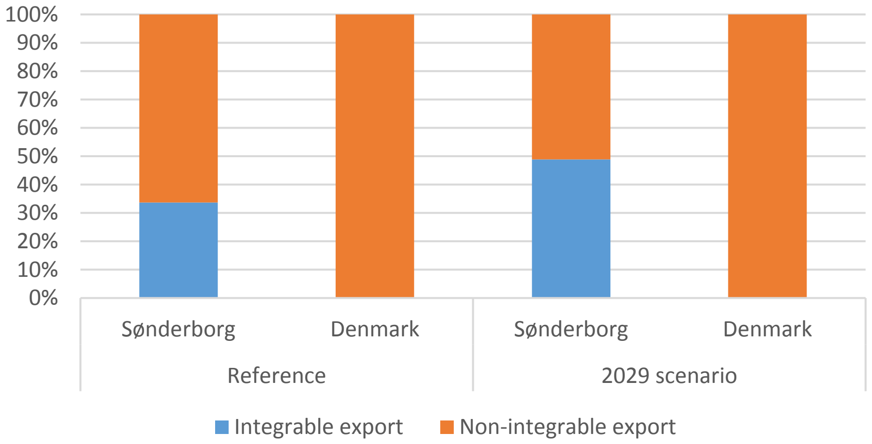

Figure 6.1 Amount of the excess electricity in Sønderborg and in Denmark that can be exchanged between each other. Reference scenario is based on the CEESA 2030 scenario, where the 2029 scenario is based on the concrete plan from Sønderborg. [84]

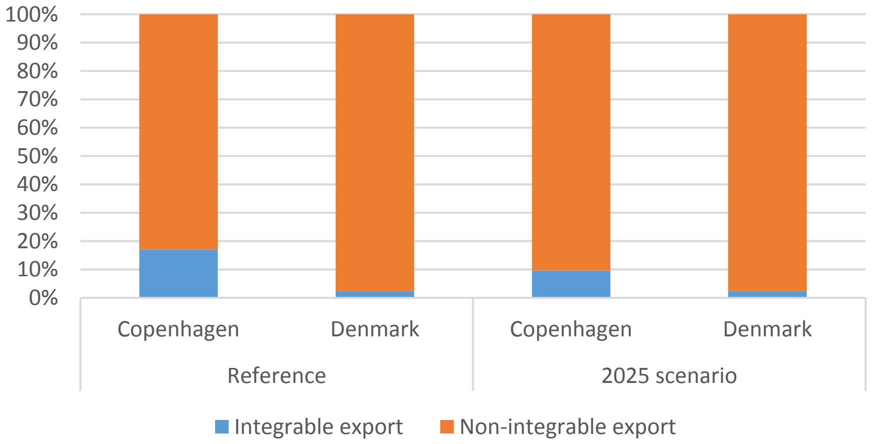

Figure 6.2. Amount of the excess electricity in Copenhagen and in Denmark that can be exchanged between each other. Reference scenario is based on the CEESA 2030 scenario, where the 2025 scenario is based on the concrete plan from Copenhagen. [84]

The results show that the locally designed Sønderborg system is better designed to integrate with the Danish smart energy system. The plan designed by the Copenhagen municipality results in a lot of exportable electricity and a large use of biomass. Thus, the plan designed by Sønderborg creates much better resource utilisation. Tables 6.1 and 6.2 shows the consequences of the different plans in terms of fuel utilisation.

Table 6.17. Total fuel outputs for all of Denmark. The table shows the fuel consumption for Sønderborg and the rest of Denmark following the CEESA 2030 scenario, and Sønderborg following its 2029 plan and the rest of Denmark following the CEESA 2030 plan.

	Reference Sønderborg + Rest of Denmark	**Sønderborg 2029 + Rest of Denmark**
Biomass [TWh]	62.13	62.52
Natural gas [TWh]	22.90	22.17
Oil [TWh]	43.81	43.81

Table 6.2. Total fuel outputs for all of Denmark. The table shows the fuel consumption for Copenhagen and the rest of Denmark following the CEESA 2030 scenario, and Copenhagen following its 2025 plan and the rest of Denmark following the CEESA 2030 plan.

	Reference Copenhagen + Rest of Denmark	**Copenhagen 2025 + Rest of Denmark**
Biomass [TWh]	62.43	70.37
Natural gas [TWh]	22.99	17.98
Oil [TWh]	43.81	43.81

When comparing this to the designed smart city energy system that serves as a reference in the model, the smart city energy system of Copenhagen in particular has a much better interplay with the surrounding energy system. The resource use is lower in the total system. The consequence for Copenhagen is that the city cannot use as much biomass in its energy system, but on the other hand it creates better opportunities for the surrounding country to achieve sustainable energy systems.

In terms of smart city energy systems, this study specifically compares specific local plans of Copenhagen and Sønderborg with a local development based on smart energy systems. The specific local plans, the Copenhagen 2025 plan and the Sønderborg 2029 plan, to some extent implement the ideas of smart city energy systems, but an investigation into the plans shows this is in neither case their sole emphasis. Instead, the goal of the plans is only the development of a sustainable city or a city with net-zero emission of CO2. The plans themselves do not investigate the link between the local smart city and the national energy system. As such, they do not take the geographical context into account and it is difficult to say to what extent the plans leave room for the local development of other cities and municipalities.

The paper provides an insight into this geographical context of smart energy systems. From looking at the results, it is clear that the Copenhagen 2025 plan might create a sustainable local system, but it hinders the development of other cities, as it uses too much biomass. This is especially a problem when the system is not able to interact with the surrounding energy system to the same extent as a smart city energy system. The Sønderborg systems perform more or less equally in the smart city energy system and the Sønderborg 2029 plan. The Sønderborg 2029 plan, however, also places an emphasis on not importing biomass from other regions to reach a CO2 neutrality target, as is the case for the Copenhagen 2025 plan. This gives the city the freedom to design an integrated energy system that allows for better interaction with the surrounding country.

This paper therefore emphasises why it is important to take the geographical aspect of a city into account. Within a narrow scope of the city itself, it might be possible to achieve renewable or sustainable targets, but the choices affect the possibilities left behind for the remaining municipalities and cities in the country. When analysing geographical context, city planners can identify how the plan interacts with the rest of the country, and thus not only consider local targets but also help contribute to the national targets in a way that does not limit opportunities for other cities.

Based on this paper and the use of the MultiNODE tool for EnergyPLAN, it is possible to identify when a local system over-utilises one resource, such as Copenhagen using too much biomass. This would be possible to identify to a certain extent without the tool, but the tool adds the necessary perspective of how flexible the local system is when it interacts with the surrounding national energy system. The results show that Sønderborg provides a more flexible system than Copenhagen, as well as a system that works better in relation to the national energy system. In order to justify Copenhagen’s use of biomass, it would have had to be in correlation with the national energy system development and part of the process of creating a flexible Copenhagen energy system.

CHAPTER 7. SYSTEM INTEGRATION AND SYSTEM INTERCONNECTION

This chapter discusses smart city energy systems in terms of the geographical context and system integration context. The basis for the discussion is the concept highlighted in Figure 1.1, namely that a smart city energy systems analysis should be seen from the point of view of the city and the interplay between the two contextual aspects. This interplay between the cross-sector system integration and system interconnection between two geographic locations is examined in the paper “Cross-border versus cross-sector interconnectivity in Renewable Energy Systems” [88], found in Appendix E. The paper provides the basis for discussing the benefits of system integration in relation to system interconnection. The paper leads into a broader discussion on the analysis and planning for smart city energy systems. The papers offset is that in many cases there has been a division between looking at system interconnection, for instance between countries [89–92], and system integration, for instance between the gas, thermal and electricity grids [75,93–95].

The system integration of smart energy systems seeks to utilise excess energy originating from one energy sector in another. One example is the use of excess electricity from renewable energy to supply heat and transport demands. Thus, it can be an alternative to exporting electricity through cables. For smart city energy systems, it is relevant to investigate the system integration context based on what options the city has to integrate the different parts of the energy sector. This is compared to the extent to which it needs to interplay with the surrounding energy system.

Ref. [88] analyses this comparison between utilising excess electricity within the energy system by integrating different sectors and importing and exporting excess electricity. With the increasing amount of excess electricity in energy systems as they transition to more and more renewable energy sources, it becomes increasingly relevant to investigate how to utilise this excess. Two primary strategies are either system integration or the interconnection between countries. [96] To analyse these two scenarios, the paper investigates two archetypical energy systems, one representing a southern system and one representing a northern system. This enables the study to consider the difference in electricity production due to weather patterns.

The study uses a combination of the MultiNODE tool and the EnergyPLAN analyses to investigate both the transmission of electricity and the specific performance of these energy systems before and after the transmission of electricity. The goal is to see to whether and to what extent either system integration or system interconnection provide the greatest benefits for the energy systems.

Figures 7.1 and 7.2 show the primary results from the analysis. From this, it is possible to see that system integration provides a higher benefit for the northern and southern systems compared to system interconnection. Increased system integration reduces the use of primary energy more than system interconnection. An interesting aspect is that system integration also leads to a lower utilisation rate of transmission cables. More electricity is simply used internally in the energy system.

In an energy system with only individual boilers, power plants and renewable energy, the systems benefit much more from cables, as there is a clear prioritisation of the use of renewable energy. In an integrated energy system, this utilisation is much more complex, and in many cases, it becomes more clear that it should be used it in heat production or electric vehicles.

