The future of energy systems in cities

A smart system approach vs a non integrated renewable system approach to designing a future energy system

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Synopsis:

In recent years, the ever rising awareness about climate change among nations around the world has motivated countries, regions and local authorities to start planning a development of their future energy systems, many of them aiming for a 100% renewable system. There are various ways to develop a 100% renewable energy system and choosing the optimal one depends on a series of factors.

This thesis tackles that problem by comparing two possible ways of developing a 100% renewable energy system, using Zagreb, the capital of Croatia, as a case. The first one is a so called traditional non-integrated renewable energy system, where each energy sector is developed independently, while the second one is a smart energy system concept, where different sectors are linked together in order to achieve synergies and increase efficiency of the system.

Both scenarios are modelled in EnergyPLAN, an energy system analysis tool that enables a user to model energy systems with high shares of fluctuating renewable energy sources.

The scenarios are compared based on primary energy consumption, CO_2 emissions, total annual system costs and the level of biomass consumption. While both future systems have zero emissions, utilize less primary energy and are cheaper than the reference scenario, the biomass consumption in the traditional renewable energy system is above the sustainable level, which makes it technically unfeasible. The smart energy system utilizes a sustainable amount of biomass at total annual system costs only 1% higher than the traditional renewable energy system. This means that a smart energy system is a beneficial option for Zagreb in terms of technical feasibility, while the total costs are essentially at the same level.

Preface

This thesis has been written as a part of the 4th semester master's degree programme in Sustainable Energy Planning and Management at Aalborg University in Aalborg, Denmark. The thesis has been developed in the period from June 1, 2017 to September 1, 2017, with the initial considerations, ideas and research being carried out somewhat earlier.

Reading instructions

Chapters are numbered chronologically, while sections and subsections are numbered according to the chapter. For example, Section 4.1 is the first section in Chapter 4, while Subsection 4.1.1 is the first subsection in Section 4.1 and so forth. Figures and tables are also presented chronologically, with the first figure being named Figure 1 and the rest following the same pattern. The IEEE referencing system is used in the thesis, showing references chronologically by their appearance in the text, starting with the first reference shown as [1]. The details on all references are given in Chapter 9 at the end of the thesis. All monetary values are presented in Euros (EUR) as it stood at January 1, 2017 with the following conversion rates: 1 EUR = 1.0521 USD = 7.5578 HRK = 7.4345 DKK.

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Finally, to the closest ones - my mom, dad, sister, Nikola, Emina and so many of my friends in Croatia, Denmark or wherever else in the world. Thank you for giving me your constant support and understanding throughout this whole experience.

I wish you a pleasant reading!

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Nomenclature

BAU	Business-as-Usual
CAES	Compressed Air Energy Storage
CEEP	Critical Excess Electricity Production
CEI	Centre for Monitoring Business Activities in the Energy Sector and Investments
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
DH	District Heating
DHW	Domestic Hot Water
EIHP	Energy Institute Hrvoje Požar
ENTSO-e	European Network of Transmission System Operators for Electricity
EPEEF	Environmental Protection and Energy Efficiency Fund
EU	European Union
EV	Electric Vehicle
GDP	Gross Domestic Product
HERA	Croatian Energy Regulatory Agency
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Electricity
O&M	Operation and Maintenance
PES	Primary Energy Source
PV	Photovoltaic
REGEA	North West Croatia Regional Energy Agency
RES	Renewable Energy Source
SEE	South East Europe
SES	Sustainable Energy System
SECAP	Sustainable Energy and Climate Action Plan
TRES	Traditional Renewable Energy System
TSO	Transmission System Operator
V2G	Vehicle-to-Grid
VAT	Value Added Tax
WHO	World Health Organization

1 Introduction

The energy sector is facing major changes today and energy transition is one of the key points on the political agenda of countries all over the world. The first-ever global climate deal was adopted in December 2015 in Paris, committing 195 countries worldwide to fight climate change by keeping the increase in global average temperature bellow 2°C above pre-industrial levels [1]. To date, 144 parties have ratified the agreement [2], while the 2016 Climate Change Conference in Marrakech decided that detailed implementation steps for turning the Paris agreement into practice should be set out by 2018 [3].

Ever growing investments in renewable energy sources (RES) is another indicator that energy transition is slowly coming into force. In 2015, the newly installed capacity of renewables (excluding large hydro) represented the majority of all technologies installed, with a share of 53.6% of the global installed capacity. Moreover, a new record for global investments in renewables was set in 2015, with USD 285.9 billion, 5% higher than the previous record set in 2011 [4]. The trend continued in 2016, when renewables represented 55% of the total installed generating capacity, while a drop in per unit capital costs caused a fall in overall investments in renewables in comparison to the previous year [5]. These trends are, however, only the initial indicator of a much larger process of energy transition, as fossil fuels still represent around 80% of total primary energy supply (PES) [6] and only about 23% of the global electricity is generated from RES today [7].

One of the major players in the global energy transition will be cities. According to the United Nations, 54% of the world's population lives in cities today and that share is expected to continuously grow, resulting in a projected 66% of the total population to be urban in 2050. In Europe alone, 73% of all the population is urban already today and it is expected that over 80% will be urban by 2050 [8]. Furthermore, urban areas account for 65% of the global energy demand and 70% of energy-related CO_2 emissions. As shown in Figure 1, based on the estimates made by the International Renewable Energy Agency (IRENA), the share of urban energy use has grown considerably faster than the urbanisation rate in the last 25 years, meaning that cities are facing increasing energy consumption per capita, mainly being the result of income growth and a rise in technology use [9].

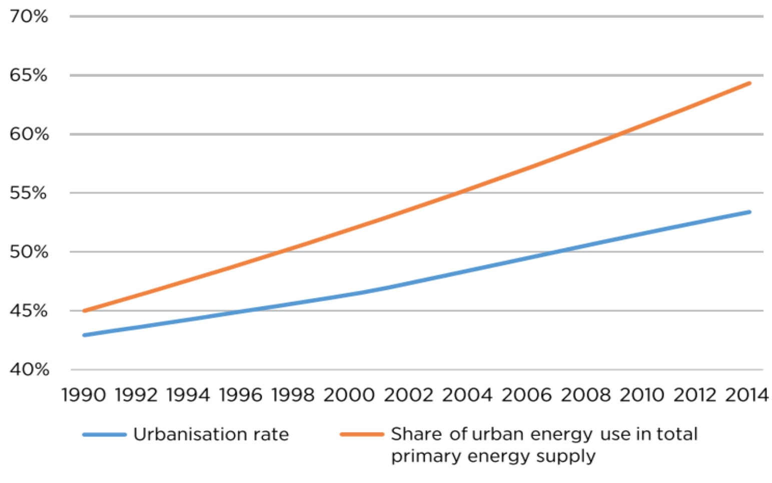

Figure 1. Global urbanisation rate and share of urban energy use in total PES [9] *(the term urbanization refers to increase in the proportion of population living in urban areas)*

Moreover, according to the World Health Organization (WHO), more than 80% of the population living in urban areas are exposed to air quality levels that are below WHO recommendations and the main reasons for such a situation are urban transportation, energy production and waste management [10].

All this is to demonstrate the importance and significance of cities in the global energy trends, reshaping the energy industry and providing a higher quality of life to their citizens. Today's energy systems in cities, but also beyond, are fairly simple to describe – they are usually based on a few large power plants fuelled by either coal, natural gas or nuclear, that sometimes use its waste heat from the power production process to heat dwellings in its surrounding, thus being a combined heat and power (CHP) plant. However, in many cities, the dominant share of heat is produced on-site, by means of individual boilers or wood furnaces. The transport sector is almost exclusively based on oil, with the exception of electrical public transport in some places. Industries also mostly consume fossil fuels and the excess heat from various industrial processes is rarely utilized for heating, but rather wasted in the air, rivers and seas. Lastly, interactions between different energy sectors in traditional energy systems are on a very low level, thus leaving unused potentials to achieve synergies and more efficient overall performance of the system [11].

One city with such a traditional energy system is Zagreb, the capital of Croatia and a home to nearly 20% of the total population of the country – roughly 800,000 citizens. In 2008, the city joined the Covenant of Mayors for Climate & Energy, an initiative that brings together towns and cities in implementing the European Union (EU) climate and energy goals, by providing a framework to develop a Sustainable Energy and Climate Action Plan (SECAP). The main vision of the initiative is to accelerate the decarbonisation of energy systems by providing secure, sustainable and affordable energy [12]. In their initial form, SECAPs focused only on achieving the EU 2020 goals: reducing CO_2 emissions and energy consumption by at least 20% and increasing the share of RES to more than 20% by 2020 [13]. The city of Zagreb published its SECAP in 2010 and the document includes an overview of energy consumption and CO_2 emissions by sectors, as well as a brief description of policy measures that have to be implemented in order to be on track of achieving the 2020 goals [14]. Future efforts, however, need to include planning for a longer term, as well as more ambitious and thoroughly elaborated strategies, in order to meet the 2050 goals and develop a sustainable and affordable future energy system.

Beyond its obligations to play an important part in the Croatian energy transition and commitments it made by joining the Covenant of Mayors initiative, Zagreb and its citizens are facing a series of problems related to the energy system – an old energy production and network infrastructure, combined with an inefficient operation is causing high losses and thus high energy bills for citizens; an undeveloped system of measuring heat consumption for district heating (DH) consumers is a reason for numerous political debates and misunderstandings about functionality and benefits of the system among citizens, while a lack of efficient waste management results in an unsustainable waste disposal that apart from being environmentally hazardous, is causing various inconveniencies for citizens. Moreover, the energy system is entirely based on fossil fuels – including two old CHP plants that burn oil and natural gas and operate completely independently from each other, although under the same ownership, as well as the traditional transport sector based primarily on diesel and petrol. Apart from that, an insufficient amount of electricity is produced within the city boarders to meet its own demand, leaving Zagreb as a city with the largest share of dependence on electricity import among all cities in Croatia, annually importing 60-80% of its electricity demand (75% or 2.27 TWh in 2015). Its geographical position, however, leaves relatively limited options for implementing renewable technologies, while lack of awareness among citizens and decision makers about benefits of renewable energy and energy efficiency makes implementing any changes even harder. All of that is supported by lack of comprehensive studies and plans of how should Zagreb's energy system develop.

A clear conclusion from everything stated so far is that Zagreb needs to introduce a series of changes in its energy system, in different energy sectors and on different levels and scales, in order to become an active player in the global energy transition. IRENA identifies the three main priority areas for the energy transition in cities: renewable energy in buildings, sustainable options for transport and creating smart integrated urban energy systems [9].

This thesis deals with elaborating on these three areas further, by developing technical solutions for a future energy system in Zagreb and comparing different development pathways. Moreover, the thesis gives an overview of different socio-economic and institutional opportunities and barriers implementing these solutions brings, that need to be understood in order to design an implementation framework and address all the relevant stakeholders.

The following section gives an overview of the existing research and work in the field of energy transition, renewable energy in cities and smart energy systems – the main concepts to be applied in this thesis, therefore important to understand before giving a final formulation of the problem.

1.1 Concepts - state-of-the-art & literature review

The three main concepts are elaborated further in order to understand their fundamentals, but also develop more detailed understanding of their state-of-the art and the progress in the research. Moreover, the following subsections are used to better define the overall scope of the thesis and to pinpoint the main aspects the analysis will focus on.

1.1.1 Energy transition

The process of energy transition, apart from the technical aspect, requires an equally holistic approach in policy and institutional transition, in order to successfully implement technical solutions and achieve maximum benefits for a society. Some researchers expanded on that by investigating transformation polices and various obstacles in implementing new energy solutions and experiencing energy transition.

Lutz et al. [15] examined the driving factors in renewable energy implementation process on a regional level and found the three most important implications for successful governance of energy transition: comprehensive and well-structured approach that requires long term planning, but enables regions to deal with policy changes; a strong engagement in formal networks; and a strategy combining funding from different sources, including community initiatives and public funding. Using Germany's energy transition as a case, Kuzmenko et al. [16] examined the importance of governing demand side innovations for energy transition and concluded that including citizens and corporate actors in a transition process influences political debates and enables governments, that lead transition processes, to gain more support.

Furthermore, major renewable policy instruments in light of transition management framework were analysed in [17]. The study introduces the transition management theory and proposes that the regime of actors influencing the energy transition needs to be re-organized in a way to optimize the levelized cost of electricity (LCOE) which would in turn influence the cost-effectiveness of the policy instrument. Kelly-Richards et al. [18] identified four major concerns in governing the transition to renewable energy, with a special emphasis on small hydro power: confusion in renewable technology definitions in a policy making process; a lack of knowledge and acknowledgment of social, environmental and cumulative impact of renewables; contradictories in promoting small hydro power and climate change policy; and a lack of institutional analyses needed to facilitate renewable energy integration with existing environmental laws.

The structure of policy networks, as well as interests of different actors among those networks largely influence the outcome of an energy transition process, sometimes presenting a bigger challenge than the actual technical implementation [19]. Therefore, applying a comprehensive approach in analysing and designing policies is of a great importance for a successful energy transition.

1.1.2 Renewable energy in cities

Focusing more closely on the concept of integrating renewable energy in cities and developing sustainable urban solutions, a significant amount of work can be found. In addition to the aforementioned Covenant of Mayors and SECAPs that various towns and cities throughout Europe are developing, some cities have made somewhat more ambitious steps in analysing how different renewable technologies could influence their energy systems and which development strategies they could apply to achieve the future energy goals.

Traditional leaders in making the first steps towards renewable energy integration are Nordic countries and Germany. For example, Copenhagen, the first capital in the world to officially set a goal of being carbon neutral, developed its 100% renewable energy strategy, following the country's goals to be independent of fossil fuels by 2050 [20]. The strategy implemented the smart energy system approach and is based on six key technologies: heat savings in buildings, large-scale heat pumps, flexible fuel efficient power plants, low-temperature district heating, higher share of public transport and the electrification of the transport sector [21]. Furthermore, Østergaard et al. [22] created a scenario of the energy system of Aalborg, Denmark exclusively based on RES, at a cost at a comparable level with a fossil fuel-based business-as-usual (BAU) scenario. Similarly, a case of Frederikshavn Municipality in Northern Denmark showed that a renewable energy scenario, based on locally available resources, can lead to a reduction in primary energy consumption and consequently CO_2 emissions, even without implementing end-use savings. Some other interesting examples include the city of Malmö, Sweden, that is expected to be run on 100% renewable energy by 2030 [23] or the city of Frankfurt, Germany, that developed a carbon neutrality plan for 2050.