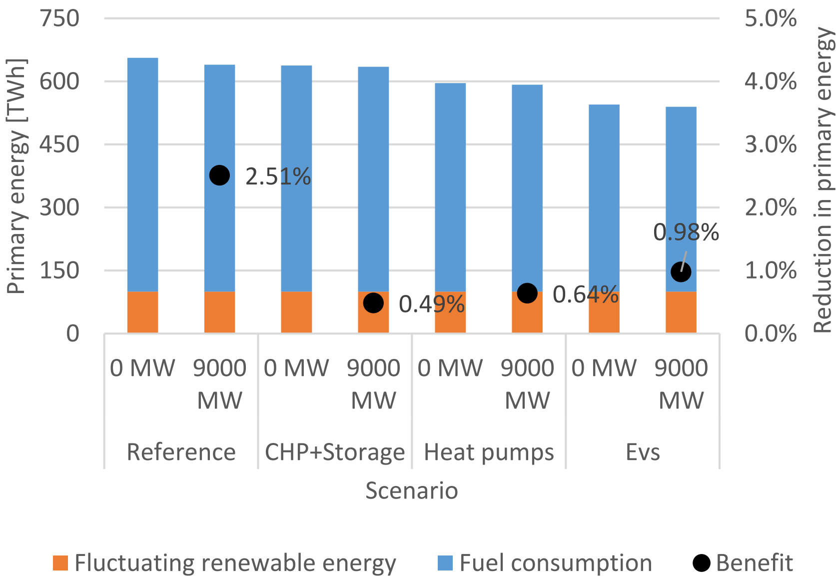

Figure 7.1 Benefit of increased system integration and benefit of system interconnection at each scenario. [88]

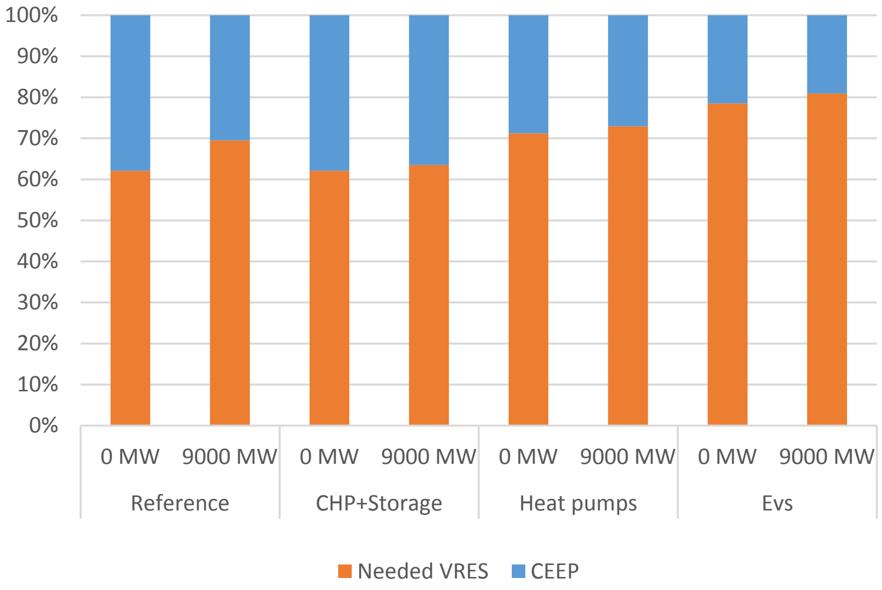

Figure 7.2 Utilisation degree of variable renewable energy at the different scenarios for system integration and system interconnection.. [88]

The study thus emphasises that from an overall perspective, system integration creates better technical performance for the energy system than segregated sectors and that the interconnectors increase the usage of renewable energy.

The study shows, with the emphasis placed on smart city energy systems, that to operate an energy system most efficiently, the city should have an integrated energy system. An energy system in a city with low integration between the energy sectors will not create a more efficient use of the variable renewable energy production, even if it has a high level of interconnection. Such a system might exchange more electricity, but it is potentially at the cost of fuel efficiency. Instead, a highly integrated energy system for the city is a much more efficient solution. With a focus on the integration context of smart city energy systems, it is possible to identify solutions using district heating and heat pumps, as well as electric vehicles with smart charge technology [31]. These technologies are necessary to create a more efficient use of variable renewable energy that does not put a strain on scarce resources such as biomass [68,71]. The local energy planner should therefore strive to create a city in which system integration allows for the usage of variable renewable energy.

When combining the knowledge from Chapter 5 and Chapter 6, it becomes possible to identify solutions as to how the combination of the geographical context and the system integration context can improve the planning of smart city energy systems.

The analysis in Chapter 5 shows that system integration results in more efficient solutions; thus, for the local energy planner, it is essential to investigate what options the city has for system integration and utilise these potentials. In that regard, system integration also defines the framework for the implementation of other important solutions. For instance, with the implementation of energy savings in the heating, and the electricity sector, the smart city energy system affects how much the system can benefit from changes in demands.

The risk the planner takes by not including the system integration context in assessing the implementation of technologies is that the best performance is not achieved. If, for instance, the implementation of heat savings is not related to the performance of the integrated energy system, the planner will miss out on the situation where a combined heat and power plant must produce electricity due to an electricity demand. Thus, the energy planner must consider the system integration context of smart city energy systems to avoid situations of sub-optimisation.

Chapter 6 analyses the geographical context of smart city energy systems. Both the Copenhagen and Sønderborg case are not designed with the surrounding country in mind, but the Copenhagen case most clearly illustrates the issues of not considering the geographical context of designing Smart City Energy Systems.

The Copenhagen 2025 plan designs a local energy system that relies on large-scale biomass-fired combined heat and power plants. These units must produce a specific amount of excess electricity to offset the CO2 emissions from the transport sector, which the plan does not address. The plan does implement some amount of heat savings, as well as some renewable energy. The consequence of the plan is, however, that due to the size of the biomass-fired combined heat and power plant, the Copenhagen plan utilises so much biomass that the rest of Denmark cannot make a sustainable transition to 100% renewable energy. Copenhagen uses more than what the total Danish system can sustain. In a bubble, Copenhagen achieves CO2 neutrality with the 2025 plan, but it does this at the expense of the remainder of Denmark. Thus, not taking the geographical context into account can potentially lead to solutions that are unsustainable on a national scale.

The geographical context can also help in assessing the technologies chosen. The Copenhagen plan implements large combined heat and power plants that require a certain load due to the heat demands in Copenhagen thus producing electricity in hours with too little demand that can only be exported. However, the MultiNODE tool allows the local energy planner to see that if the rest of Denmark transitions to a smart energy system, there are not many situations where this export makes sense from a technical point of view. Thus, the Copenhagen plan does not allow for integration with the rest of the country.

If the urban systems can seek integration locally and be sufficiently flexible to utilise interconnection to the surrounding systems, more efficient solutions can be achieved. This means that the implementation of renewable energy, such as wind turbines, in one system can be utilised in an urban area with more electricity demand. This is shown in the Sønderborg case, where interconnection leads to an efficient energy system that does not limit the opportunities for the surrounding country. The study in Chapter 6 also shows that a Copenhagen system with more heat pumps would enable better integration, as Copenhagen would then have to import more electricity from a country with plenty of excess instead of producing more excess electricity to a system with plenty due to large amounts of variable renewable energy production from wind turbines.

The final point that is important to mention in relation to the geographical context is that the surrounding country should also leave room for the development of the city. This means that pathways for the national energy system should be designed so that the smart city energy plans can operate within them without jeopardising the plan. Furthermore, the plan needs to be so concrete that the smart city energy systems can make the right decision. To be able to achieve 100% renewable energy systems on a national level, most countries would need the right local action from local planning authorities. This specific discussion has not been investigated in detail in this thesis, but needs to be in place to enable the smart city planner to make the right analyses. The national energy planning has an important role to play in terms of being the one who guides the overall energy system development.

The analysis in Chapters 5 and 6, combined with the discussions above, illustrate that both the system integration context and the geographical context are important in the analysis and planning of smart city energy systems. However, the initial analysis and discussion here in Chapter 7 illustrate that it is equally important to utilise both the contextual aspects together in the planning of smart city energy systems. By investigating the system integration and the geographical contextual aspects of the same smart city energy system, it is possible to achieve the most efficient solutions in terms of increasing system integration, but also always in relation to how it affects the surrounding country and how much interaction it enables between the system. This interaction should lead to an overall system efficiency that not only benefits the local energy system, but also the national energy system. In some cases, it might even be necessary to sacrifice performance in a local energy system if it can improve the national energy system.

The combination of system integration and an overview of geographical interconnection opens up the possibility of achieving sustainable solutions both in the city and for the surrounding country.

One benefit of this approach is that different development strategies can be assessed, both for the city and for the country. By assessing these alternatives, it is possible to define the choices [31] the city has and relate them to the possible developments the national energy system might experience in the future. This enables the city to act, even in an environment where other cities have not started acting yet or the national plans are not fully developed.