Some researchers investigated the role of specific technologies in future energy systems of different cities. The study in [24] focused on a role of fuel cell electric vehicles (EVs) in renewable energy-based smart city areas and found that wind and solar photovoltaics (PVs), together with hydrogen as an energy carrier, can provide a cost-efficient, 100% renewable energy system in a smart city. Furthermore, using the city of Osijek, Croatia as a case, Novosel et al. [25] concluded that DH systems have a significant impact on increasing flexibility of future energy systems and the integration of intermittent RES (namely wind and PVs).

A particularly interesting area for researchers when looking at future energy and urban systems is the transport sector. Garau et al. [26] evaluated the Urban Mobility Plan of the city of Cagliari, Italy by comparing it with the urban mobility performance of 18 other European cities and their main conclusion is that inexperienced cities such as Cagliari need to strengthen the process of adapting facilities and services related to modern urban mobility. In a context of a much larger city, Steurer & Bonilla [27] analysed ways to create a more sustainable, low carbon transport system for the Mexico City Metropolitan Area and developed four stakeholder-led scenarios for reducing CO_2 emissions in the city. Dominković et al. [28] modelled a transition towards sustainable transportation sector for the entire EU, emphasising the electrification as the key step in the transition, along with the biofuels and electrofuels.

Also, the future of urban mobility has motivated the world's largest business consultants and knowledge think tanks to study the area and publish their expertise on the topic. Some examples include McKinsey & Company's report on opportunities for automotive industry in the future transportation system [29] or Deloitte's report on digital innovations in urban mobility [30].

So far, general frameworks have been introduced through global energy trends in cities, as well as through a brief explanation of the situation in Zagreb. In order to narrow the scope of further, the main concept analysed in this work is introduced in the next subsection.

1.1.3 Smart energy systems

When analysing energy systems, it is important to understand what an energy system is and its main components are, what is the connection between those components and how can the energy systems be developed in the future. In recent years, there has been a rising awareness and research among scientist and technology developers in a concept known as smart grids - an electricity supply networks which include a variety of operational and measuring technologies such as smart meters, smart appliances and renewable and energy efficient sources, which can monitor electricity flows and adjust to changes in supply and demand accordingly [31]. As much as this concept may be important for the development of electricity supply and demand in the future, a more holistic approach needs to be applied when looking at an energy system as a whole. Besides electricity production, energy systems consist of heat production units (either for space heating and domestic hot water or for industrial processes), as well as transport and industry sector, today usually treated separately from the former two. Also, storage and distribution systems are integral parts of an energy system. An approach that takes into account merging all those sectors when planning future energy systems with a high share of fluctuating RES is called the smart energy system [32]. It is based on RES, sustainable transport, renewable fuels and various types of heat, electricity and fuel storage, as well as cross-sector integration needed to sustain fluctuations, but at the same time be fuel and cost efficient (see Figure 2 for more interactive explanation). Apart from this, smart energy systems are in the final stage 100% renewable, consume sustainable amount of bioenergy and often have the same level of costs as the fossil-fuel based system [33].

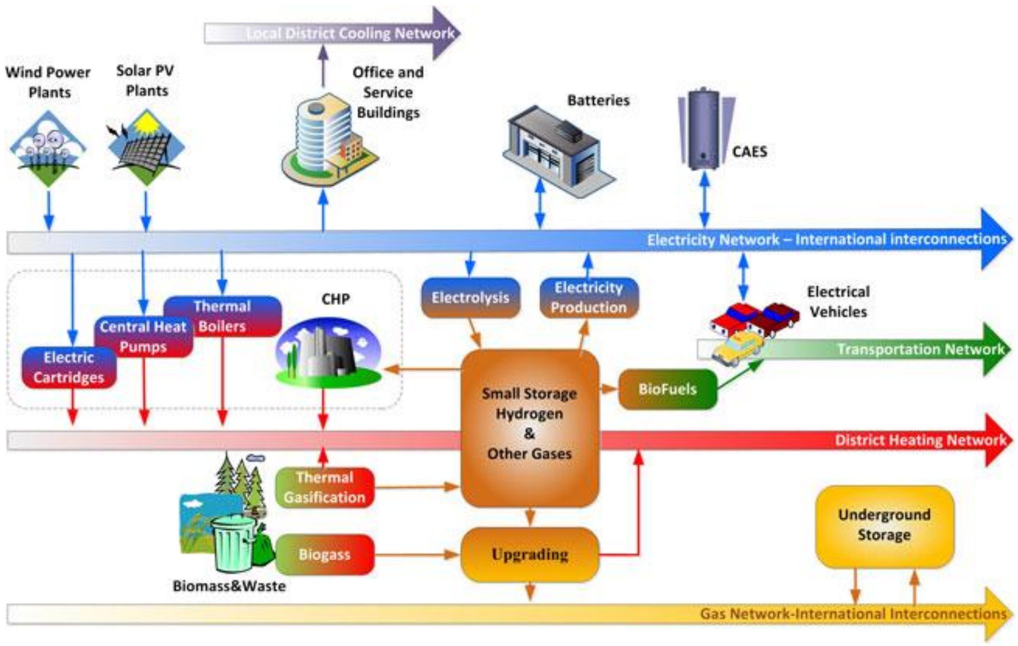

Figure 2. A representation of a smart energy system [34]

In their work [35], Mathiesen et al. argue that the smart energy systems approach can lead to identifying least cost solutions for integrating large shares of fluctuating renewable energy sources and especially when designing 100% renewable energy systems. Moreover, they define smart energy systems as those where smart electricity grids, smart thermal grids and smart fuel grids are integrated together, with transport sector and other infrastructure to achieve technically feasible integration of large share of renewables. Connolly et al. [36] conducted a robust study on a European scale and showed that if using a smart energy system approach, a 100% renewable energy system of the entire EU is technically feasible, without utilizing an unsustainable amount of bioenergy and being import independent. The scenario they created results in slightly higher total annual socio-economic costs than a BAU scenario, however reveals an opportunity to create 10 million direct jobs within the EU. Similar conclusions were made in the study in [37], where a 100% renewable, smart energy system of the South East Europe (SEE) region was created. The study showed that sector integration, renewable energy and energy efficiency are the key factors in creating a system that is cheaper than the one existing today.

Furthermore, a significant amount of research can be found in the field of implementing the smart energy system approach on a national scale. Cases of Denmark [38], Ireland [39] and Macedonia [40] are some examples of that, while many other researchers focus on investigating 100% renewable energy systems, but not explicitly using the smart energy system approach. The Danish example provides a threshold for further similar analyses in the field by being a pioneer in such an approach, but also emphasised the problem of excessive bioenergy use in 100% renewable Danish energy system. The Irish and Macedonian examples showed the theoretical possibility of creating 100% renewable energy systems, however concluded there is a need for further research to optimize biomass utilization, increase energy efficiency and find an optimal combination of technologies to be implemented in the system.

Smart energy systems are, however, not the only solution for developing 100% renewable energy systems. In some cases, they are not even the most optimal solution. For example, many places around the world do not have any heating demand, so the benefits of integrating multiple sectors, as the smart energy system concept emphasises, are somewhat diminished in that case. Another example might be places with a vast biomass resources, where the cheapest way is to utilize all the biomass for energy production and not implement any other sources. To summarize, deciding on which concept to apply in planning a future energy system is very case specific, meaning the characteristics of a given case need to be taken into account in the decision making process - including natural resources, climate conditions and economic situation. Also, 100% renewable energy systems, under certain circumstances, can be developed in a much less complex way – simply by transforming each sector into a renewable one independently.

In order to evaluate which is the most optimal way to build a 100% renewable and sustainable energy system in Zagreb, more than one option needs to be considered. The following section summarizes everything stated so far and outlines the main goals of this thesis.

1.2 Problem formulation

All the listed work shows a significant potential for developing renewable energy systems in cities by transforming their electricity and heat supply sectors, as well as energy supply in industry and transport. Moreover, the transition could bring additional benefits to the citizens and a city's economy, hence increasing the quality of life. Finally, it contributes to achieving a country's climate and energy goals, hence actively participating in global efforts towards sustainable energy systems.

As a first step in this transition, Zagreb needs to create a comprehensive plan of its energy system development, that as a priority has the solving of the major problems that exist today.

The following six key facts have been identified to summarize the main problems in Zagreb's energy system:

- Heat and electricity production almost 100% based on fossil fuels.
- A transport sector based exclusively on fossil fuels.
- A large dependency on electricity import.
- Geographical position and available resources leave limited options for implementing renewable technologies.
- Lack of awareness of benefits of energy efficiency, RES and DH among citizens and city leaders, while decision makers are largely driven by political interests rather than expertise.
- Lack of detailed and concise development strategies.

Moreover, the plan needs to assess which is the most feasible development pathway the city should follow by comparing different solutions from a technical and economic perspective. Many other studies focused on comparing existing energy systems with future alternatives, however not as many compared two different renewable energy systems. This work compares two ways to develop future energy systems and both include 100% renewable energy. The first is a smart energy system, explained in Subsection 1.1.3, while the second is the more well-known, "traditional", non-integrated renewable energy system. Both concepts are compared and the actual benefits of each in the case of Zagreb are analysed, in order to determine whether it is feasible for Zagreb to develop a smart energy system. Apart from the technical side, the thesis gives a brief description of policy and institutional requirements that need to be considered when developing such a concept.

To synthetize the problem and the approach in solving it, the following research question has been formulated:

Using the city of Zagreb as a case, what are the differences in a smart energy system approach vs a non-integrated renewable energy system approach from a technical, economic and implementation perspective?

In order to properly address the research question, the three main sub-questions will be examined:

- What does the current energy system look like in Zagreb?
- Which system performs better in terms of energy consumption, CO_2 emissions and total system costs?
- What are the key implementation steps that need to be considered and how different they are between the two approaches?

1.3 Delimitations

The thesis seeks to find differences between a smart energy system and a non-integrated renewable system using a case, which brings uncertainties about applicability of conclusions on any other given case. These are discussed and elaborated later, but the reader should be aware of their existence from the very beginning.

Furthermore, the three perspectives of differences mentioned in the research question should be defined. Technical differences refer to specific characteristics that can be obtained with the energy system analysis tool used in this work – namely primary energy supply, energy production distribution, hourly behaviour of a system and CO_2 emissions. They do not include, for example, design specifics of energy plants, neither the specifications of distribution networks. Economic differences refer to total annual system costs, including investment, operational and CO_2 emission costs. Finally, implementation differences refer to stakeholder engagements, policy interventions and infrastructure requirements and do not include detailed implementation steps but rather general considerations.

Other assumptions, limitations and uncertainties in different aspects of the analyses are raised and discussed along the way. After introducing the overall delimitations, specifically related to the research question, the structure of the thesis can be explained.

1.4 Thesis outline

The thesis consists of eight main chapters, each further divided into sections and subsections.

Chapter 1 introduces the problem, starting from a global perspective and narrowing down to the city level. It also gives a literature and state-of-the-art review of the main concepts applied later in the analyses. Finally, it includes the synthesis and contextualization of the problem by giving the problem formulation and the research question.

Chapter 2 describes the two main theories applied in the thesis and sets the general methodology framework, explaining the approach in the energy system analysis and data collection, the purpose of the sensitivity analysis and the reasoning behind the stakeholder and policy analysis.

Chapter 3 gives the main information on the city of Zagreb, first introducing its economic, demographic and geographic characteristics and then switching to its energy system and problems it is facing.

Chapter 4 starts with the modelling of the current energy system in Zagreb, continues with the validation of the model and then switches to detailed steps of modelling the two future scenarios – a traditional, non-integrated renewable energy system and a smart energy system.

Chapter 5 gives the main results of the three scenarios and compares them in fuel consumption, energy production, total system costs and the hourly behaviour. It also includes the sensitivity analysis, which tests how the results of the scenarios change when some of the main variables in the model are gradually altered.

Chapter 6 focuses on the implementation analysis and other factors that need to be considered, apart from the characteristics of the energy system. It describes the stakeholders gives a brief current policy overview, discusses the infrastructure requirements and gives the main general policy recommendations.

Chapter 7 discusses the main findings, as well as the main lacks of the thesis. Some of the crucial assumptions are elaborated and their impact on the results is explained. Also, the future work on this topic is suggested.

Chapter 8 gives an overview of the main observations and conclusions of the work, based on the issues examined in the previous chapters, with the main purpose of answering the research question.

2 Theories & methods

This chapter introduces the main theories and methods applied in the thesis. First, a brief description of the Choice awareness theory is given, followed by the Case study theory and the rationale behind choosing to use that theory, as well as the main advantages and disadvantages of it. Energy system analysis is introduced next, describing the selection process of the modelling tool and giving the main information on the selected tool. Furthermore, the data collection process is described in details, defining sources and modifications done in different types of data. Lastly, a short description of the three other analyses applied in this work is given, namely sensitivity analysis, stakeholder analysis and policy analysis. These are defined from a theoretical standpoint, but more important, it is explained what are they used for and why are they important for this work. The process of using them on the case of Zagreb is also explained.

2.1 Choice awareness

When dealing with analyses of technological changes, such as transition towards future energy systems, one has to be aware what steps need to be taken in order to implement those changes, as well as what are the potential obstacles that might appear during the implementation. Choice awareness theory deals with how to implement a radical technological change at the societal level.

Firstly, to understand the concept of radical technological change, one has to understand Technology theory, that defines technology as a combination of the following five constitutes: *Technique, Knowledge, Organization, Product* and *Profit*. Using this definition, Lund [41] defines radical technological change as a situation when more than one of these five components is changed. An example he uses to describe the radical technological change is a transition from fossil fuel-based to renewable energy systems. On a first sight, that is clearly a change in a *technique* of generating energy, however it leads to transition from usually single-purpose large supply companies in today's systems to potentially multi-purpose, geographically distributed, smaller competitors in the system, which can be defined as an *organizational* change. Furthermore, it involves an economic redistribution, as new investment opportunities appear, resulting in redistribution of *profits*. Finally, it requires a new *knowledge* and expertise of how systems and markets work and how to achieve benefits from new frameworks.

Radical technological change is a threat to existing organisations that depend on the technologies that should be replaced in renewable energy strategies. As a result, those organisations respond to the threat by eliminating a choice, through public debates and collective perception. This is known as the first thesis of the Choice awareness theory. It further defines that when a society seeks to implement radical technological change, the influence and discourse of existing institutions will affect the implementation by eliminating certain alternatives and creating a perception of "no choice" but to implement technologies that will save existing position. As a tool to fight such a situation serves the second thesis of the Choice awareness theory, that argues that society needs to raise the awareness that alternatives do exist and that it is possible to make a choice. Lund [41] offers a simple methodology for raising the awareness of alternatives in reality. It is composed of four main steps, which are described in Figure 3.

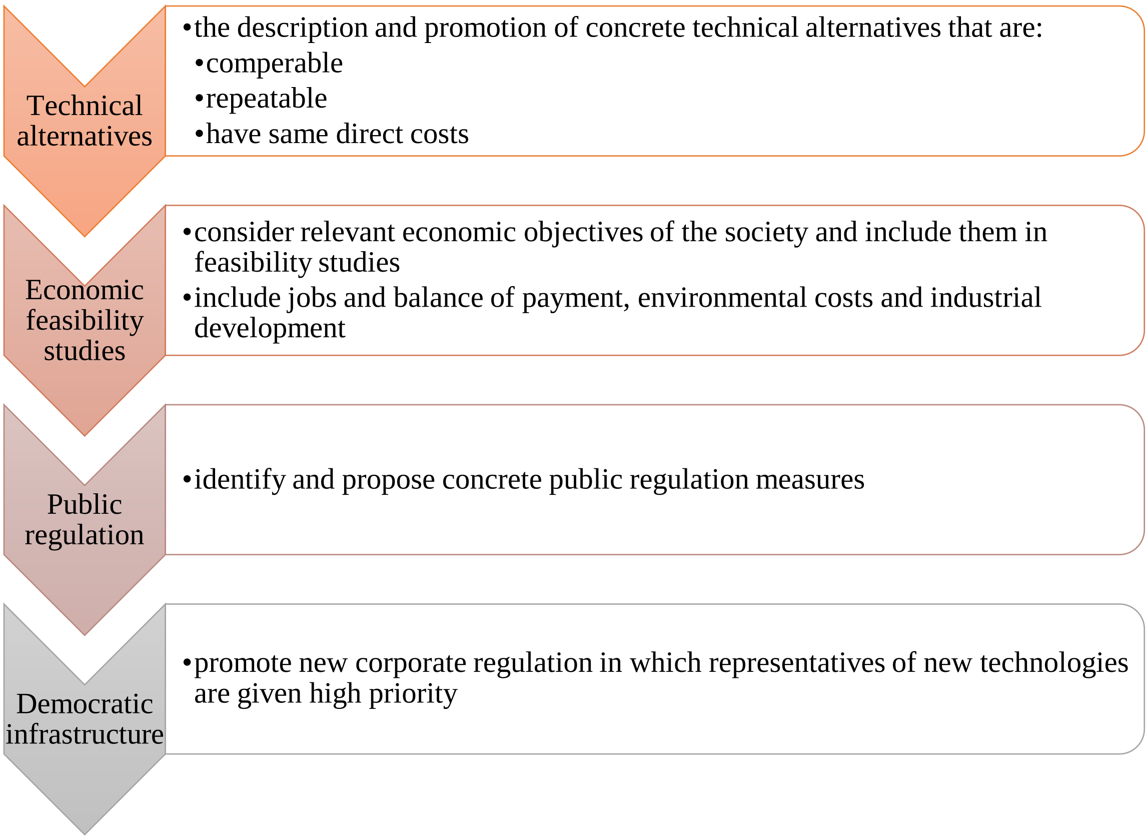

Figure 3. Choice awareness strategies methodology [41]

This thesis offers the suggestions for the first three steps of this methodology, using the city of Zagreb as a case, whereas the last step – the promotion of new alternatives - is considered as effective if implemented simultaneously with all the other steps. The first part of the thesis deals with the creation and description of technical alternatives and economic evaluation of the alternatives, while policy and public regulation proposals are given in the second part.

In order to create concrete technical alternatives for a future energy system, one needs to define a case and conduct an energy system analysis, respectively described in Sections 2.2 and 2.3.

2.2 The case study theory

The focus of this thesis is on how energy systems in cities could develop and more specifically, what are the differences between two approaches of that development. However, the scope is further narrowed down to investigating all that on a specific case, by addressing the specific problems related to the case at the same time. While the main goal is to identify the optimal approach to build a renewable energy system in Zagreb, it is also important to gain general conclusions about the differences between smart and traditional renewable energy systems that can be applied in any given case. Therefore, understanding the fundamentals and limitations of the case study theory is important when using a specific case to answer broad and general questions.

Zainal [42] defines case study as a method for closely examining the data within a specific context. More precisely, case studies investigate real-life phenomenon through detailed analysis of a limited number of events and conditions and their relationships. In the context of energy system analysis, these events could be energy supply facilities and consumers, whereas conditions range from weather conditions to economic situation in the case.

Furthermore, Yin [43] defines that the goal of a case study is to establish the parameters that can be applied in all the research, rather than set a framework applicable in a single case or a series of cases. When designing a case study, Zainal [42] emphasises it is important to be able to prove six key facts related to the appropriateness of the method:

1. It is the only viable method to gather relevant data on the subject
2. It is appropriate to the research question
3. It properly follows the set of procedures
4. The scientific conventions used in the related field are followed
5. A "chain of evidence" is systematically recorded and achieved
6. It is linked to a theoretical framework

The six points can be easily applied to the appropriateness of using Zagreb as a case for analysing future energy systems in cities. Energy system analyses are generally based on cases (either real or theoretical), the data has to be site specific and cannot be generalized (1), while the results of analyses (characteristics of two energy systems) directly answer the research question of this work (2). The process has it logical steps from setting up the reference system to gathering conclusion from modelling scenarios (3). Furthermore, the modelling is based on already established and widely-used models developed specifically for the purpose of analysing future energy systems (4), while every step of the modelling process and gathering the results is described in details and supported by the reasoning and implications of the results (5). Finally, a variety of theories is directly or indirectly included in the process, ranging from energy conversion fundamentals to simple investment theory (6).

There are the two most important advantages of case studies in comparison to experimental or survey research. First, the data is examined in the context of its use, which leaves very little space for misinterpretation of the relationship between different types of data. Second, both qualitative and quantitative examination of the data is possible which gives opportunities for different approaches in the analyses and therefore more comprehensive conclusions [42].

Apart from advantages, case studies also have important limitations. They lack robustness and are dependent on a single case, so provide very little basis for scientific generalisation as they use a small number of subjects. Also, they are sometimes long, difficult to carry out and require a massive amount of documentation. This is especially the case when collecting the data [42].

Case studies are useful as a research method as they enable researcher to examine the micro-level data and in energy system analysis, they are often the only available method. Moreover, case studies in this field are often used both as a method and as the primary subject of investigation, as some specific questions related to the case are explored.

The next section describes the energy system analysis process and gives some insights that help to better understand why case studies are especially useful and applicable in this field.

2.3 Energy system analysis – modelling tools

The general goal of the energy system analysis in this thesis is to measure the impact of different energy technologies from a technical (fuel/energy use), economic (costs) and/or environmental (greenhouse gas emissions) standpoint. In order to properly represent and analyse various aspects of, usually rather complex systems, different computer modelling tools are used.

Herbst et al. [44] divided energy system models into the two main groups: top-down and bottom-up models. Top-down models are used to describe systems on a local, national or a regional level as a whole, taking an aggregated view of the energy sectors and the economy. Hence, they are used to assess the aggregated effects of different energy policies in monetary units. Herbst et al. furthermore divided them into four different types: input-output models, econometric models, computable general equilibrium models and system dynamics. Bottom-up models usually use a business economic approach to simulate and evaluate different technologies and assess future energy demand and supply. There are however examples of models using a socio-economic approach and having the same goal. The four main groups of bottom-up models according to Herbst et al. are: partial equilibrium models, optimisation models, simulation models and multi-agent models [44].

One of the most comprehensive comparisons of different computer tools for analysing energy systems was conducted by Connolly et al. [45]. They analysed 37 different tools in collaboration with the tool developers and provided relevant information needed to identify a suitable tool for the analysis of any given case. Their main focus was to analyse tools suitable for the integration of renewable energy technologies on different scales – from single building systems to national energy systems. Out of 37 tools, 11 focus primarily on the electricity sector, however with different objectives – from analysing the feasibility of new facilities to electricity market simulations. The remaining tools have a possibility to include heat or transport sector in addition to the electricity. However, only 11 of the remaining tools can account for all technologies in electricity, heating and transport sector, whereas only four use hourly time steps - especially beneficial for modelling and optimising energy systems highly based on fluctuating RES, such as PV and wind. Out of these four tools, only two have previously been used for modelling 100% renewable energy systems, namely EnergyPLAN and Mesap PlaNet. Mesap PlaNet has been used to model 100% renewable energy systems of the Canary Islands [46] and in the Greenpeace’s 100% renewable energy scenario for the entire world [47]. Mesap Planet has approximately 20-30 users and costs around EUR 6,800 to purchase [47]. EnergyPLAN, on the other hand, has been used in numerous studies on 100% renewable energy systems on different scales, as well as to assess the impact of different technologies on energy systems. Moreover, it has thousands of users worldwide and it is free of charge [48]. As it meets all the requirements for the analysis of energy systems with a high share of fluctuating RES and it is easily accessible, EnergyPLAN has been chosen as a modelling tool in this thesis.

EnergyPLAN is an energy system analysis computer model that has been developed at Aalborg University, Denmark since 1999. The main purpose of the model is to analyse energy, environmental and economic performance of different energy systems, with the objective to model a variety of options which can then be compared, rather than finding one optimal solution endogenously. The focus of the model is on future energy systems and the integration of future technologies. Therefore, the model includes fairly detailed modelling of technologies such as electrolysers, biomass gasification, compressed air energy storage (CAES) and many more. Also, the model covers different energy sectors, including electricity, heating, cooling, transport and industry, as well as the possibility to integrate those sectors, through technologies such as CHPs and heat pumps in district heating, EVs, hydrogen or synthetic fuels. A schematic description of the model in Figure 4 gives a representation of how different sectors are integrated using EnergyPLAN. This makes EnergyPLAN suitable for modelling smart energy systems [49].

EnergyPLAN is a deterministic model, meaning that with the same input, it always gives the same results, as opposed to stochastic models or models using Monte Carlo methods. General inputs are electricity, heating and fuel demands in different sectors, capacities of power plants, RES and energy storages, costs and regulation strategies. Outputs are energy balances and annual productions, fuel consumption, electricity import and export, CO_2 emissions and total annual system costs. In that manner the model is divided into the four main input tab sheets – *Demand*, *Supply*, *Balancing and Storage* and *Cost*, and one additional tab sheet called *Output*, where the user can choose between different ways of showing output components. Each tab is further divided to sub-tabs, generally following the logic of different energy sectors [49]. This defines EnergyPLAN as a bottom-up tool, as the main focus is on identifying and analysing specific energy technologies and finding different investment alternatives, rather than taking a macroeconomic approach to assess different energy policies.

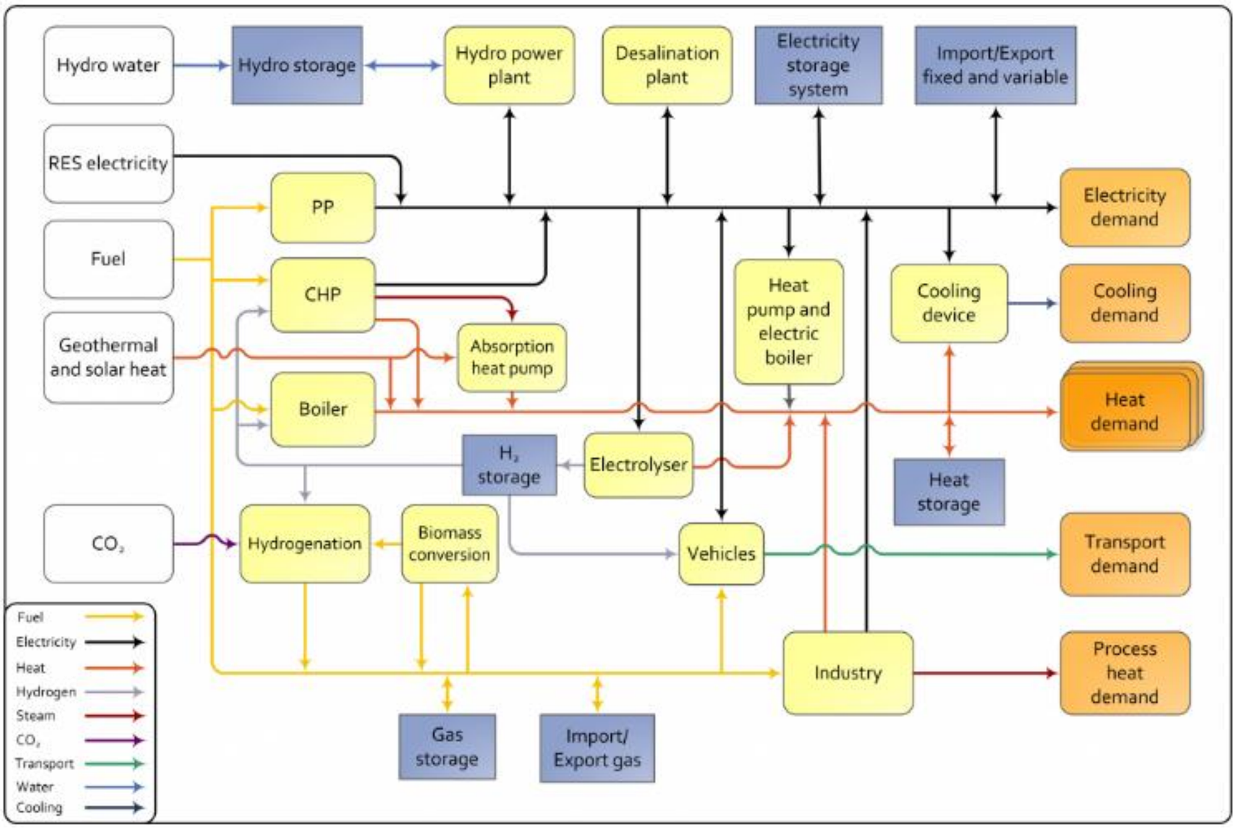

Figure 4. A schematic representation of the EnergyPLAN model [45]

Furthermore, the model operates on an hourly basis (8784 time steps – the number of hours in a leap year), which makes it suitable to analyse the influence of intermittent RES on the system, as well as hourly, daily and seasonal differences in electricity and heat demands. It seeks to achieve the balance between supply and demand in every hour throughout the year. A key input component that defines hourly behaviour of a system are distribution files, text files consisted of 8784 numerical values created externally and uploaded to the model. Typical distribution files being used are electricity demand curve (hourly network load curve), heat demand curve based on outdoor temperatures, wind power curve based on wind velocity, solar/PV curve based on solar radiation and several more. An overview of distribution files needed for modelling in EnergyPLAN, as well as a process of gathering data and creating the distribution curves is given in [50], while a guideline for finding all the data needed for EnergyPLAN models is given in [51].

The model gives an option to indicate whether the analysed system has interconnections with surrounding areas. Hence, it can be operated in island mode, i.e. without any interconnection, or in connected mode, by setting an interconnection capacity. In the latter case, the system has an option to import or export electricity in any given hour, if technical or market economic conditions require so.