It can potentially be a problem if those who act first do not leave room for the rest of the country to achieve 100% renewable energy systems, but on the other hand, if everybody waits, then nothing will be achieved. The combination of system integration and the geographical aspect, alongside the assessment of different alternatives, makes it possible for the city to act based on an actual assessment of the surroundings instead of acting based on a narrow-minded city-only focus. The study in this chapter as well as Chapter 5 illustrates that local system integration allows for the most efficient systems. Thus, local smart city energy systems should strive towards system integration, as the most efficient systems with many flexible technologies leave the greatest room for the remainder of the country’s energy system to develop along the path of 100% renewable energy systems. These systems have the potential to act together across geographical borders with the remaining energy systems, as they include a broad number of technologies that act cross-sector. This creates a flexibility in which systems can potentially act together. Thus, wind energy can be used not only in a local system but also in an efficient smart city energy system in the neighbouring municipality. This once again emphasises the necessity of investigating not only the geographical context and the system integration context separately, but also including both to get a two-dimensional view of the development of smart city energy systems.

CHAPTER 8. CONCLUSIONS

Through the works within this thesis, the conclusions can be divided into three main categories: a theoretical conclusion, reflecting on the concept of smart city energy systems and the need for an analysis of the contextual aspects; a methodological conclusion that discusses the use of EnergyPLAN and the MultiNODE tool as a methodological approach to the analysis of smart city energy systems and the contextual aspects of smart city energy systems; finally, the analytical conclusion will extract the main conclusions from the analyses of smart city energy systems and the contextual aspects.

8.1. THEORETICAL

This thesis investigates the concept of *smart city energy systems*, which is the idea of achieving 100% renewable energy systems for a smart city through the application of the concepts of smart energy systems.

Many cities have plans for transitioning their energy system towards targets associated with renewable energy, such as sustainable cities, CO2-neutral energy systems and systems with 100% renewable energy. Most of these targets centre on the city itself and on achieving local renewable or sustainability targets. However, one of the key messages from this thesis is that these targets cannot be seen only from a local perspective. For a local energy system to be sustainable, it cannot leave the surrounding country worse off, nor can a local 100% renewable energy system be a good system if it eliminates other systems’ potential for achieving the same targets.

Therefore, to assess the smart city energy system, the planner cannot only investigate the performance of the city itself. Instead, the planner must include the context of the smart city energy systems.

Two crucial contextual aspects are identified in the thesis. The first is the system integration context and the second is the geographical context. As the smart city energy system relies on system integration, the researcher or planner should identify to what extent the local system benefits from the system integration and identify how technologies fit within the integrated energy system. This aspect enables the researcher to assess how the system design affects the overall performance of the energy system.

In the analysis of smart city energy systems, the geographical aspect must be considered in order to be able to consider the development of the smart city in relation to the remainder of the country. When analysing geographical context, there are two main purposes: the first is to see whether the smart city energy system limits the development of the surrounding country. This could be in terms of the use of resources. The second is how well the city interconnects with the surrounding energy system. This reflects how well resources can be exchanged between the two systems.

The two contextual aspects should in the end be related to each other to achieve the solution for a smart city energy system that both utilises system integration within the city and integrates with surrounding energy systems using interconnection. By not identifying solutions for only the city itself, the analysis of the contextual aspects enables the identification of solutions that fit within development of the overall national energy system.

8.2. METHODOLOGICAL

To analyse the contextual aspects of smart city energy systems, a methodological approach is identified. The smart city energy systems should be modelled in an energy system analysis tool. The tool identified must be able to model the city’s energy system, must be able to focus on system integration and should be able to link systems to each other.

From a methodological point of view, the key point of the investigation of the system integration aspect is to see how different technologies correspond to the integrated energy system. Thus, the user should identify how the performance of the smart city energy system changes with the implementation of different technologies. To systemise this, the user should model an increasing implementation of a technology in steps to identify to what extent the specific technology can be implemented within the core principles of smart energy systems. In this thesis, the EnergyPLAN tool is used to investigate the performance of the smart city energy system and the system integration context.

One of the main outcomes of the thesis is the development of a new tool to investigate the geographical context of smart city energy systems. The tool development was initiated because, currently, the available models able to undertake system interconnection cannot consider the whole energy system, are not simulating hourly operation, or have a strictly cost-driven logic behind their transmission. To analyse smart energy systems and smart city energy systems that operate on well-connected grids within the same electricity markets, it was deemed necessary to investigate the option of creating a tool that could theoretically identify in what situations there is an actual demand for import and export—that is, in what situations import and export make the systems more efficient.

The MultiNODE tool developed is an add-on to EnergyPLAN and uses the EnergyPLAN framework to identify hours in which an energy system produces electricity it cannot utilise itself as well as other hours where the energy system has insufficient capacity or uses inefficient power plants. The surrounding energy systems are subjected to the same analysis and through a network, the tool matches these periods to find situations in which excess electricity can be transferred from one system to another. This approach is rooted in the smart energy systems framework, in which the integrated energy system seeks to utilise as much energy locally as it can before exporting that energy. The concept allows for the investigation of interconnection, based on the principles of smart energy systems, and allows for the analysis of interconnection without the implementation of an economic framework.

This is one possible approach to the investigation of the geographical context, but it is also possible to investigate this based on other approaches, for instance based on short-term marginal costs. This thesis suggests one approach that in principle allows any model in EnergyPLAN to be linked with another. The approach can be further refined, as it currently does not differentiate based on power plant efficiency. Furthermore, more technologies can be considered to identify situations in which an energy system should import electricity.

8.3. ANALYTICAL

The thesis applied the theoretical framework and the methodological approach to several analyses and cases. These can be found in appendices C to F and are discussed in Chapters 5 to 7. The studies specifically discuss the integration context from the point of view of an integrated energy system based on electricity and heating and the geographical context of linking local energy planning in cities and municipalities with national energy planning. The final study furthermore investigates the interplay between system integration and geographical interconnection to investigate a two-dimensional approach to smart city energy systems (an approach that is going to be further investigated in the Re-Invest research project [97]).

When analysing smart city energy systems with the system integration context in mind, the studies show that system integration is more efficient than systems not including system integration. Within the scope of smart energy systems, it is more important that the studies show that system integration influences the performance of certain technologies. A certain technology might stop improving the system at a certain point, since different sectors are integrated. The contextual aspect of system integration is therefore crucial for the energy planner in terms of understanding the performance of the system and for the implementation of the right amount of a certain technology, as the integrated energy systems are more sensitive to changes.

The studies show that the geographical aspect in relation to smart city energy systems is crucial to investigate in order to identify the actual performance of local energy systems. While a local system is potentially efficient within its local framework, it can easily result in limiting the options for the surrounding country by using too much of a single resource. The geographical context emphasises that the performance of the local energy system must be seen in relation to how it affects the performance of the surrounding energy system. One simple way of doing this is through evaluating the resources used and the remaining resources available. However, the thesis also shows that the interaction between the local and national energy systems is important. The systems should be designed so that they can interact with each other. If a system does not consider this interaction, it will reach a solution that also cannot fully utilise system integration. It is therefore necessary to investigate the geographical context from the perspective of hourly simulations of smart city energy systems and national smart energy systems.

The final analysis of the thesis combines the geographical context with the system integration context to initiate a two-dimensional approach to the analysis of energy systems. This analysis shows that the system integration and geographical interconnection affect each other. In the case of countries with plenty of resources, the study shows that system integration in general leads to fewer situations where interconnection improves the system. However, it also shows that some interconnection increases performance, as not all technologies are readily available to both systems. In the city context, this effect is amplified since the technology discrepancy between a city energy system and a rural energy system is higher than that between two countries. Hence, here the system interconnection can play a crucial role in achieving all the benefits of system integration. System integration allows for more efficient energy systems that leave more room for the development of the surrounding energy systems, especially if these systems can interconnect. Since not all resources are available to all cities, system interconnection allows all systems to also move towards system integration. Thus, more knowledge regarding the performance of the smart city energy system can be achieved through not limiting the analysis to only considering the two contexts individually, but also through combining them to investigate how the system benefits from system integration and how it benefits from system interconnection.

While the idea of the two-dimensional approach is interesting on the city level, it becomes more relevant when discussing it on a country-to-country level, as a country has better resource access than a city. The two-dimensional approach is therefore interesting when performing further analyses on a continent level, especially in the light of ideas such as super grids. The two-dimensional approach can potentially reveal that it is better to go for system integration than system interconnection in several cases. The study in Appendix E already suggests that such situations might occur, and it will be further investigated in the up-coming Re-Invest project [97].

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APPENDICES

Appendix A:
Developing MultiNODE

Appendix B:
MultiNODE Documentation Version 1

Appendix C:
Energy saving synergies in national energy systems

Appendix D:
Roles of local and national energy systems in the integration of renewable energy

Appendix E:
Cross-border versus cross-sector interconnectivity in renewable energy systems

Appendix F:
Multi-model approach to analysing heating systems in low carbon energy systems: The case of Ireland

APPENDIX A

Developing MultiNODE

DESIGNING THE MULTINODE TOOL FOR ENERGYPLAN

In developing a new tool for EnergyPLAN that should have the capability of connecting several EnergyPLAN analyses, the purpose of the tool and in what framework the tool should work are both central components to be considered. Within the scope of this thesis and smart city energy systems, the tool has to be able to operate within a technical simulation strategy. The tool is modelled as an addition to EnergyPLAN [1–3], as this tool can simulate energy systems based on technical principles that integrate as much variable renewable energy as possible in a fuel-efficient way.