A system modelled in EnergyPLAN can be operated using two general simulation strategies: technical simulation or market economic simulation. The technical simulation has a goal to minimise the import/export of electricity and to find the least fuel-consuming solution. It is typically more accurate when simulating systems with very large shares of intermittent renewables. If choosing the technical simulation, the user needs to further define which of the following four for strategies is to be used:

1. Balancing heat demands – all heat production units are producing only according to heat demands
2. Balancing both heat and electricity demands – electricity export is minimised by the use of heat pumps and CHP plants, simultaneously increasing electricity demand and decreasing electricity production
3. Balancing both heat and electricity demands (reducing CHP also when partly needed for grid stabilisation) – replacing CHPs by condensing power plants and achieving lower efficiency but less excess electricity production
4. Balancing heat demands using triple tariff – using the Danish triple tariff instead of meeting the heat demand (used in specific cases)

The market economic simulation is based on a short-term marginal price market model and focuses on minimizing short-term electricity consumer costs and short-term district heating costs. This strategy only uses variable costs and it optimizes only the supply side of the energy system [49]. A comprehensive overview of EnergyPLAN simulations is given in [52].

In this thesis, the technical simulation strategies 1 and 2 are used, depending on the scenario. The reason for such a choice lies in the fact that the primary goal is to get technical representations of different options for Zagreb's energy system and the main requirement is that all the analysed options are technically feasible, in terms of balancing the grid and limiting excess electricity production. Thus, lowering the costs and generating market income (the main objectives of the market economic analysis), although desirable and used as one of the comparison factors, is not the main objective of the analysis. Also, with a complete switch of the energy system, there are no hourly market prices to optimise against, as used in today's systems, hence using the market economic simulation would be practically hard to carry out.

Some of the main constraints of the EnergyPLAN model are aggregated modelling of power plants, where all the condensing power plants are represented as a single unit, defined by the total capacity, efficiency and fuel distribution shares of different fuels, namely coal, natural gas, oil and biomass. This makes it complicated to model systems based on more than one condensing power plants that utilize different amounts of different fuels. Similar goes for district heating plants and heat storages, which are modelled in only three groups. Also, the system is treated as a single point, without considering possibilities of internal congestion. As a result, there is no option to spot imbalances or a congestion between different geographical parts of an energy system, e.g. regions or municipalities. Finally, the model treats biomass as a single fuel, rather than distinguishing between different types of biomass – e.g. wood chips, wood pellets, residues from agriculture crops, wet/dry biomass etc. Different types have different chemical properties, which in turn have an impact on resulting fuel consumption and related CO_2 emissions.

2.4 Data collection

Data and information are collected for two main purposes: to feed the EnergyPLAN model in order to carry out energy system analyses; and to get insights in policy and institutional frameworks to create policy suggestions. A structural overview of the main types of data is given in Figure 5. The first two components – technical and economic data – are used for the energy system analyses, whereas the rest of the data and information are used for policy and stakeholder analysis.

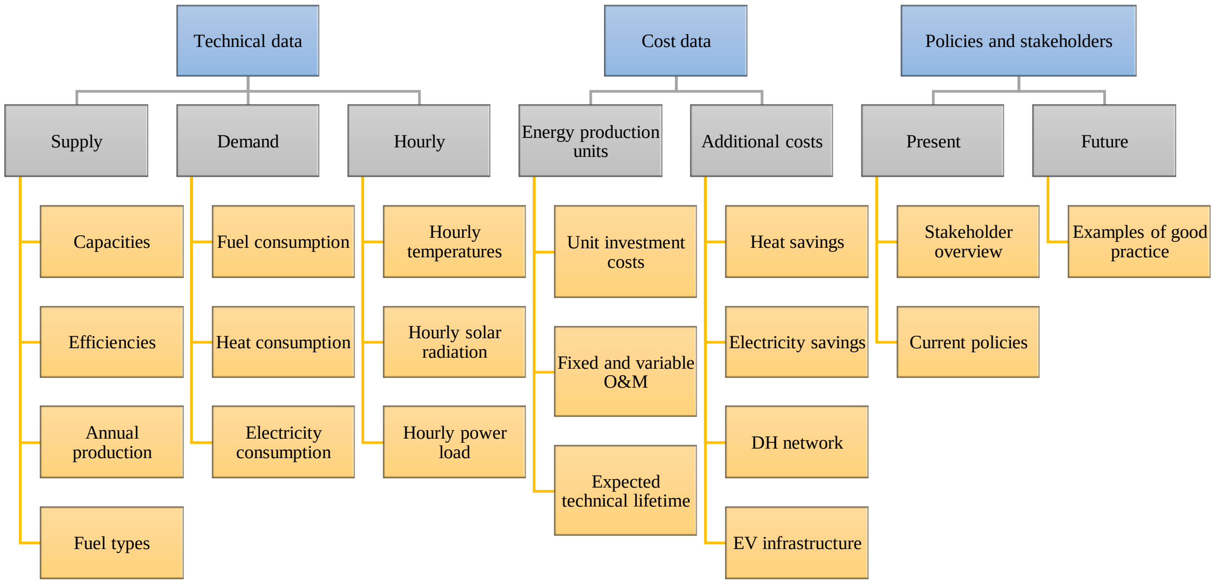

Figure 5. Overview of types of data and information used for analyses

The following sections elaborate on each type of data and give a detailed description of the data sources, as well as any relevant modifications implemented to adjust it to be suitable as an input to the model.

2.4.1 Energy supply and demand data

Used primarily to model the Reference scenario, energy supply and demand dana is collected from three different sources. First, information on the capacity and annual heat and electricity production for two CHP plants in Zagreb is gathered from the official websites of HEP [53], the owner and operator of all the major energy facilities in Croatia. They however, only give the total heat and electric capacity of each plant, without distinction of what capacity operates in CHP mode and what in boiler mode. This is therefore estimated and all the related assumptions are elaborated in Subsection 4.1.1, where the supply side of the Reference scenario is described in details. HEP also gives the total annual heat and electricity production for the period 2010-2015, as well as some other basic technical characteristics of the plants, such as turbine and boiler types or fuels used. The amount of each fuel used, as well as the efficiency of the, is however not provided among that information. Hence, the overview of national heating and cooling efficiency potential is used [54]. This is the document where Energy Institute Hrvoje Požar (EIHP) gives a very detailed technical description of CHP and heating plants in Croatia, as well as some estimations regarding the future share of district heating in the country. The share of network losses is estimated based on the difference between the heat production (on the plat site) and final heat consumption (on the consumer side).

Finally, energy consumption data is gathered from the Energy Efficiency Action Plan of the City of Zagreb for the period 2017-2019 [55], where apart from some short-term recommendations regarding renewable energy and energy efficiency, a detailed sectoral energy consumption for the year 2015 is given. The document gives the demand data divided into five sectors – households, services, industry, agriculture and transport. For the purposes of the EnergyPLAN model, households and services are merged and used as an input to *Individual* tab, and industry and agriculture sectors are merged and put into *Industry* tab of the model. Transport sector is without any modifications used as an input into the *Transport* tab in EnergyPLAN.

2.4.2 Cost data

In order to calculate one of the main results of the energy system analysis – total annual system costs, different cost data need to be used as a model input. As shown in Figure 5, the first component of the costs that needed to be collected is the investment costs of various energy production units, together with operation & maintenance (O&M) costs and technical lifetime. This information can be gathered from a variety of sources, from online catalogue material of manufacturing companies to research studies of already implemented projects. It is however, a challenging tasks to find the same source for all technologies needed, which is important to keep consistency and make fair comparison. It is even more challenging to find the estimations of the future technology prices, which is essential for modelling future scenarios.

Already created cost files with all the necessary unit investment costs, O&M costs and technical lifetime are provided and can be downloaded from the official EnergyPLAN website [56], both for the present state of technologies (used for modelling the Reference scenario) and for the year 2050 (used for modelling two future scenarios). The majority of the data in the cost files is taken from "Technology data for energy plants" [57], a catalogue of energy production technologies created by joint efforts of the Danish Energy Agency and Energinet.dk, the Danish electricity transmission system operator (TSO). As most of the data in this catalogue is in Danish context and some of it in more broad, European context, it might raise questions regarding validity of putting it in Croatian context. However, even technologies potentially implemented in Croatia, are likely to be purchased on the larger European market, which is the reason to assume that it is reasonable to use these cost files in Croatian context. Moreover, total annual system costs are essentially used more to compare different scenarios, rather than give precise costs of each system. Hence, as long as the same data is used in every scenario, the comparison is fair.

The second component of costs are additional costs. As shown in Figure 5, they are divided into four categories: heat savings, electricity savings, DH network expansion and EV infrastructure. Heat savings costs are estimated based on reviewing the publications on technical characteristics of buildings in Croatia [57, 58], where EIHP gives some estimations on energy efficiency costs in different types of buildings in two geographical areas in Croatia. Moreover, using the same framework for building types, Mikulić et al. [60] calculated the price of saving one unit of energy in each type of the building. For the purposes of this work, that price is set to 1,000 EUR/MWh. This is also in line with other studies from the field, that made the same type of estimation, such as the case of Aalborg Municipality [22] or the Stratego project in Croatia [61]. Those two sources are also used to estimate the price of saving one unit of electricity, which is set to 540 EUR/MWh. Furthermore, EV infrastructure costs are assumed to be 1,000 EUR/vehicle (directly adopted from the Stratego project), while DH network expansion costs are set to 297 EUR/MWh (median between conventional and low-temperature DH grid from the Stratego project).

Finally, the discount rate is set to be 3%, following the methodology of other similar studies on smart energy systems that used the same rate, such as the one on the European scale by Connolly at al [36], the case of future Danish energy system [38], the case of Aalborg municipality [22] and many other long-term analyses. This is because no official recommendation by the Croatian Government regarding the discount rate for energy projects or any type of projects exists. The impact of the discount rate on the results is thoroughly analysed in Subsection 5.2.1.

Detailed information about all the costs used in modelling the scenarios are given in Appendix II.

2.4.3 Hourly distribution data

Hourly distribution data is necessary for simulating the intermittent hourly behaviour of energy production units, as well as hourly, daily and seasonal differences in energy demand. Therefore, several distribution curves are used. As a part of this work, three distributions are created from scratch, whereas three other are taken from different sources, but their relevance is explained in this section.

Electricity demand distribution is used for a country level, since local branches of the national TSO do not make this data publicly available, neither provide it on a request. Country level data is obtained from the European Network of Transmission System Operators for Electricity (ENTSO-e) [62]. All demand distributions in EnergyPLAN are relative values related to the defined annual value, therefore this has no significant impact on aggregated results. Some differences in results however, might occur, due to larger representation of cooling demand on a national level because of much warmer southern part of the country, or because of a large amount of tourists that come to Croatian coast during the summer. Another possible difference is in the electricity demand during the night, which is possibly much higher in Zagreb as the largest city in the country than on an average national level. For the purpose of this work, that is assumed to be negligible, as no better data is available.

To create the heat demand distribution, hourly temperatures are obtained from Meteonorm [63], a software with the database that contains weather information for any place in the world. Having the temperature data, the curve is created using the degree-hour method assuming that the spaces are heated to 21°C if outdoor temperature drops below 18°C. Domestic hot water (DHW) is assumed to be 20% of the average annual heat demand in every hour throughout the year, which is the average share in the EU according to the Association of European Heating Industry [63]. It is furthermore assumed that, in the period from beginning of May until the beginning of October, there is no heating demand, but only DHW demand.

Solar radiation data is also gathered from Meteonorm and solar output is calculated based on the methodology of the EnergyPRO software [64], explained in details in [65]. The methodology takes into account geographical characteristics of the location, orientation of the panel (inclination of the surface, orientation of the inclined pane), and technical characteristics of the solar panel, such as efficiency coefficients, angle factors and dimensions. Technical characteristics are taken for a sample panel from [66]. Three distribution curves created as a part of this work can be seen in Appendix I.

Transport energy demand distribution is provided by the authors of the study in [67], who modelled the hourly transport energy demand in four Croatian cities (including Zagreb) using the agent-based modelling tool MATSim.

Finally, CSP and run-of-river hydro distribution curves are taken from EnergyPLAN distribution library and can be downloaded within the latest version of EnergyPLAN [68]. The former is called *Croatia_run_of_river_hydro_2007* and it has previously been used by Krajačić et al. [69] in their study on modelling 100% renewable energy system in Croatia. The latter is called *CSP_with_storage_55_percent_capacity_factor* and it has previously been used in creating a zero carbon energy system of South East Europe region [70]. Therefore, it is assumed that it is reasonable to use them in the context of Zagreb.

2.5 Sensitivity analysis – purpose and method

Sensitivity analysis is a method to investigate potential changes in parameter values and assumptions of a model and their impact on results and conclusions drawn from the model. It is especially useful when the model is used to support decision makers and make recommendations of any kind. Usually, it is used for one or more of the following reasons: to test the robustness of a solution, to identify critical values (e.g. break-even values where optimal solution changes), to identify sensitive variables, to develop flexible or sub-optimal recommendations or to test risks of strategies and scenarios [71].

The crucial step in conducting the sensitivity analysis is choosing the most important parameters to be varied and identify a range for each parameter within which it can be realistically expected to change. Next, it is important to determine logical steps of change that can provide meaningful and insightful conclusions.

In this work, sensitivity analysis is conducted to analyse the variations of the main components of the results, such as fuel consumption, total annual system costs and critical excess electricity production when the most influencing variables are changed. This serves to test the robustness of each of the scenarios created and point-out the main issues and uncertainties in the conclusions from the main analysis.

2.6 Stakeholder analysis

Stakeholders are individuals, groups or organizations who are affected or have the power to affect a certain action [72]. There are different standardised methods for analysing stakeholders, such as power vs. interest grid, which ranks the stakeholders at hand by the level of their power and interest around the given problem, or stakeholder-issue interrelation diagram, which helps to understand how different stakeholders influence each other. In this thesis, however, a customized method is used. The stakeholders are arranged into six different categories, which represent their main role in the decision making process. Categories are arranged top-down, where the category on the top has the highest level of influence. The framework for assessing the stakeholders is shown in Figure 6.

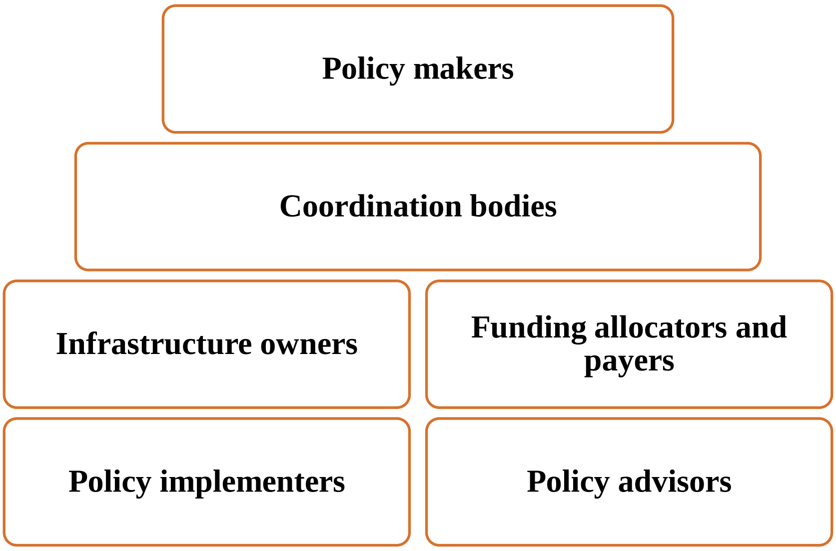

Figure 6. Template for assessing the stakeholders – six main stakeholder categories representing the top-down decision making system. See Figure 26 for the details about which stakeholders are placed in each category.

Policy makers are stakeholders with the highest level of influence in the policy and the decision making process. These are essentially ministries related to energy and infrastructure problems. They design all the major policies, including acts and strategies, define the long term goals and provide the framework for policy implementation.

Coordination bodies act as a link between policy makers and other categories by managing the strategy implementation and regulating a broad range of business activities in the energy sector, such as energy markets, prices and investments.

Infrastructure owners own and manage energy plants and distribution networks and their business activities highly depend on, but also influence, the future energy strategy in Zagreb, hence their impact is fairly high, however can be overruled by the aforementioned categories.

Funding allocators and payers and payers are stakeholders that either take part in providing the money for public energy investments (e.g. through their energy bills or taxes) or coordinate the allocation of that same money.

Policy implementers carry out actual energy projects and create energy plans on the local level. Their power is therefore relatively small, but they are rather executors of concrete, specific tasks and projects. They, but also other stakeholders, often engage ***policy advisors*** for opinions and suggestions about technical and regulatory issues when designing strategies and plans, but also when implementing concrete projects. These are mainly research institutions that with their knowledge and experience provide a support to the rest of the system.

2.7 Policy overview

Following and supplementing the stakeholder analysis, policy overview helps to understand the current policy situation, both on the national and the local level and to identify what are the crucial components that are missing and are needed in the implementation stage of developing a new energy system.

First, an overview of the existing policy framework is carried out by reviewing available literature on various acts, laws, regulations and publications within the field of energy efficiency, renewable energy, (district) heating, energy infrastructure, investments in energy projects and city infrastructure. The main documents are then identified and divided into three major areas: *strategic documents, research studies & reports* and *legal acts*.

Strategic documents are short or long-term plans of developing the energy system as a whole, or a certain sector of the energy system. Both national and local strategic documents are included. Research studies & reports provide information about the existing system or give an overview of the future development potential. In both cases, they give detailed data important for building analyses, assessments and models of the future system. They can also be found both on the national and the local level. Finally, legal acts include the main laws regulating activities in the energy sector. They exist only on the national level and are divided by energy sectors.

In each category, several most important policies are identified and their brief description is given. The details can be seen in Section 6.2.

After all the relevant theories and methods are explained, the next chapter gives the main facts about the case of Zagreb, needed for better understanding of the rest of the analysis.

3 City of Zagreb - introducing the case

This chapter introduces the case of the city of Zagreb, giving the most important general information in Section 3.1 and continues with the focus on the energy system, as well as the most important issues in Section 3.2.

3.1 Population, economy & importance

Zagreb is the capital of Croatia and its administrative, cultural and economic centre. With 790,017 inhabitants (2011), it makes roughly 18% of the total Croatian population [73], being by far its largest city (followed by Split with 178,102 inhabitants [74]). It is located in the north-western part of the country, surrounded by Krapina-Zagorje County on the north and Zagreb County on the east, west and south (see Figure 7). Although having almost the same name, Zagreb County is a different administrative area than the city of Zagreb. The city is divided into 17 districts and it is naturally split into two parts by the Sava river. With 1,233 inhabitants per km^2, Zagreb is the most densely populated area in Croatia, having approximately 10 times higher population density than Međimurje County, the second most densely populated area [75]. This gives an opportunity to build an efficient district heating system in the city, however might represent a concern when it comes to implementing technologies that require large areas to build.

Figure 7. Location of the city of Zagreb in Croatia ([76] *and own elaboration)*

Zagreb is the seat of the central government, multiple administrative bodies and all of the ministries. It is also an industrial, media, market and research centre of the country, as the majority of the largest companies and research institutions are headquartered in the city. Moreover, Zagreb is a cross-point of all the major highways and railways in the country, as well as the home to the largest airport (the airport is left out from the energy system analysis, as discussed in Subsection 4.1.2), hence being the main Croatian transport hub. It is located at the crossroad of Central Europe, Mediterranean and South East Europe, which makes it commercially important on a regional level.

Economy-wise, Zagreb is a fairly rich city for Croatian standards. In terms of gross domestic product (GDP), with a total of EUR 14.3 billion in 2014, it makes 33% of the total Croatian GDP. This results in a very high difference between Zagreb and other cities and counties in Croatia – its GDP per capita of EUR 17,908 is slightly over 105% higher than the GDP per capita of Međimurje County, the second next on the list and 76% higher than the Croatian average [77]. This in turn, makes an average energy consumer in Zagreb more comfortable in paying the energy bills and potentially, investing in small-scale RES projects or energy renovations.

3.2 Overview of the existing energy system, largest issues and development plans

The current energy system in Zagreb consist of two thermal power plants, namely TE-TO Zagreb and EL-TO Zagreb, both owned and operated by HEP, the largest Croatian energy company. Different parts of the energy system are however, owned and operated by different branches of the company, i.e. HEP Generation, HEP Distribution, HEP TSO and HEP Supply. The two plants are located in the north-west and south-east part of the city, respectively, as it can be seen in Figure 8.

Figure 8. Location of the two main power plants in Zagreb [78]

TE-TO Zagreb has the total electric capacity of 440 MW and the total thermal capacity of 850 MW consisting of:

- Five heat only boilers with thermal capacities ranging from 52 MW to 116 MW
- Three CHP units with capacities of 120 MWe/200 MWt, 208 MWe/140 MWt and 112 MWe/110 MWt
- A thermal storage system with the capacity of 750 MWh, commissioned in 2015.

The size of the storage system is fairly small compared to the installed generation capacity of the plant, which means that on an annual basis, its utilization is almost negligible.

EL-TO Zagreb is small, with the total capacity of 89 MWe/566 MWt, consisted of the following components:

- Three heat only boilers with capacities of 2x116 MW and 64 MW
- Three CHP units with capacities of 11MWe/45 MWt, 30 MWe/125 MWt and 48 MWe/100 MWt

However, neither of the two plants runs throughout the entire year, as their main purpose is to generate heat for district heating consumers. Hence, only TE-TO Zagreb operates during the summer period, but only to meet the domestic hot water demand. Moreover, even in winter, these plants do not operate at their full capacity, but only according to the heat demand. Whether they are to be operated in heat only mode or in CHP mode, heavily depends on the price of natural gas and it is often cheaper to import electricity than to run the CHP units and generate electricity on site. Therefore, electricity production varies quite significantly by years. Figure 9 shows how the electricity production from both plants has dropped significantly from 2010 but also indicates that the drop might be caused by the increase in the price of natural gas, as they follow the completely opposite pattern in every year apart from 2014 (the higher the price, the lower he production) [53].

There are currently 86,358 households connected to the DH system in Zagreb, which represents a share of 28.3% of the total number of households and the total heated area is around 7.17 million m^2. The DH system is geographically divided into five areas, of which three supply hot water and two supply steam. The total pipeline length of the hot water distribution network is approximately five times larger than the steam distribution network – 216 km with 2,509 substations in comparison to 44 km and 125 substations. The network is generally fairly old, with an average age of around 28 years, whereas some parts have been used for over 35 years without renovations. This results in water losses of around 2690 m^3/km (and around 0.82 GWh of heat per km) annually, which is very high if compared with other, more developed DH systems. For example, water losses in Aalborg DH system, which has a total network length of 1,386 km are around 80 m^3/km annually, which in absolute numbers means that a system 6 times larger in terms of pipeline length has approximately 5 times lower water losses [70]. This certainly means that the DH network in Zagreb requires significant investments in refurbishments in order to decrease the losses and increase the overall performance of the system.

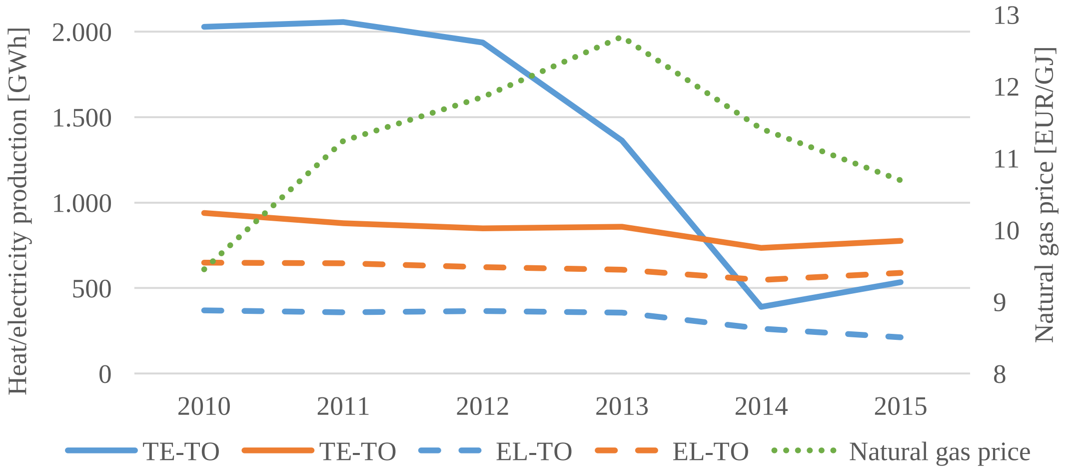

Figure 9. The relation between energy production in the two plants in Zagreb [53] *and natural gas prices by years* [79]

Almost 50% of all buildings in Zagreb were constructed before the 1970s, when no restrictions or policies regarding building energy efficiency existed. This results in very high heat losses in those buildings and therefore high specific heat consumption. A typical building from that period, such as one shown in Figure 10, normally has an annual specific heat consumption between 160 and 175 kWh/m^2 [80]. In fact, an average heat consumption in Zagreb is around 10% higher than the national average, which was 162 kWh/m^2 in 2015 [81]. The average energy consumption for space heating in the EU is around 140 kWh/m^2, with many countries with similar climate as continental Croatia, such as Bulgaria, Romania and Slovakia, recording even lower values [82]. This clearly indicates that investments in refurbishments of residential buildings is necessary in Zagreb to reduce energy consumption in the residential sector.

Figure 10. A typical building from the 1960s in Zagreb [80]

Another issue in the residential sector is measuring heat consumption of the district heating consumers. Until 2016, when the Croatian Government introduced the act that all district heating consumers need to introduce individual heat meters in their households, heat consumption of an individual apartment was being estimated on a per-area basis. This means that a calorimeter (a heat measuring device) measures the heat consumption of the entire building and individual consumption is area-proportionally distributed among individual apartments. Individual heat meters, which are currently being used by around 50% of all district heating consumers, raised a large amount of public debate, both between experts and citizens, about their benefits and feasibility. This is currently an on-going problem and the Government is considering various options of solving it, among which is also going back to the old metering system.

Zagreb was one of the first European members of Covenant of Mayors initiative and it developed its SECAP in 2010. In 2008, Zagreb become a member of Energy Cities [82], an organization connecting local and regional authorities in taking efforts to increase the use of renewable energy and energy efficiency. Every two years, the city council publishes the energy efficiency action plan for the next two year-period, giving an overview of the current consumption and short term investment measures. This is the only official document on the local level revealing how should Zagreb's energy system develop in the future, however it is also an important part of national plans and strategies.

4 Setting up scenarios

After the problem, the methods and the case itself have been introduced, the goal of this chapter is to set foundations for analysing the energy system of the city of Zagreb, both the existing one and future options according to two different scenarios. More specifically, this chapter gives a detailed description of the reference energy system in the year 2015, as well as the criteria for modelling two future scenarios for the year 2050. Moreover, the differences between the two scenarios are defined in order to develop a fair ground for comparisons and understand why it is relevant to compare them. First, the design and validation of the Reference scenario is given, followed by the main criteria for designing 2050 scenarios. The description of the future scenarios is divided into two parts – modelling the demand and defining supply capacities to meet the demand.

4.1 Reference scenario design & validation

The Reference scenario represents the energy system of the city of Zagreb in the year 2015. That particular year has been chosen because the latest data on sectoral energy consumption is available for 2015. As the only more up-to-date information would be for the year 2016, it is assumed that 2015 fairly represents the present situation. In terms of climate conditions on the country level, 2015 was a warm year with a median annual temperature 1-2.2°C higher than the 50-year average temperature and Zagreb was no exception in that. Looking at the precipitation data, the year was fairly dry on the national level, however Zagreb remained around the average level, with 93% of the 50-year average precipitation for the area [83]. In terms of number of sunny hours, northern Croatia had around 1800-2000 sunny hours in 2015 [75], while Zagreb's 30-year average is 1898 [84]. Climate conditions are critical when analysing energy systems and in this particular case, higher average temperature might cause higher electricity consumption for cooling, while high number of sunny hours impacts the solar electricity production. However, all the major weather conditions factors for 2015 are approximately similar to most of the years in the past and no unusual weather events took place during the year, therefore it can be assumed that 2015 reasonably represents an average year in the future and using the 2015 weather data for modelling future scenarios will not cause any significant or unexpected errors.

4.1.1 Supply side

Focusing on Zagreb's energy system in 2015, it can be characterized as a centralized one with only a few major components, whose technical characteristics can be seen in Table 1. Although the majority of the data can be found on the official websites of HEP, the main Croatian energy production company and TSO, as well as the owner of almost all the energy infrastructure in the country, some data needed to be assumed. For example, as both CHP plants are primarily used to produce heat, hence they do not operate at the full capacity, their electric capacity was set based on the annual electricity production and thermal capacity was then set based on the plant efficiencies.

Finally, boiler capacity was determined as a value needed to meet the rest of the heat production of the entire plant. Network losses are estimated to be 16% for the entire DH system, based on the data from the overview of national heating and cooling efficiency potential [54]. A smaller share of district heating (around 2% of the total production), accounts for smaller systems, usually those that operate on a neighbourhood level or even provide heating for only several buildings within a neighbourhood. Those are not included in Table 1, but modelled separately (DH group 1 in EnergyPLAN).