The approach in designing the MultiNODE tool is therefore to base it on the same technical principles of EnergyPLAN. The main objective of the technical simulation in EnergyPLAN is to reduce the use of electricity produced in power plants and heat produced in heat-only boilers [1,2]. Within this sense, the main objective of the MultiNODE tool, operating in technical mode, is to utilize interconnection to reduce the use of power plant production. Furthermore, the MultiNODE tool should also be able to handle situations wherein one system lacks the electrical capacity to fulfil the system's electricity demands.

The achievement of this overall goal should enable the user to put a given system into a geographical context. If the tool identifies situations wherein import or export is possible, this interaction should happen with the surrounding energy system. The direct impact of such an action, which is a direct consequence of the specific smart city energy system, should be immediately making the surrounding energy system either produce more or less energy. This change in production would therefore change the resources used so the user can assess how the given smart city energy system affects the potentials of the surrounding country's energy system.

To set up a model that works with the technical principles of EnergyPLAN, it is necessary to understand exactly what options the user has in tweaking the technical simulation strategy in EnergyPLAN. By tweaking these elements, the user can influence the amount of excess electricity created in the system. There are three main activities that can be adjusted: the operation of CHP plants, the balancing of the electricity grid in the system, and how the system handles critical excess electricity (CEEP) [1].

The amount of excess electricity the modelled energy system produces is to a large extent dependent on how much variable renewable energy is introduced into the energy system. However, it is also dependent on how the system balances.

If the system balances the production of combined heat and power plants based on heat demand, the plants will produce electricity with no regards to the electricity demand, thus also producing excess electricity. This can be avoided by balancing combined heat and power plants with both heat and electricity demands, but doing so will leave less electricity available for export.

The balancing of the electricity grid can also result in more excess electricity being produced. This can be a consequence of limiting large power plants' ability to shut down. In hours with sufficient production from renewable energy, and when the power plants are unable to ramp down, this will result in excess electricity available for export. The requirements for grid stabilization can also result in more electricity being produced that can potentially be exported.

EnergyPLAN uses the main measure of critical excess electricity to define the excess electricity that the system cannot handle (by using transmission cables, for instance) [1]. To reduce the amount of critical excess electricity, EnergyPLAN enables the user to reduce the amount of power produced by a CHP plant, to use excess electricity in electric boilers, to shut off wind turbines and other variable renewable energy sources, and to increase the hydrogenation of CO2.

The goal for the MultiNODE tool is to utilize this described excess electricity from EnergyPLAN to express the available electricity a system offers to the grid, and into which one or more other systems can potentially tap. It is clear that the amount of excess electricity can be regulated by the user. In that sense, it is necessary to tweak how much is available for the grid and how much the system should try to utilise itself.

With this possibility of identifying the amount of electricity available for export in given systems, such as the smart city energy system or the surrounding energy systems, it is necessary to identify in what cases this available excess electricity can actually be used in another system. To identify this, the approach is still based on the technical operation of EnergyPLAN.

EnergyPLAN seeks to limit the use of boilers and power plants with the goal of utilizing more efficient energy sources, such as combined heat and power plants, or renewable energy sources. In that sense, the MultiNODE tool assumes that the utilization of excess electricity in one system has the same main technological assumptions. Thus, the MultiNODE tool should reduce the use of power plants for electricity production. Hence, in situations where a system relies on power plant production, but available excess electricity from another system is available, the MultiNODE tool should turn off the power plant production and instead utilize the excess electricity. Another situation wherein the MultiNODE tool should introduce the excess electricity is if insufficient capacity is available in the given system.

The reason the MultiNODE should not regulate the production of combined heat and power plants is that it does not know to what extent these are utilized for heat production. Thus, if the tool were to reduce combined heat and power plant production, it would in many cases replace the heat production by a fuel boiler, making it questionable to what extent the electricity would reduce fuel usage.

An argument could be made for the tool to be able to ramp up combined heat and power production in one system to displace power plant production in a different system, as this would provide an overall better degree of system efficiency. This capability is difficult to achieve in a standalone tool that does its operation outside EnergyPLAN, and thus it is not implemented in the current version. Instead, most of the effect can be achieved by having the user set up EnergyPLAN to balance the CHP plants based on heat demands, as this would provide as much excess electricity as possible from the combined heat and power plants.

Thus, the basic principles for the MultiNODE tool operating within the technical framework of EnergyPLAN is to identify the available excess electricity in the given systems. This can be exported to another system if that system has a lack of capacity or is producing electricity in a power plant. This should balance out so that the amount exported should only equal the power plant production in a given hour. Furthermore, the systems should not be able to import more than what is available in terms of excess electricity. This principle should be applied to every hour.

The balance between two systems is simple to calculate since it basically requires an hourly simulation of both systems and an hourly check to see if the systems produce excess electricity and if they have power plant production in other hours. These two situations are balanced out with a transmission cable, so export from the first system is utilized instead of a power plant in the second system, and vice versa. This is illustrated in Figure 4.1. The approach does, however, become more complicated if more than two systems are connected. The next part will discuss approaches to linking several systems. These will be dependent on determining a merit order and defining the network in which the systems are connected.

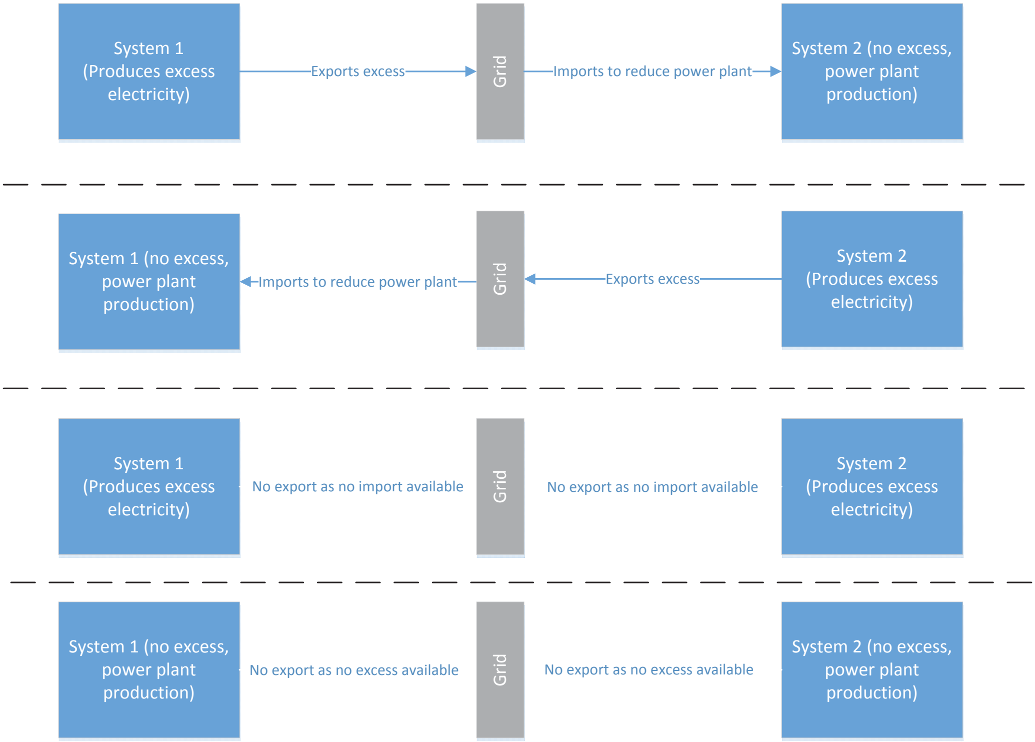


Figure 4.1 Principle operation of the exchange of electricity over a grid from a technical perspective, with the aim of reducing production in power plants.

DETERMINING AND MODELLING THE NETWORK

When modelling the interconnection between several energy systems, the electrical network should be laid out. Figure 4.2 illustrates the European high voltage transmission grid from 2004 [4]. From this illustration, it can be seen that interconnection between some countries only happens in one spot, such as between Norway and Denmark, while in other places, the grids spanning country borders are more intertwined, as seen around Italy and Austria, for instance. However, when looking at the transmission grids within countries, it is seen that the grids are generally either more dispersed or consist of a central line into which the smaller grids can tap.

Based on this observation, two types of network models are considered for the tool: the mesh network and the star network. These concepts are illustrated in Figure 4.3. In the star network, the transmission grid is modelled as a central node with which all the connected energy systems exchange electricity and which is only limited by the capacities of the interconnectors. In the mesh network, the transmission grid is the edges between every system. This means that between every transmission line, the specific energy system is modelled. The mesh network is the approach used in several studies, such as [5–8] and [9], and this approach is generally applied more often, such as when identifying the optimal electricity exchange in a market context grid [10,11] or in the analysis of a European grid [5,7,8]. These analyses do, however, very often focus only on the electricity system without regarding the rest of the energy system.

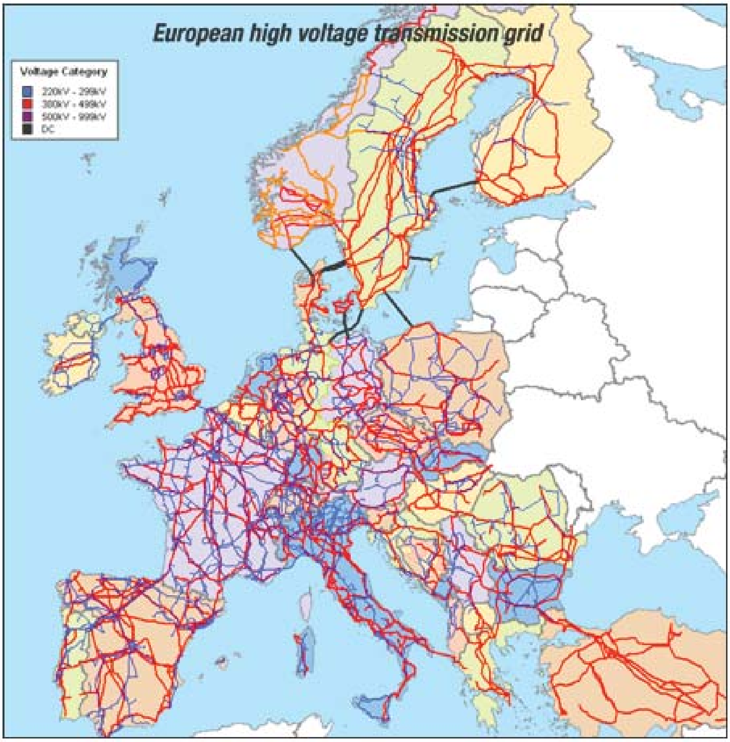
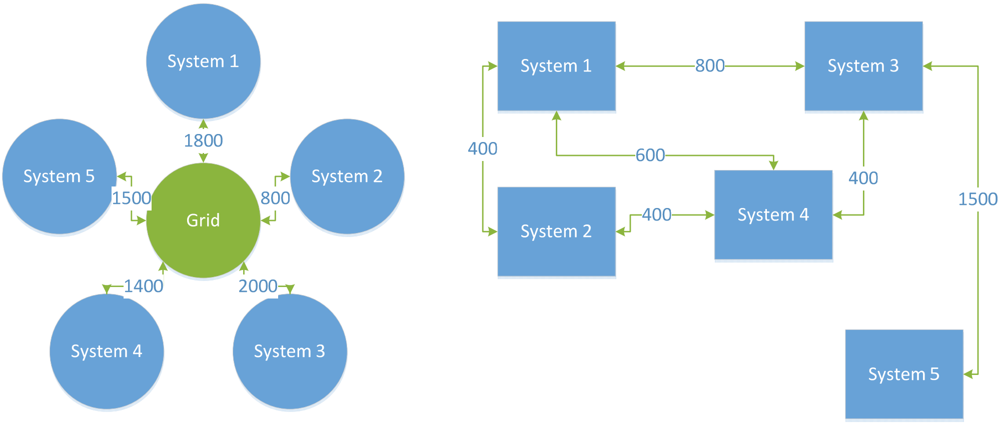


Figure 4.2 The European high voltage transmission grid in 2004. [4]



Star network

Mesh network

Figure 4.3 Illustrations of the basic concepts of a star network approach and a mesh network approach

The mesh network provides an advantage in terms of modelling each system with the specific capacity between the separate systems, enabling it to capture situations of bottlenecks between systems, such as when taking the system illustrated in the mesh network in Figure 4.3. In the situation of an excess production of 1800 MW in the system, and with the only demand for import being in System 5, the mesh network illustrates that only 1200 MW can be sent to System 5 even though the capacity in the transmission cable between System 3 and System 5 is 1500 MW. The reason for this is the bottleneck of the low transmission capacity between System 1 and System 3. The star network does not have this capability since it transfers between systems through a central grid. If comparing the same scenario of System 1 and System 5, the star network does allow for a transmission of 1500 MW. It is important to note that this bottleneck issue primarily becomes a potential problem in cases with weak grids and large geographic areas with several weak links. Furthermore, this can potentially be overcome to some extent within the star model if the problem exists in the end of the grid. In that case, the central grid can be modelled first, after which the simulation is run between the systems connecting the appendix system.

The benefit of the star network is its simplicity in terms of connection points, meaning that each system has one connection to the grid. This makes it simpler to create a balance for each system and to establish balances between the systems utilising one single common grid. This becomes more complicated in the mesh network, since it includes several connections between countries and no common hub for balancing can be identified. The mesh network thus requires that the whole grid and all systems be balanced at any given time, while in the star network it is sufficient to simply measure the balance in the central grid. With the star network, it is possible, based on a merit order, to simply determine in each hour how much electricity a system can deliver to the grid and how much electricity it has to take out of the grid. Based on the merit order, the systems therefore export electricity to the grid and import electricity from the grid one by one, with just the central grid to balance. Due to the increased connection and the fact that no central grid exists, it is harder to identify the merit order in the mesh network. The systems have to be ranked between them through direct links, but there is also the possibility of transferring from one system to another indirectly through a third system. In that case, the merit order has to take into account the fact that it might change according to analysis of all the potential ways the current can flow through the network.

This thesis primarily focuses on the analysis of cities and the surrounding areas; in this case, a rather reinforced grid is assumed. This enables the option of assuming a simpler model for the network. The MultiNODE tool is therefore based on the star network assumption. It is also identified that, in the necessary cases, it is possible to do a workaround of the bottleneck issue highlighted earlier. Furthermore, the author believes that this simplification is in line with the overall principles of EnergyPLAN, which aggregates parts of the energy system to achieve simpler and faster calculations without losing the main perspective of the subject analysed. The star network should be seen as a simplification of the grid, connecting different energy systems and enabling the user to quickly calculate the benefits of interconnection.

DETERMINING MERIT ORDER

When connecting more than two energy systems, it becomes necessary to determine in what order the systems should exchange electricity. This means which system should provide the excess electricity in situations with plentiful excess electricity and, in scenarios with scarce availability of excess electricity, decide which system should receive the excess electricity and in what order.

The MultiNODE tool operates under the assumption that if a system can deliver excess electricity, it delivers as much as possible. Likewise, if a system has been identified as an importer of electricity, it imports as much electricity as possible, based on the lack of capacity or the amount of electricity produced on power plants.

The thesis considers three ways to determine the merit order of energy systems in terms of electricity exchange.

The first principle is that the user simply defines the order. The benefit of this approach is that the user can ensure the specific operation of the grid and give priorities to certain systems. Thus, it enables a certain level of flexibility since the user can determine the order based on several different principles while also making it easy to test the performance of the grid with other merit orders. The disadvantage is that it becomes quite difficult to change the merit order during the run year due to the amount of data points. The user-determined merit order would have to be fixed for, most likely, the whole run period. This makes it difficult to take into account temporal changes that might make it beneficial to change the merit order several times over a year.

The second principle is based on parts of the overall concept of the technological simulation strategy in EnergyPLAN in order to reduce the amount of electricity produced in power plants. To do this, the principle would be to export to the systems with the worst power plants based first on their efficiencies. Thus, the systems replace the units with the highest amount of fuel consumption first and then so on. The advantage is the clear linkage to the overall strategy of EnergyPLAN. The disadvantage is that it is a fairly limited way to determine merit order and will also be locked in for the whole operation period since EnergyPLAN does not change power plant efficiencies over the year.

The third principle would enable the MultiNODE tool to change the merit order over the year. The principle would rely on the system cost for producing electricity and order the systems so that the most expensive systems would import first and the cheapest systems would export first [1]. This would base itself on the principles of short-term marginal costs. The advantage is that the tool can change the merit order over the year and that it can take into account situations where import or export might make sense based on a reason other than fuel efficiency. The disadvantage is that this principle is not aligned with the technical operation of the EnergyPLAN system. Thus, issues can arise from applying different methodologies to the operation of the energy system: a technical perspective in the EnergyPLAN part, and an economical perspective in the MultiNODE part. Second, the models will also require a detailed cost database to provide the necessary economic details.

It is the intent to implement all three operation strategies for the MultiNODE tool, but for the scope of the thesis, only one has been selected. In this case, the first principle has been chosen. The MultiNODE tool therefore operates based on a user-determined merit order. The reason is that it provides the most flexibility and fits within the framework of technical operation of the smart city energy systems analysed in EnergyPLAN. Second, the second principle can be implemented in the first principle; the user simply has to determine merit order based on power plant efficiencies. Furthermore, this approach enables the user to determine merit order on several principles, in which the network layout discussed previously can be taken into account. Finally, several orders can be tested to determine the sensitivity the transmission system has on the merit order.

MULTINODE

The MultiNODE tool is designed based on these key principles of the operation of interconnection between a smart city energy system and the surrounding systems, the layout of the network, and the merit order of these systems. The operation of the tool is recorded in the documentation [12] and can be found in Appendix B.

The key principle of MultiNODE is that through a star network and with a user-defined merit order, the exchange of electricity between systems can be identified. The basic principles of the exchange rely on creating an hourly balance between the excess electricity produced in some systems and the need for import of electricity in other systems. The excess electricity comes from combined heat and power pants, waste incineration, and variable renewable energy. The need for import is determined as situations with a lack of capacity and the production of electricity in power plants.

Currently, the tool will only exchange electricity if both of these situations occur. Thus, it will not ramp up a power plant in one system to fill under-production of electricity in another system. Hence, the tool examines how excess electricity can be used and does not guarantee the balancing of production and demand in all hours in all systems. In the long run, this feature can be implemented in the system, but it is not key to investigating how the smart city energy system interacts with the surrounding systems. The user just has to be aware that remaining excess might result in the curtailment of wind power and that the lack of capacity might result in an increase in power plant production. Both of these are related to the overall system operation and not to the interplay between the smart city energy system and the surrounding energy system.