Table 1. Main information on the energy generation and storage facilities in Zagreb (CHP and boilers are in fact two plants – TE--TO Zagreb and EL-TO Zagreb, but for the purposes of this analysis their capacities are merged)

	Capacity	Efficiency	Fuel	Ref
CHP	144 MWe/166 MWt*	39% / 45%	90% natural gas, 10% fuel oil	[53], [54]
Boilers	696 MW	95%	90% natural gas, 10% fuel oil	[53], [54]
Thermal storage	750 MWh	-	-	[53]

4.1.2 Demand side

Figure 11 shows the demand side of Zagreb's energy system in the year 2015. As typical for cities and densely populated areas, transport takes the largest share of the total final energy consumption, where diesel with 64% and petrol with 28% account for large majority of all fuel consumption in the transport sector. Analysing the industry and individual heating sector, it can be seen how both are largely predominated by natural gas, which makes up half of the industry fuel demand and 80% of individual heating. This is due to the relatively well-developed natural gas distribution network, which today reaches 60-80% of the households, excluding those connected to district heating network [85]. Looking at the numbers more deeply, it can be seen that district heating represents around 38% of the total heat demand today. Also, industry has the smallest share among all sectors, mostly because other sectors are much larger and represent the energy consumption of over 700,000 consumers.

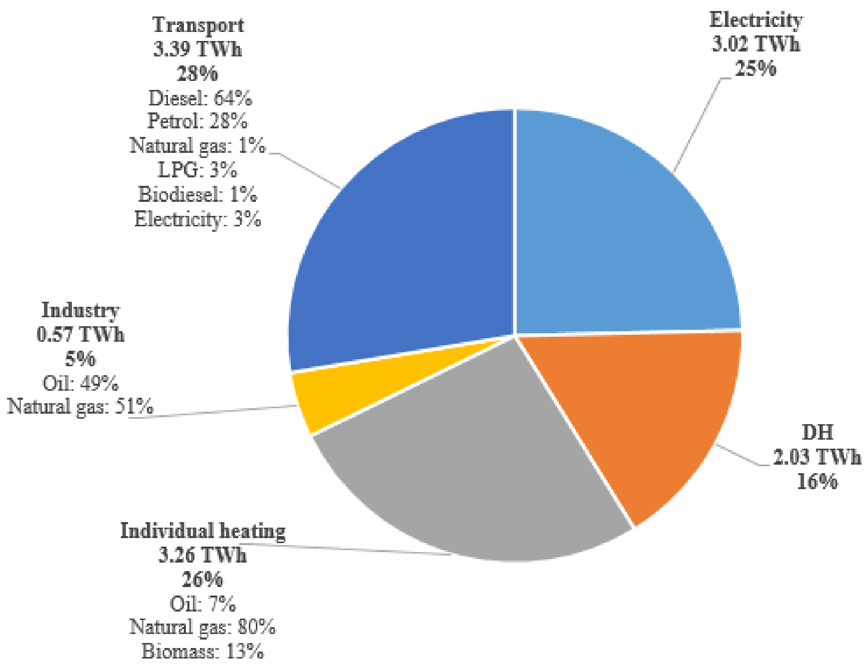

Figure 11. Final energy consumption in Zagreb in the reference year [55]

Furthermore, there are two important assumptions in the Reference scenario. First, as the city itself does not produce a sufficient amount of electricity to be self-sustained, it largely depends on electricity import, as already mentioned as one of the largest problems in Section 1.2. This import is modelled as a condensing mode power plant fuelled by natural gas, in order to give a better representation of the actual amount of fuel and CO_2 emissions consumed and produced due to Zagreb's electricity demand. Choosing natural gas as a fuel is based on the fact that all the major CHP plants and condensing mode power plants in Croatia are fuelled by natural gas and the average Croatian CO_2 emission factor (tCO_2/kWh of PES) is at the same level as the emission factor of natural gas (10% difference) [86]. To simplify the modelling process, this is assumed as acceptable, as it does not cause any significant differences in the conclusion from the results. Therefore, the only difference appearing is in fuel consumption and CO_2 emissions. As future scenarios are modelled as self-sustained, this also gives a better ground for comparing them with the Reference scenario.

Second, Zagreb is a home of by far the largest airport in Croatia, serving around 2.5 million passengers with more than 40,000 flights each year [87]. Including this airport in the Reference system would cause a significant increase in fuel consumption and a need for a more comprehensive approach in the transition of the aviation sector in future scenarios (which could be a topic for itself), it was decided to exclude the airport from the model of a current energy system in Zagreb.

4.1.3 Validation

Once the input data for the reference scenario is defined, its results from the EnergyPLAN model can be compared with the available official data from the literature. This serves as a validation of the data, modelling approach, assumptions and all the applied methods in general. When validated, data sources and methods can be used for other scenarios as well.

Usually, EnergyPLAN modellers primarily use fuel consumption and CO_2 emissions to validate their models. In this case however, information on CO_2 emissions on a city level does not exist as such, but only the national level emissions. Scaling that figure down to the city level is possible, however it would require additional assumptions which needed to be somehow validated themselves, but still could lead to unreliable results. For example, taking CO_2 emissions per capita does not take into account the amount of energy actually produced in the city, but only the average amount on the national level, hence does not provide a relevant level of accuracy. Similar conclusions can be obtained for using population or GDP proportional CO_2 emissions. Therefore, CO_2 emissions are not included in the validation here.

Another option for validating the results is by comparing the total consumption of each fuel. In the case of Zagreb, there are no data on the total final fuel consumption that includes both consumer sectors and energy plants. Also, the energy plant operator only gives the share of each fuel used (which is sufficient for creating an EnergyPLAN model), but not the exact figures. This implies that respective fuel consumptions could not be compared either.

The next possible solution is to compare sectoral fuel consumptions. Although this comparison implies that the model perfectly represents the real situation (0% difference in every sector, see Table 2), the fact is that EnergyPLAN does not modify any of the fuel consumption components in the Individual, Transport and Industry sector. This means that the model input values for sectoral consumption are exactly the same as output, and the main purpose of using them is to calculate related CO_2 emissions and costs. Although not completely reliable, this comparison proves that the demand side accurately represent the real situation in the reference year.

The only relevant component left for comparison is energy production from different plants. EnergyPLAN determines the productions based on the demand and available resources, therefore it is an indirect result component. Comparing heat and electricity consumption obtained by the model with the official data provided by HEP [53], very small differences can be seen, which implies that the supply side of the system is accurately represented. Limited validation options, due to not showing any considerable errors, give sufficient foundation to consider the methods, sources and the assumptions reliable for further use.

Table 2. Reference scenario validation

	Reference	EnergyPLAN	Difference
CHP electricity production	0.747	0.75	0.4%
CHP + boiler heat production	1.99	1.98	-0.5%
Households & Services fuel consumption	3.78	3.78	0.0%
Transport fuel consumption	3.44	3.44	0.0%
Industry fuel consumption	0.57	0.57	0.0%

4.2 Future scenarios design

Two future scenarios are developed in this work, in order to answer the question of what are the benefits and lacks of a smart energy system in comparison to a "traditional" renewable energy system. Note that the term "traditional" here is used to describe the concept of an energy system that is 100% based on renewable sources, however does not include technologies that allow cross-sector integration, but observes each energy sector (heat, electricity and transport) separately, as opposed to a smart energy system. The two scenarios developed for the purpose of this analysis are called Traditional Renewable Energy System (TRES) and Smart Energy System (SES). The following subsections give a detailed description of both demand and supply side of each scenario and emphasise the main differences between them.

4.2.1 Defining the main criteria

Although fundamentally different, both scenarios have the main criteria in common. The main reason for that is to allow a fair comparison ground, i.e. to not give a competitive advantage or disadvantage to any of the scenarios, as the main goal of this analysis is to assess which scenario performs better in terms of both technical and economic aspects of an energy system. Those criteria have also been used as the main guideline when designing scenarios, i.e. the main requirements that have to be fulfilled. The five main criteria are as follows:

1. 100% renewable heat and electricity production and fossil-free transport and industry sectors
2. Sustainable use of biomass of 2.876 GWh (population proportional national potential from [88], also used in other studies such as [89])
3. Energy system is considered isolated, i.e. operated in an „island mode" (no interconnections with neighbouring systems)
4. The system can balance itself – no critical excess electricity production (CEEP) and no critical import demand in any hour throughout the year
5. Technologies used in modelling the supply side are technically feasible in the context of the city of Zagreb

If a scenario does not meet a certain criterion, it is considered as technically unfeasible. The following subsections elaborate more in detail on the actual technical design of each scenario, giving the input values for EnergyPLAN model, both on the demand and supply side of the system.

4.2.2 Modelling the demand

To allow a fair comparison, heat, electricity and fuel demand for the year 2050 are quantitatively identical in both the TRES and the SES scenario, although there are some structural differences, e.g. in terms of fuels used in a certain sector or individual/district heating share. Those differences are specially emphasised in this subsection.

Predicting electricity demand is quite a challenging task, given the fact that it is very much sensitive to changes in multiple variables, such as population, economic development (GDP), industrial growth, customer behaviour and technological changes (e.g. introduction of new energy efficient appliances or maybe the opposite-new appliances that are very energy intensive). Therefore, the electricity demand for the year 2050 is estimated using multiple references; either studies on the EU level such as Heat Roadmap Europe [61] and the Stratego project [61], or energy plans of other cities and regions in Europe, that give similar estimations. Heat Roadmap Europe and Stratego both predict around 25% increase in electricity demand in Croatia until 2050. However, studies conducted on a more local level, such as Copenhagen Energy Vision [21] and Aalborg Municipality energy plan [22], predict total decrease in electricity demand in residential sector in 2050 of 30-50% and 50% respectively, in comparison to the reference year. The study conducted on the SEE region level [37] also assumes 50% drop in total electricity demand. As Zagreb expects a population drop of around 7% between 2015 and 2050 [37] and it is expected that electric appliances (kitchen appliances, lighting and cooling devices) will become more energy efficient in the future, it is assumed that conventional electricity demand (excluding demand for industry and transport) will decrease by a total of 40% between 2015 and 2050, or 1.45% p.a. However, due to introduction of additional electricity demand from industry (0.286 TWh), as well as the electrification of the transport sector, total electricity demand is expected to drop by only 0.69% or 0.02% p.a. Figure 12 shows the estimated development of electricity demand towards the year 2050. The drop in the conventional demand is caused by increased energy efficiency in that sector, however, growing electrification of transport and industry sector gives an opposite effect, resulting in almost constant demand throughout the observed period.

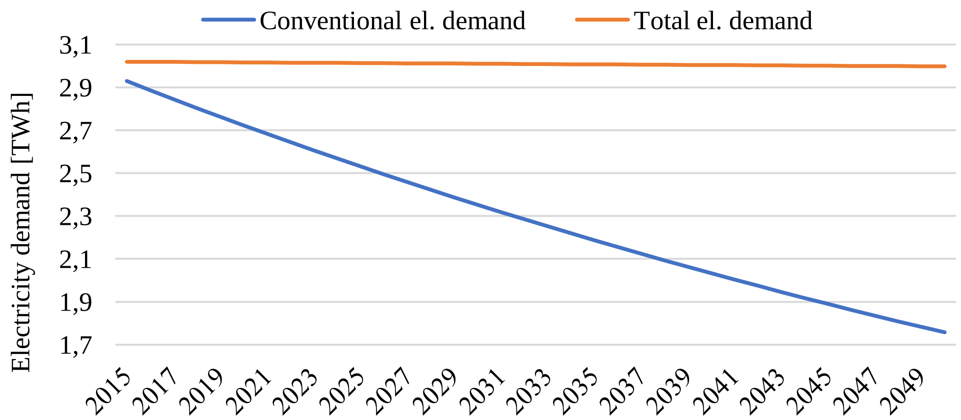

Figure 12. Expected changes in conventional and total electricity demand in the city of Zagreb in the period 2015-2050

Heat demand is estimated following the forecast made by Energy Institute Hrvoje Požar, the largest Croatian research centre in the energy field. In their report on the potential for energy efficiency in heating and cooling sector, they predict 25% drop in heat demand and 60% share of DH in Zagreb by 2030. In this work, it was assumed that the same trend continues until 2050, resulting in overall 52.3% decrease in heat demand and 100% share of district heating in the city. This is mainly the result of increased energy efficiency but also of a drop in the population. The Stratego project gives predictions that some buildings in Zagreb can go from current specific heat consumption of 170 kWh/m2 to 45 kWh/m2 (73.5% drop) if properly insulated [80]. Furthermore, at the country level, it assumes a 40% decrease in total heat demand. This however includes the whole country, meaning also the southern part of the country which has significantly lower heat demand already today. Looking at the data for building characteristics of different types off buildings built in different periods, both in continental and Adriatic Croatia, an average annual specific heat demand is 36.5% lower in Adriatic than in continental Croatia [59] and [58]. To conclude, a total drop in heat demand of 52.3% in Zagreb seems like a fair and reasonable assumption. It is also in line with the paper on the SEE region level [37], that estimates 50% decrease in heat demand by 2050 on a regional level.

Regarding the share of district heating, its benefits in densely populated areas (but also in other areas) have been shown on multiple examples, including the most recent and comprehensive research studies on district heating in Europe (such as Heat Roadmap Europe and the Stratego project). Moreover, some cities already account for an almost 100% share of district heating, e.g. Aalborg, Denmark. To evaluate the role of district heating for a specific case of the city of Zagreb, a simple analysis is carried out. Using a slightly modified Reference scenario, where CHPs are set to use their maximum capacity (in the Reference scenario, a large share of the heat production comes from heat only boilers instead), different shares of the existing individual heat demand are switched to DH, until reaching 100% share of DH.

Figure 13 shows the main indicators of the energy system performance, mainly total costs, CO_2 emissions and primary energy supply, for different shares of DH. It can be seen that all three indicators tend to decrease as the share of district heating increases, meaning that the system with higher shares of DH consumes less primary energy, generates less CO_2 emissions and has lower costs. It is worth noting that all the other characteristics of the system are identical to the Reference scenario, including the total heat demand that remains constant in every step.