Another interesting development that has not yet been implemented is the allowing of storage to influence the determination of import and export demands. Thus, in hours with remaining capacity in an electricity storage (and potentially a thermal or gas storage), the system might be able to import excess electricity under the assumption that it is able to utilize the electricity at some point. Currently, this has not been implemented because EnergyPLAN simulates storage based on the principle of being able to utilize the stored energy within a defined time frame. Since MultiNODE works without interfering with the EnergyPLAN operation, the inclusion of storage might be difficult without interfering with the current EnergyPLAN operation of storage. The author believes that for storage to be included in the assessment of import and export in the MultiNODE tool, it has to be done in a way that corresponds with the principles of EnergyPLAN. Such an approach has not yet been achieved and is therefore left out of the current version of the MultiNODE tool. The goal is to include it in a later version.

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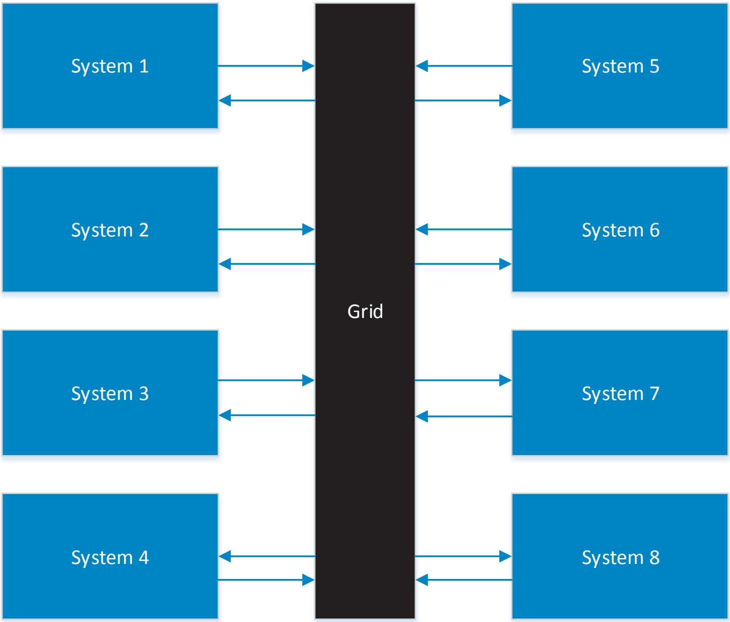
APPENDIX B

MultiNODE Documentation
Version 1

Energy PLAN
Advanced energy
system analysis
computer model

BREAKING NEW GROUND
AALBORG UNIVERSITY

MultiNode v1 for EnergyPLAN
Documentation



Jakob Zinck Thellufsen

September 2016

www.EnergyPLAN.eu

Preface

The MultiNode add-on tool for EnergyPLAN is developed as a central part of the PhD project “Energy System Analysis of Multiple Systems”. The PhD is part of the Centre for IT–Intelligent Energy System in Cities (CITIES) Research Project funded by Innovation Fund Denmark. Besides, the tools draw on research and development related to EnergyPLAN, the 4DH Research Center also funded by Innovation Fund Denmark, and the various Heat Roadmap Europe Studies.

Jakob Zinck Thellufsen has done the main development of the tool, but with assistant and feedback from Henrik Lund, Prof. AAU, and Anders N. Andersen and Henning Mæng from EMD International.

Contents

The MultiNode Concept in EnergyPLAN

The goal of the MultiNode Add-on Tool to EnergyPLAN is to be able to run and link several EnergyPLAN analyses. The concept currently only looks at the electricity sector and defines the link through cables. MultiNode has the possibility of linking between 2 and 28 different systems. These energy systems can be of all kind of sizes, meaning it is suitable to run both on local-national analyses and when linking multiple national energy systems, e.g. the European Union.

MultiNode is part of the current development strategy for EnergyPLAN. This means that instead of making radical changes to EnergyPLAN, the development goes towards creating add-on tools that utilizes EnergyPLAN as a base framework. Therefore, MultiNode does not make changes to the way EnergyPLAN runs. This is reflected in the overall concept of the MultiNode add on tool, as exchange possibilities have to be identified in a certain way.

Figure 1 shows the overall concept of the MultiNode add on tool. The figure illustrates how the tool identifies exchange options. First, MultiNode runs all selected energy systems without any interconnection. From this analysis, MultiNode identifies two sets of information for each system: 1) the hourly amount of exportable electricity and 2) the potential for electricity import every hour. MultiNode identifies a potential import demand as hours with:

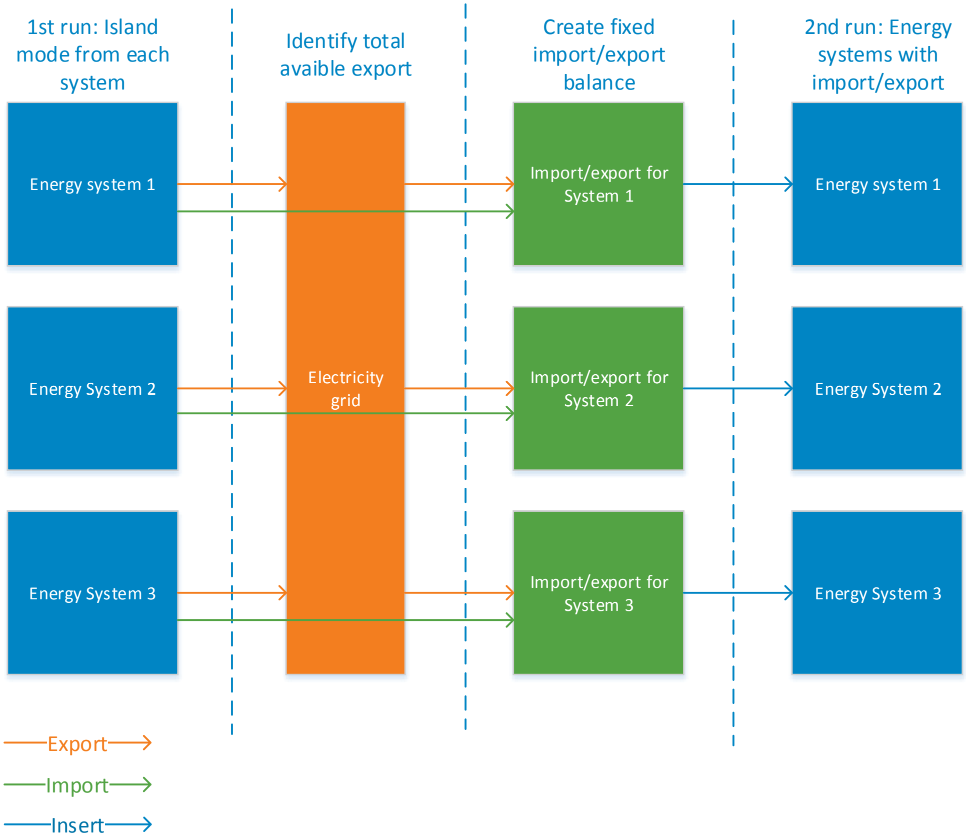
- Lack of sufficient capacity
- Hours with power plant production

From the information regarding the hourly available exportable electricity and hourly potential for importing electricity, MultiNode now tries to link the exportable electricity with the demand for import. In hours with import demand and available export, each system will try to fulfill its demand for import as much as possible. Each individual energy system will get access to the electricity available for import on the grid based on a merit order.

After utilizing as much of the exportable electricity as possible in each of the energy systems, an import/export balance is created for each energy system and the yearly net export is identified. Together, the balance and the net export identifies each system’s interaction with the grid.

Note that the tool uses a total grid capacity for transmission since it views the electricity grid as one unison between all systems that has a defined grid capacity over zero.

Finally, the MultiNode add-on tool runs each of the selected energy systems again now with the information regarding import and export. Based on these simulation results the MultiNode has the option of summarizing all systems together.



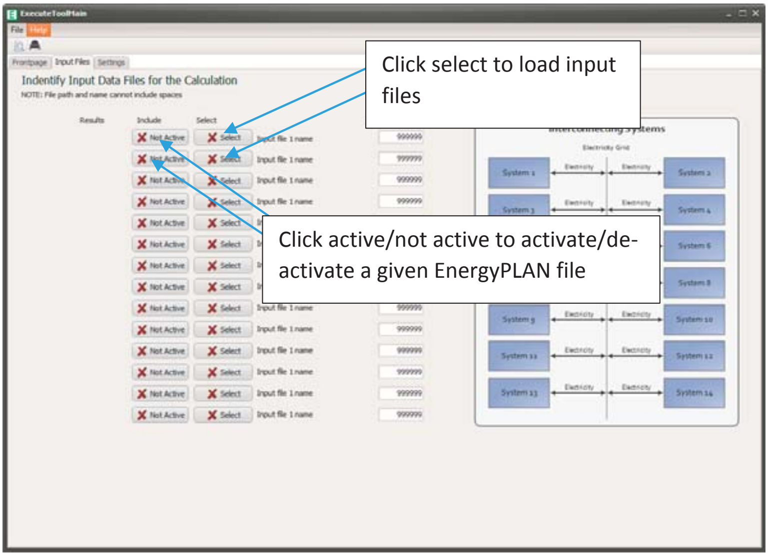
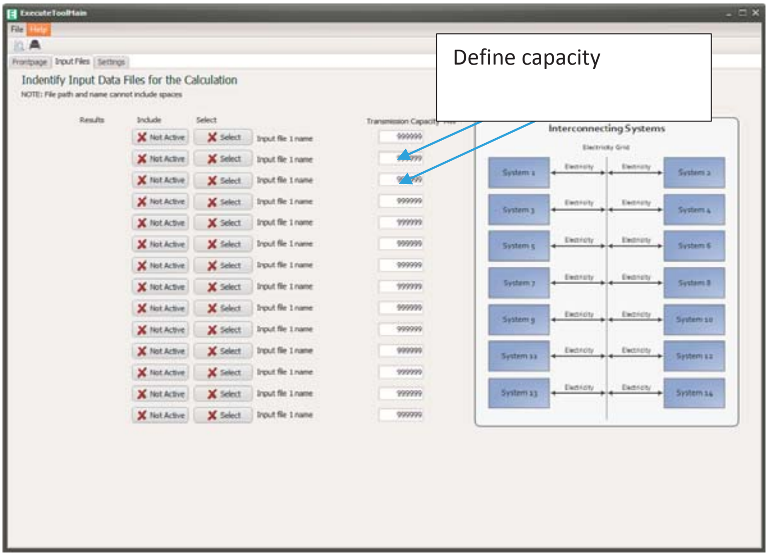
Using the MultiNode tool

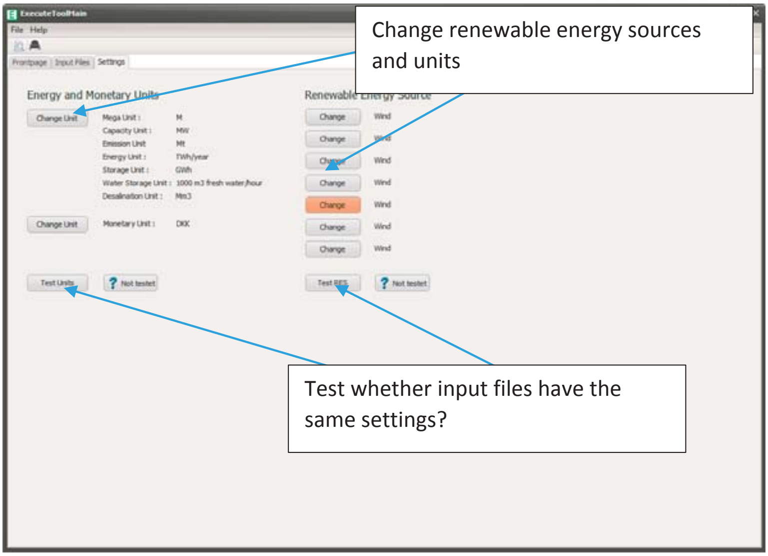
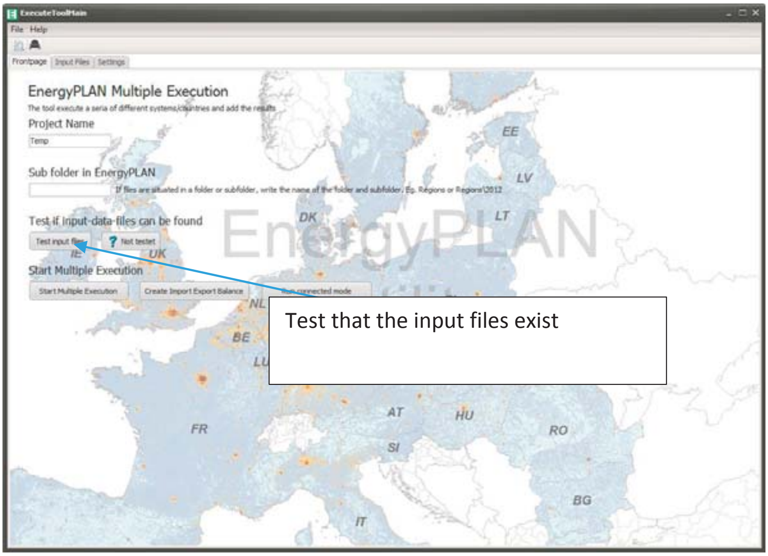
MultiNode is structured in four tabs. The “front page” where the user defines the model and runs the different parts. The “input files” where the user defines the different energy plan systems. “Transmission” where the user defines transmission capacities and “settings” where the user defines energy units and RES sources.

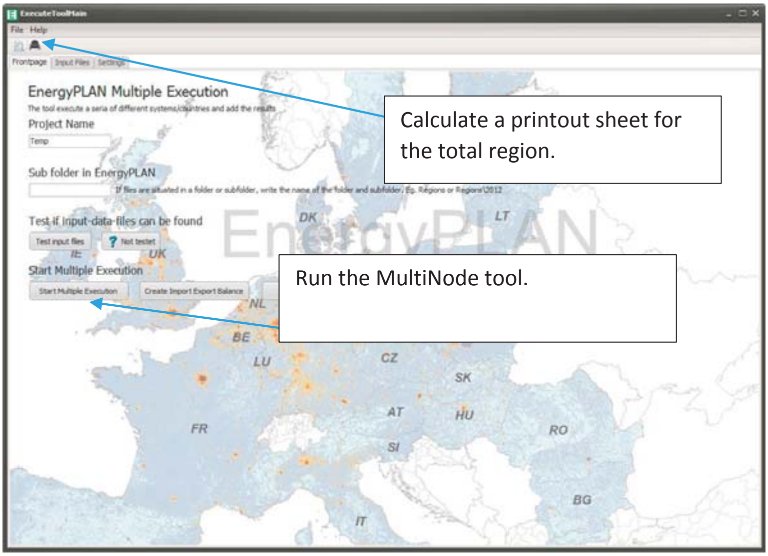
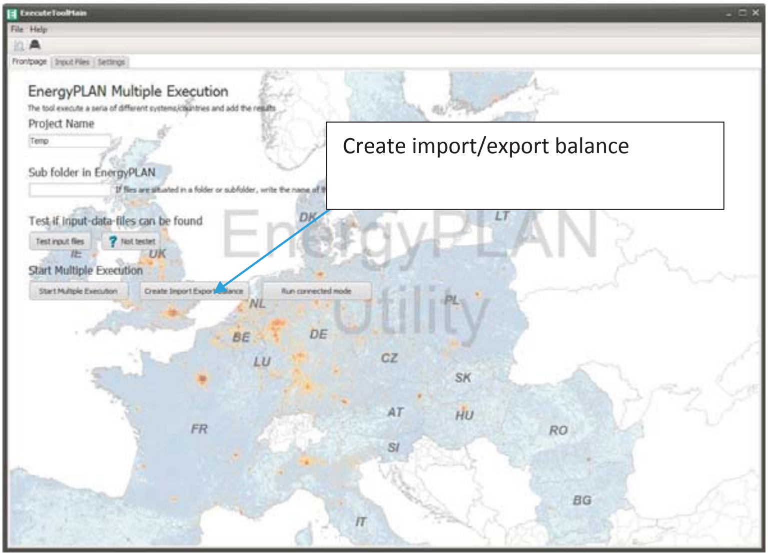
When opening MultiNode the first screen is the front page. To run the model either use the automatic generation of country names (currently only works for EU28, the Nordic Countries, and the Baltic Countries). Be aware that to use this function you have to follow a certain naming standard. Else just leave these functions be, as they are not necessary.

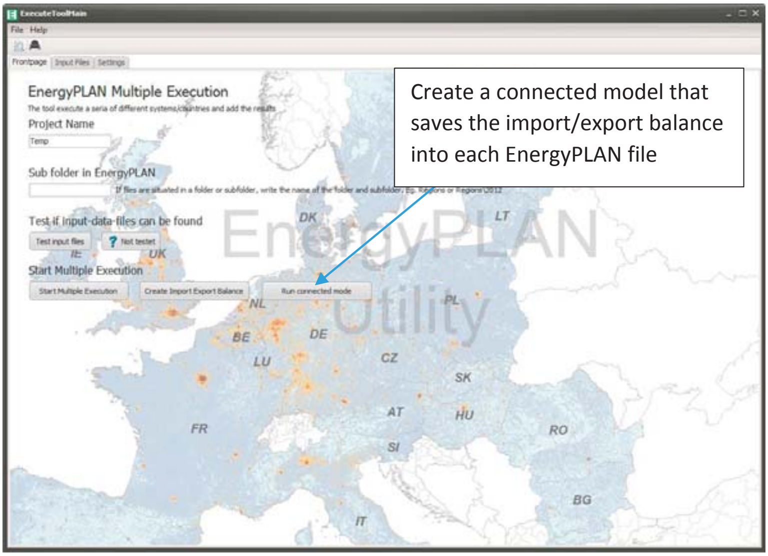
The button for selecting operation mode defines the methodology for merit order in the system in terms of utilizing excess electricity. The standard procedure is to define the merit order based on the order of energy plan files in the input files tab. Otherwise, the tool can use the system priced calculated in each system to define merit order. Note that this requires that you have defined costs in each EnergyPLAN system. Be aware that the MultiNode tool does not check your cost assumptions and unit settings.

The following takes you through the tabs, to run your model successfully.