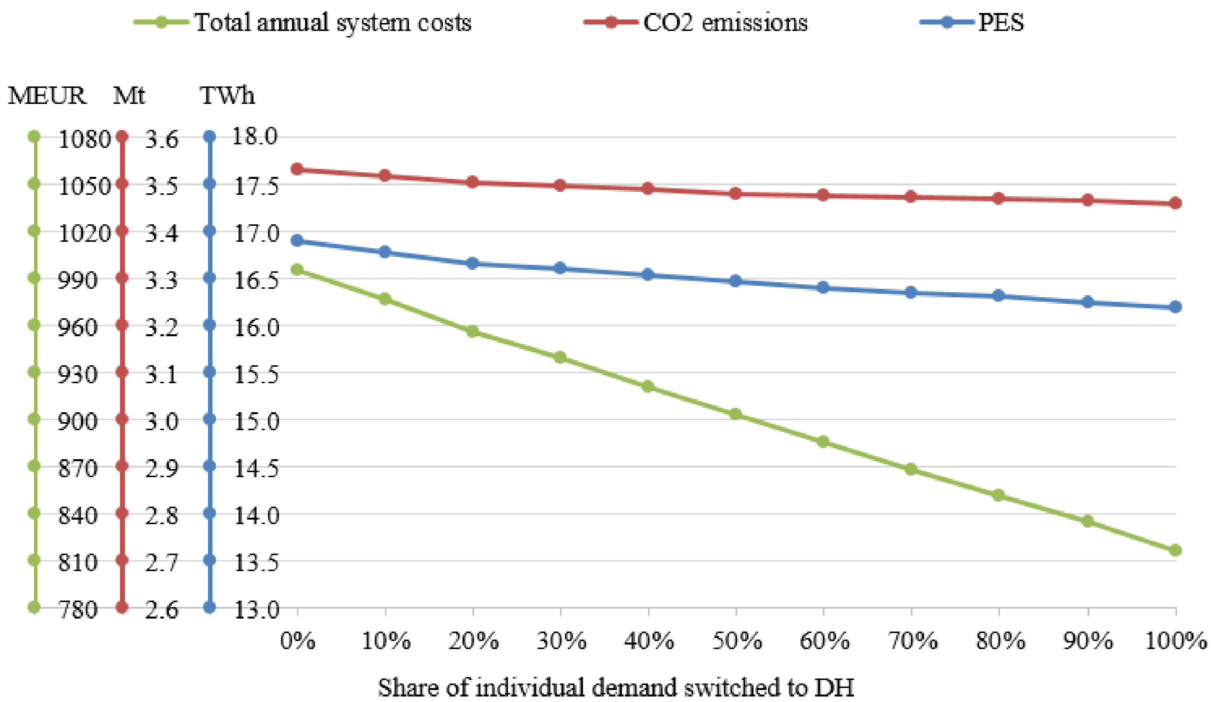

Figure 13. Change in total annual system costs, CO_2 emissions and PES when different shares of individual heat demand is switched to DH. Note that all the other technical properties, including the total heat demand, are identical to the Reference scenario. 0% share represents the Reference scenario, where CHPs are set to use their maximum capacity.

Figure 14 shows one potential way of transitioning to energy efficient DH system in Zagreb. Note that the actual transition is not the focus of this work, however figures obtained for the year 2050 are used as an input when modelling future scenarios (total heat demand in both the TRES and the SES, but share of DH only in the SES).

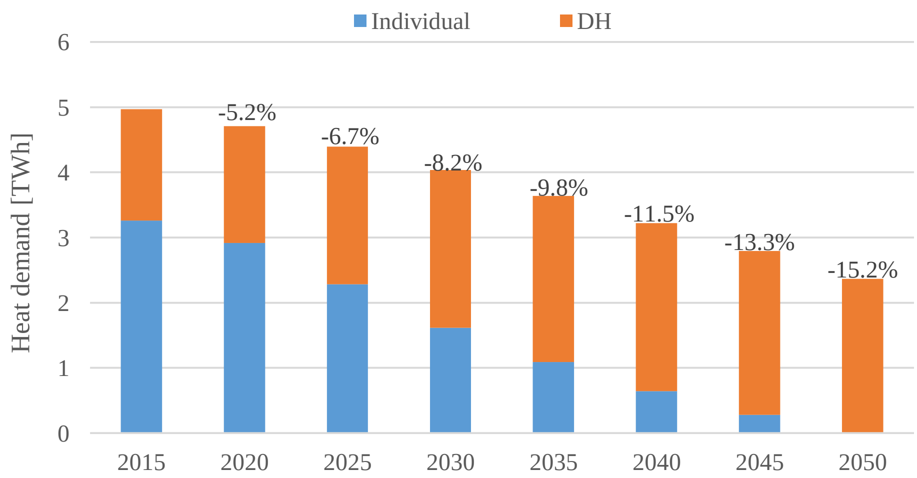

Figure 14. One potential way of a transition towards energy efficient heating sector in Zagreb

The transport demand is firstly modelled for the SES scenario, after which two changes are made in order to adapt it for the TRES scenario. When modelling the transport demand, it is assumed that the number of passenger cars drops by 10% until 2050, due to an increased share of public transportation that could replace some individual transport, improved light-rail system and promotion of a healthier lifestyle through bicycles in the future. This goes in line with, for example, study in [90], that emphasises the importance of reduced transport demand in future energy systems and predicts 20% reduction in transport demand.

Furthermore, 90% of all passenger cars fuel demand, as well as all mopeds and buses fuel demand is switched to electricity. Electric vehicles industry is growing faster than ever and the technical potential of highly electrified passenger transport sector has been proven in numerous studies, including the one based on analysing different vehicle profiles over the three-week period in Germany [90]. The study concluded that the technical potential of EVs for that case is 87% penetration. Medium and heavy transport sector are also highly electrified. It is assumed that 75% of all goods-vehicles demand is shifted to electric (50% are medium-heavy vehicles that can be electrified directly and 25% is modal shift from heavy to medium-heavy). Although the heavy transport sector is one of the biggest challenges towards sustainable transportation today, some studies suggest that electric vans with a proven range of 160 km can meet all the logistics requirements within cities [91]. Finally, the rest of the passenger cars and goods-vehicles fuel demand is replaced by electrofuels, another component of a smart energy system that allows cross-sector integration – in this case integration between electricity and transport sector. The most comprehensive overview of benefits and potential of electrofuels in future energy system was conducted by Ridjan et al. [92].

There are the two main differences between the TRES and SES scenario regarding the transport demand. While in RES scenario all the electricity demand is dumb charge, in the case of the SES scenario, it is equally divided by dumb and smart charge. The difference between the two is that smart charge allows flexible charging schedule, whereas dumb has fixed charging operation, which makes it less suitable for utilizing electricity production from fluctuating sources. Another difference is that instead of electrofuels, RES scenario utilizes biofuels instead, in order to make a differentiation and to keep electrofuels as a characteristic of smart energy systems exclusively.

The last segment of the demand side is industrial fuel demand. Two scenarios are identical in that segment and four fairly simple assumptions have been made. First, it was assumed that the overall improvement in energy efficiency is levelled out by an increased industrial activity, resulting in an unchanged total demand. A study on energy efficiency potential in industry and possible policy mechanisms [93] shows a broad range of possibilities for energy savings in the industry sector and estimates that certain measures can lead to 3-10% savings by 2030. Furthermore, 50% of the demand is replaced by electricity, based on the fact that induction furnaces are being used more often and they can sufficiently replace oil or gas-fired furnaces, hence significantly reducing fuel consumption and saving CO_2 emissions [94]. As the last step, the remaining oil demand was replaced by biomass and natural gas demand by biogas, resulting in final consumption of around 0.14 TWh of both biomass and biogas and 0.29 TWh of electricity (manually added to conventional electricity demand).

As the change in all aspects of the energy demand are defined, the next logical step is to focus on the supply side of the scenarios. The following subsections give a detailed description of that and emphasise the main differences between them.

4.2.3 SES and TRES scenario supply side design

Supply side design includes major differences between the SES and TRES scenario. It is important to emphasise again that the main goal of making this analysis is to investigate what are the differences between the two scenarios in terms of energy consumption, costs and environmental impact, as well as why do those differences appear. Hence, the scenarios have to be conceptually different and many assumptions are made in that sense. In practice, optimality may lie in between the two.

The structure of this subsection is as follows: first, the methodology of sizing the EnergyPLAN scenarios is described in order to provide a better understanding of how energy systems are designed. In this case, this description refers to the SES scenario, whereas TRES scenario is obtained by implementing various changes in the SES scenario. Next, the components that are the same in both scenarios are then listed and it is explained why that is important for the comparison. The third part is the explanation of the concrete differences between the scenarios - those are essentially the fundamental differences between a smart energy system and a “traditional” renewable energy system, that does not include smart interactions defined earlier in this work. Lastly, the final structure of the supply side of both scenarios is given, which enables the reader to compare every individual component.

Modelling an energy system that includes a large variety of energy sources among different sectors is a rather complex process. In order to describe it in a logical and systematic way, Figure 15 is created. The entire process is led by the five main criteria defined in Subsection 4.2.1; the energy demands need to be met, CEEP cannot occur, only renewable technologies feasible in the context of Zagreb can be used and biomass consumption needs to be maintained at the sustainable level.

The process starts with introducing the technologies of a limited size, i.e. the technologies that are either already planned to be built in reality or whose maximum potential is estimated based on other research and publications. Typically, the size of those technologies is not sufficient to meet neither the entire electricity nor heating demand, but they are a good starting point before adding other technologies. Their capacity is set to maximum possible in a system’s context and it cannot be altered.

In this case, several sources are used to determine the size of technologies of a limited size. The potential for geothermal heat is adopted from [95], a study on utilizing geothermal potential in Zagreb as an important factor in economic development. It is also in line with some studies that provided maps on geothermal potential in Croatia, such as the one made by Energy Institute Hrvoje Požar [96]. Geothermal power capacity is based on the insights from the same study, but also on the fact that the first two Croatian geothermal power plants with capacities of 10 MW and 17 MW respectively, are currently being built in Velika Ciglena [97], 70 km from Zagreb and Draškovec [98], 80 km from Zagreb. Therefore, further research in this field is expected to reveal new sources, but also bring technologies that can efficiently utilize lower temperature geothermal sources.

The waste potential is estimated according to [99], which states that there was 392,000 tons of municipal solid waste produced in Zagreb in 2015, of which 67% is biodegradable. The current development plan is to make a waste incineration plant that would utilize 400,000 tons of waste each year. However, the reference states that it would be optimal for Croatia to have 4x150,000 tons waste-to-energy plants in Croatia, assuming one is located in Zagreb. Therefore, it is assumed that 150,000 tons of waste (0.31 TWh) can be utilized for energy production in Zagreb each year.

Analysing the industrial excess heat potential, the Stratego project estimates 19 PJ of industrial excess heat in Croatia and their map of excess heat facilities shows that a large majority of such facilities is in the continental part of the country [78]. However, the map shows only the facilities currently included in the CO_2 quota trading system, hence many facilities are not included. Authors in [100] estimated an industrial waste heat potential of 34 GWh p.a. for a case of Sønderborg, a Danish municipality around 10 times smaller than Zagreb, in terms of population. Zagreb accounts for around one fifth of the value of industrial production sold in manufacturing [75] and it includes a variety of process industries such as food and beverages, pharmaceuticals, chemicals and petrochemicals, non-metallic minerals etc. Based on all of this, but also because of the lack of data and uncertainty of assumptions, it is estimated that 0.2 TWh/year of industrial excess heat is available today in Zagreb.

Finally, run-of-river hydro production is adopted from [85], a study on RES potential in Zagreb, while thermal storage size is estimated based on the current storage system and the expected expansion of the DH grid.

The second step is meeting the heat demand by adding heat production technologies. It starts with heat pumps as their capacity needs to be maximised – because they are a link between heat and electricity sector and do not utilize any fuel, hence they are the most efficient heating technology. They are added until their heat production stops increasing, which is a function of the available excess electricity. Normally, in the first steps, before adding high capacities of fluctuating technologies, heat pumps do not achieve large sizes. CHPs are added next, as they are another link between the two sectors. The production from CHPs stops increasing when either demand for heat or electricity is met (due to the regulation strategy that in this case is set to meet both heat and electricity demand). Therefore, in the first alterations, one of the demands might end up being met by heat pumps and CHPs, however later check on biomass consumption sustainability could indicate that CHP capacity needs to be reduced. After adding the CHPs, any residual heating demand is met by heat only boilers.

The process of adding intermittent RES for electricity production (namely PV and CSP) described in Figure 15 is an iterative process with a goal of determining the combination of technologies that gives maximum electricity production in this case. It starts with increasing the capacity of PV until CEEP appears and then recording the electricity production when having PVs only. The next step is to reduce PV capacity by a certain amount (any logical amount, e.g. 10% of the original capacity) and add CSP capacity until CEEP occurs again (while PV is kept fixed). This process repeats by reducing the PV capacity further, adding more and more CSP and recording every electricity production from different combinations of technologies. The final step is having only CSP in the system, as opposed to the first step. The combination with the highest capacity is the one used in the further modelling steps.

If electricity demand is not met at this point, a sufficient amount of condensing mode power plants capacity needs to added. The last step is testing if the biomass consumption is at or below the sustainable level. If that is not the case, the process starts over by reducing power plant and CHP capacity (the only technologies that utilize biomass fuel), adding more large-scale heat pumps (now a larger amount can be added because of more intermittent electricity in the system and consequently, more intermittent capacity can be added because there are more heat pumps to utilize it). The process repeats until all the requirements are met.

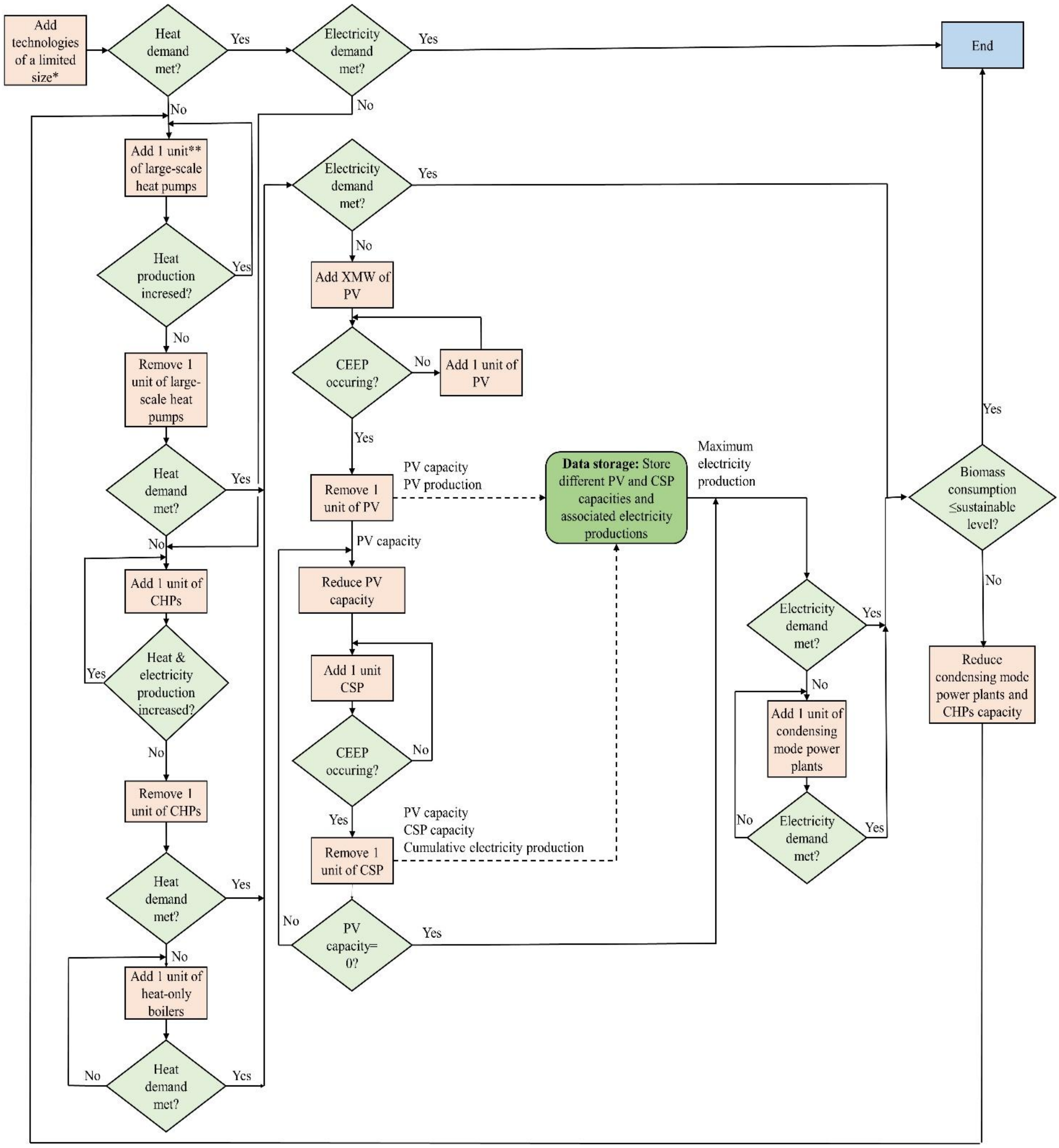

Figure 15. Decision chart behind the sizing methodology of creating an EnergyPLAN model. The chart follows the methodology behind creating the models within this work, however it can generally be applied in any case, although it might require minor modifications (e.g. incorporating technologies not applicable in the case of Zagreb, such as wind power).