Go to input files and select the number of EnergyPLAN systems you want to connect. Click select to load the files. Click the "active" button to deactivate a file if you do not want to include it in a given analysis.	 Click select to load input files Click active/not active to activate/de-activate a given EnergyPLAN file
Define transmission capacity from each system going into the grid.	 Define capacity

Go to settings to define the size of the system, the currency, and renewable energy technologies. For each setting there is a button that confirms whether the input files are set correct. These settings are not needed to run the model, but will help the user generate the right print out heet.	Change renewable energy sources and units Test whether input files have the same settings? Energy and Monetary Units Mega Unit : M Capacity Unit : MW Emission Unit Mt Energy Unit : TWh/year Storage Unit : GWh Water Storage Unit : 1000 m3 fresh water/hour Desalination Unit : Mm3 Monetary Unit : DKK Renewable Energy Source Wind Wind Wind Wind Wind Wind Wind
To run the tool the first step is to test that all the input files exist on the front page.	Test that the input files exist EnergyPLAN Multiple Execution The tool execute a seria of different systems/countries and add the results Project Name Temp Sub folder in EnergyPLAN If files are situated in a folder or subfolder, write the name of the folder and subfolder. Eg. Regions or Regions\2012 Test if input-data-files can be found Start Multiple Execution

The next step is to press the start Multiple Execution. This will run each EnergyPLAN model as an island mode, and store the results. Hereafter, you can create a printout to see how the system operates without interconnection between them.	 Calculate a printout sheet for the total region. Run the MultiNode tool.
After that, pressing the create import/export balance will analyse each system, and define how much should be imported and exported to each system.	 Create import/export balance

Finally, the “Run connected models” button will save all your systems with the import/export balance. You can load these into the MultiNode tool under input files and run the tool again, to see how the overall system performs with connection.	 Create a connected model that saves the import/export balance into each EnergyPLAN file

EnergyPLAN Multiple Execution

The tool execute a seria of different systems/countries and add the results

Project Name: Temp

Sub folder in EnergyPLAN

If files are situated in a folder or subfolder, write the name of the folder and subfolder, Eg. Regions or Regions\2012

Test if input-data-files can be found

Start Multiple Execution

Calculating connections using MultiNode

The MultiNode tool operates based on four different buttons. These operations are described in detail in the following subsections.

Start Multiple Calculation

When pressing start multiple calculation MultiNode runs each defined system as an island mode operation. It stores all information from the EnergyPLAN operation in the memory in a number of files. One file that summarizes all the selected systems and separate files for each individual system. The stored data also includes temporarily information necessary to calculate average efficiencies when running the print out button.

Create Import/Export Balance

Abbreviations:

P = Potential

PP = Power plant

Prod = production of electricity

Imp = Import

Ini = initial

N = Number of systems

1..14 = The specific system

Based on the stored output data from each individual system the tool creates an import/export balance, following the basic structure illustrated in Figure 1.

The first step of creating the import/export balance is to calculate the total amount of export available on the grid each hour. This is done by identifying the amount of exportable electricity each system delivers and add them all together for each hour:

$$export_{total} = export_1 + export_2 + export_3 \dots + export_{14}$$

Each of the individual exports can maximum equal the defined capacity on the interconnector.

After this, the amount of potential imports are identified for each system by adding together the important demand the current operation of the power plant. This is done for every hour in the year.

$$\begin{aligned} P_{imp1} &= import_{demand1} + PP_{prod1} \\ P_{imp2} &= import_{demand2} + PP_{prod2} \\ &\vdots \end{aligned}$$

$$P_{imp14} = import_{demand14} + PP_{prod14}$$

Each individual import demand can only be as high as the capacity on each transmission line.

For each system the program creates an initial hour balance that defines the export as positive and the potential import as negative for each system:

$$\begin{aligned}
&Balance_{ini1} = export_1 - P_{imp1}\\
&Balance_{ini2} = export_2 - P_{imp2}\\
&\vdots\\
&Balance_{ini14} = export_{14} - P_{imp14}
\end{aligned}$$

However, the system can only import if there is available electricity in the grid. This means that based on the merit order in which the systems are organized in the program they will each take turn in taking electricity out of the grid as import. Therefore it will check whether there is electricity in the grid for each hour with a potential import demand. If that is the case an import demand will be defined:

$$\boldsymbol{if}\left(P_{imp1} > export\ total\right)\ \boldsymbol{then}\ Import_1 = exportable_{total}\ \boldsymbol{else}\ Import_1 = P_{imp1}$$

$$\begin{aligned}
&\boldsymbol{if}\left(P_{imp2} > export\ total - import_1\right)\ \boldsymbol{then}\ Import_2 = exportable_{total} - import_1\ \boldsymbol{else}\ Import_2\\
&\qquad = P_{imp2}\\
&\vdots\\
&\boldsymbol{if}\left(P_{imp14} > export\ total - import_1 \ldots - import_{13}\right)\ \boldsymbol{then}\ Import_{14}\\
&\qquad = exportable_{total} - import_1 \ldots - import_{13}\ \boldsymbol{else}\ Import_{14} = P_{imp14}
\end{aligned}$$

These sections secure that only potential import that can be covered by the grid is included.

Therefore, the balance can now be created. This is done by taking the initial balance and replace the export, with the sum of imports needed in the other system, while the potential import is replaced with the actual import found in the previous section. This is done for every hour:

$$\boldsymbol{if}(Balance_{ini1} > 0)\ \boldsymbol{then}\ Balance_1 = import_2 + import_3 \ldots + import_{14}\ \boldsymbol{else}\ Balance_1 = -import_1$$

$$\begin{aligned}
&\boldsymbol{if}(Balance_{ini2} > 0)\ \boldsymbol{then}\ Balance_2 = import_1 \ldots + import_3 \ldots + import_{14}\ \boldsymbol{else}\ Balance_2\\
&\qquad = -import_2\\
&\vdots\\
&\boldsymbol{if}(Balance_{ini14} > 0)\ \boldsymbol{then}\ Balance_{14} = import_1 + import_3 \ldots + import_{13}\ \boldsymbol{else}\ Balance_{14}\\
&\qquad = -import_{14}
\end{aligned}$$

The result is a balance file for each system, where the export is positive and the import is negative.

The consequence of this method is that the export part is not in balance with the import part. Therefore, the final step is to remove the excess accounted electricity by diving the active export in each system in each hour with the number of systems that exports electricity. Thus eliminating excess exports. The following concept is used for each balance:

$$\begin{aligned}
&\boldsymbol{if}\,(Balance_1 < 0)\ \boldsymbol{then}\ \ Balance_1 = Balance_1\\
&\boldsymbol{else\ if}\ Balance_1 + Balance_2 \ldots + Balance_{14} = 0\\
&\boldsymbol{then}\ Balance_1 = Balance_1\ \boldsymbol{else}\\
&Balance_1 = \frac{Balance_1}{N_{active}}
\end{aligned}$$

The balances can be seen by pressing the view screen button and can be found in the EnergyPLAN distribution files folder.

Run Connected Mode

The run connected mode button uses the information from the created import/export balance and the loaded input files to create new EnergyPLAN scenario files. These are the original files but uses the fixed import/export input in EnergyPLAN to include the import/export balance created.

The import/export balance is included as a distribution file and a sum to indicate the total annual demand. A negative demand indicates an annual import of electricity while a positive demand indicate an annual export of electricity.

Printout

Abbreviations:

P = Potential

Cap = Capacity

Eff = Efficiency

PP = Power plant

El = production of electricity

Fuel = Fuel consumption

1..14 = The specific system

The final button in the MultiNode is the print out. This is used to summarize all the EnergyPLAN outputs into one single combined output. This is useful, when using the MultiNode tool to simulate systems split into several systems. This could be a country split into counties or regions, or parts of Europe modelled as each individual country. Then the printout button can make final output sheet for the country or for Europe.

Compared to the printout in EnergyPLAN, the MultiNode print out is simplified. This means it only includes information that can be either added together or defined through weighted averages.

This means that all costs, capacities and demands are added together based on. For instance for electricity demand and power plant capacity:

$$Elec\ demand_{total} = Elec\ demand_1 + Elec\ demand_2 \ldots + Elec\ demand_{14}$$

$$PPcap_{total} = PPcap_1 + PPcap_2 \ldots + PPcap_{14}$$

The average efficiencies for all fuel consuming fuel plants are calculated based on the total energy output divided with the total fuel consumption. For instance for power plants:

$$PP_{eff} = \frac{El_{PP}}{Fuel_{pp}}$$

For efficiencies for non fuel using plants, the efficiency is calculated based on calculating capacities before and after efficiency loss for each system. These are both summarized and based on this an average capacity is found. For instance for hydro power:

$$Hydro_{eff} = \frac{Cap_{after\ loss}}{Cap_{before\ loss}}$$

SUMMARY

The thesis defines the concept of smart city energy systems. The thesis emphasises the need to investigate the smart city energy system and two contextual aspects. The system integration context and the geographical context. The system integration context emphasises that increased interrelation between the different energy sectors increases the efficiency of the system. However, it also impacts the implementation of single technologies in the smart city energy system. The thesis discusses methods and tools to assess the system integration context.

Smart cities, and other concepts for urban development, often strives towards some sort of sustainability target. However, to consider a city and the smart city energy system sustainable, they cannot limit other energy systems from becoming sustainable. It is therefore necessary to investigate the geographical context. This thesis develops tools and methodologies that enables the user to investigate the geographical context of smart city energy systems. The thesis applies the concept of smart city energy systems, the system integration context and the geographical context on several cases, to test the tools and methods and to analyse the consequences of the different contextual aspects.

ISSN (online): 2446-1628
ISBN (online): 978-87-7112-941-0

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