**Technologies of a limited size are those whose capacities are either taken directly from references (already planned to be built) or whose potential is estimated based on references. They are highly case dependent. In this case, technologies of a limited size are (and they are the same in both the TRES and SES scenario): geothermal heat, waste heat, industrial excess heat, thermal storage, geothermal power plants and run-of river hydro plants.*
***1 unit of capacity of a certain technology is any relevant size that when added/subtracted makes a noticeable difference in the system. It is highly dependent on the overall size of the system and the technology observed. It is also dependent on the number of alterations (e.g. first alterations usually require lower level of finesse than the latter ones, therefore the unit size can be larger)*

Following the assumptions and steps presented in Figure 15, the SES scenario is created. The structure of the SES scenario was the basis for creating the TRES scenario. The main guideline when making modifications for TRES scenario was to create a system that utilizes all the existing renewable technologies technically feasible in the context of the city of Zagreb, however does not include technologies and concepts that allow cross-sector integration. As already mentioned in Subsection 4.2.2, heat, electricity and fuel demand are quantitatively identical in both scenarios, meaning that the same measures in energy efficiency are implemented. Furthermore, the following three characteristics are the same in both scenarios:

- Capacities of the technologies of a limited size (geothermal heat and electricity, waste and run-of-river-hydro, thermal storage) – this is to ensure that both scenarios include capacities that are either already planned to be built or likely to be built in the future in any case. This excludes industrial excess heat, which is considered as a technology that links different sectors, hence it is not included in the TRES scenario.
- All the electricity supply technologies, meaning there is no technology used in one scenario that is not used in another. Capacities of some technologies are, however, somewhat different.
- Efficiencies of all technologies.

The main differences between the scenarios are as follows:

- The TRES scenario does not include DH expansion, meaning the share of DH remains the same as in the Reference scenario.
- No smart charging in transport, i.e. no vehicle-to-grid (V2G). Although the TRES scenario includes electrification of the transport sector, which is as such a connection between transport and electricity sector, it is assumed that EVs will be introduced on a large scale in any case, hence are included in both scenarios.
- No large-scale heat pumps, a technology that links electricity and DH sector.
- No industrial excess heat.
- No electrofuels, a technology that links fuel production and electricity sector (biofuels are used instead).
- Different regulation strategy – while the SES scenario uses the strategy of balancing both heat and electricity demand, the TRES balances only heat demands. The latter strategy is often used in today’s systems, whereas the first one is a characteristic of smart energy system. Again, this was implemented to introduce another level of distinction between the two systems and to emphasise the importance of the regulation strategy.
- Different capacities of technologies of an unlimited size.

Finally, Table 3 shows the final supply side of both the TRES and SES scenario. As mentioned earlier, some technologies are not included in the TRES scenario, therefore their capacity is not shown in the table.

Table 3. The final composition of the supply side of the TRES and SES scenario

Technologies of a limited size		
Heating	**TRES**	**SES**
Geothermal heat	0.23 TWh	0.23 TWh
Waste (input)	0.3125 TWh	0.3125 TWh
Thermal storage	5 GWh	5 GWh
Electricity	**TRES**	**SES**
Geothermal power plants	33 MW	33 MW
Run-of-river hydro	170 MW	170 MW
Technologies of an unlimited size		
Heating	**TRES**	**SES**
CHPs	45 MWe/ 56MWt	210 MWe/ 262 MWt
Large-scale heat pumps	-	120 MW
Boilers	234 MW	239 MW
Thermal storage	0.75 GWh	5 GWh
Electricity	**TRES**	**SES**
Condensing mode power plants	635 MW	271 MW
PV	151 MW	510 MW
CSP	103 MW	295 MW
Battery storage for EVs	-	350 MW/2GWh*
Fuel	**TRES**	**SES**
Gasification plant	-	16 MW**
Chemical synthesis	-	51 MW**

** Capacity set to necessary minimum to meet the V2G requirements*
*** Set by EnergyPLAN, needed to meet the biogas and electrofuel demand*

Due to the fact that some major differences have been introduced in comparison to the SES scenario, and in order to meet all the requirements defined in Subsection 4.2.1, capacities of some technologies are significantly different. It can be seen that TRES scenario is much more based on centralized electricity production from condensing mode power plants and has lower capacities of intermittent renewables, namely PV and CSP.

Chapter 5 shows what impact those differences have on the overall performance of the two systems and what are the concrete benefits that the smart energy system brings, in terms of energy consumption, sustainability and the total system costs.

5 Results

This chapter quantifies advantages and disadvantages of a smart energy system (SES scenario) in comparison to a "traditional" renewable energy system (TRES scenario) for Zagreb. In some aspects, the future scenarios are compared with the Reference scenario as well. The main results from the modelling in EnergyPLAN are given in the first section, while the second section analyses the sensitivity of economic performance of the two scenarios, when some critical variables are changed.

5.1 REF *vs* TRES *vs* SES - results and comparisons

This section gives an in-depth description of the differences between the RES and SES scenarios, which represent two possible alternatives for the energy system development towards 2050, but also compares them with the Reference scenario, i.e. the existing system in the year 2015. The systems are compared based on the three result components – namely PES, energy production (heat and electricity) and total annual system costs. Additionally, hourly electricity production is also shown in order to describe the behaviour of the two future systems on an hourly basis.

5.1.1 Primary energy supply

Looking at the PES levels shown in Figure 16, the first observation is how fuel consumption significantly drops in both the TRES and SES scenarios in comparison to the Reference, respectively by 62% and 64%. This is due to the three main reasons. First, energy efficiency measures in the heating and electricity sector causes a direct decrease of 52% in the heating demand and 40% in the conventional electricity demand, hence reducing the fuel demand needed to generate now avoided demand. Next, relatively inefficient individual heating boilers are replaced by small-scale heat pumps in the TRES scenario and DH in the SES scenario, achieving higher overall efficiency of the heating sector. Finally, both district heating and electricity production are switched to renewable technologies that are characterised by higher efficiency than power plants burning fossil fuels. Note how neither the TRES nor SES scenario include any fossil fuels.

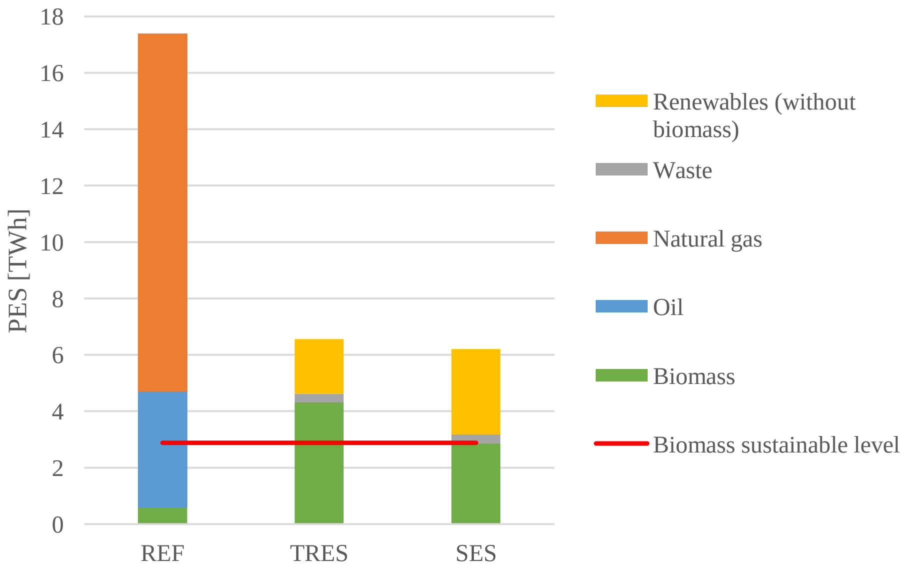

Figure 16. Primary energy consumption in the three scenarios (Note that dashed red line represents a sustainable biomass consumption level of 2.876 TWh)

Comparing the TRES and SES in this sense, there are the two main differences that represent benefits of a smart energy system. Except having 5% lower total fuel consumption than the TRES scenario, the SES scenario utilizes sustainable amounts of biomass – a total of 2.86 TWh, which is just slightly below the defined sustainable level of 2.88 TWh. The TRES scenario, on the other hand, utilizes 4.31 TWh of biomass, being around 50% above the sustainable level. This makes the TRES scenario technically unfeasible and unsustainable, since it does not meet one of the six main criteria defined in Subsection 4.2.1. The reason for this lies in the fundamental definition of a smart energy system – an interplay between different aspects of an energy system allows a much higher integration of fluctuating RES, while maintaining system stability (no excess electricity production) and reducing the demand for electricity from power plants, which essentially combusting only biomass.

5.1.2 Electricity & heat production mix

Figure 17 serves to illustrate the difference in the diversity of electricity production sources by scenarios. Although the conventional electricity demand is reduced in both the TRES and the SES scenario by implementing energy efficiency measures, the total demand in those scenarios is respectively 12% and 34% higher than in the Reference scenario, which causes higher total electricity production. The reason for that is the additional demand that comes from electricity for transport, heat pumps and, in the case of the SES scenario, electrolysers for electrofuels production.

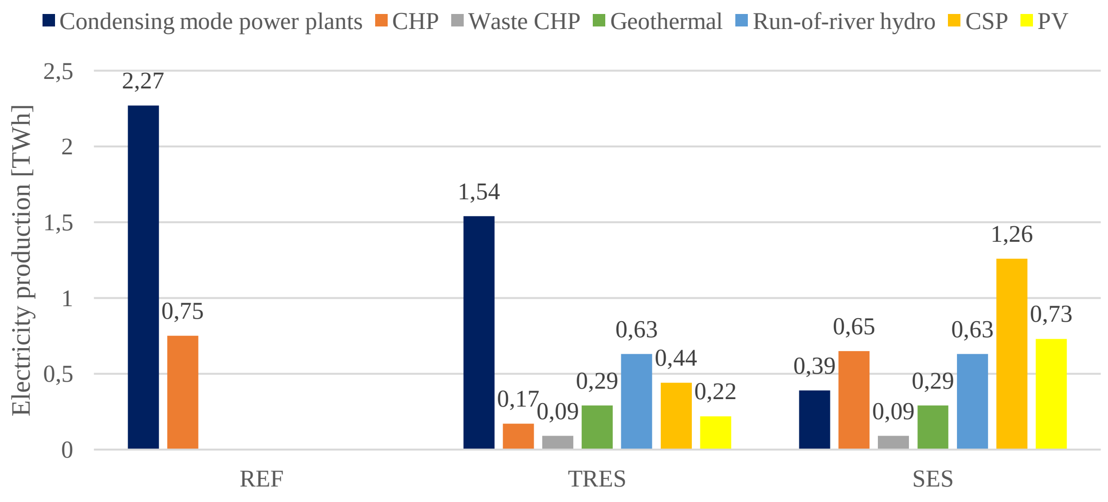

Figure 17. Electricity production mix by scenarios

While in the Reference scenario all electricity production comes from only two sources – condensing mode power plants and CHPs, the other two scenarios are much more diverse in that sense, having seven main electricity production technologies each. In the TRES scenario, 46% of the total electricity production comes from condensing mode power plants, which makes this scenario fairly traditional, as it is still largely based on stable electricity production. The productions from waste CHP, geothermal and run-of-river hydro are identical in both scenarios, as those are based on estimations of available resources or already planned capacities to be built in the future and by no means distinguish a smart energy system from any other concept. Electricity production from CHPs is, however, almost four times higher in the SES than in the TRES scenario, which is mainly due to significantly higher district heating demand in the first scenario. CSP and PV production are both around three times higher in the SES scenario, due to the reasons mentioned earlier. Although the SES scenario is largely based on solar technologies, whose intermittency might be challenging to predict in the future years, none of the technologies has a share larger than 31%, which makes this scenario much more beneficial in terms of energy security.

The heat production mix in district heating, shown in Figure 18, gives similar conclusions as those on the electricity production side. The Reference scenario is largely based on boilers (57% of the total heat production), since it is set to be operated balancing only heat demand. The rest of the demand comes from CHPs. CHP production in the SES scenario is almost the same as in the Reference, however boiler production is 92% lower in this scenario. The rest of the total district heating demand in the SES scenario, which is overall 16% higher than in the Reference scenario, is met by newly introduced waste CHP (9% of the total demand), large-scale heat pumps (34% of the total demand), geothermal heat (10%) and industrial excess heat (9%).

Furthermore, there are two main differences between the TRES and SES scenario. First, the total heat demand in the TRES scenario is around 60% lower, as it was one of the assumptions of this scenario that no further expansion of district heating will be implemented. Second, the SES scenario includes a large share of production coming from large-scale heat pumps, as well as industrial excess heat, whereas those technologies are not included in the TRES scenario. Again, it was one of the assumptions of the TRES scenario that it does not include large-scale technologies that represent a link between different energy sectors (such as large-scale heat pumps), in order to make a clear distinction between the two scenarios.

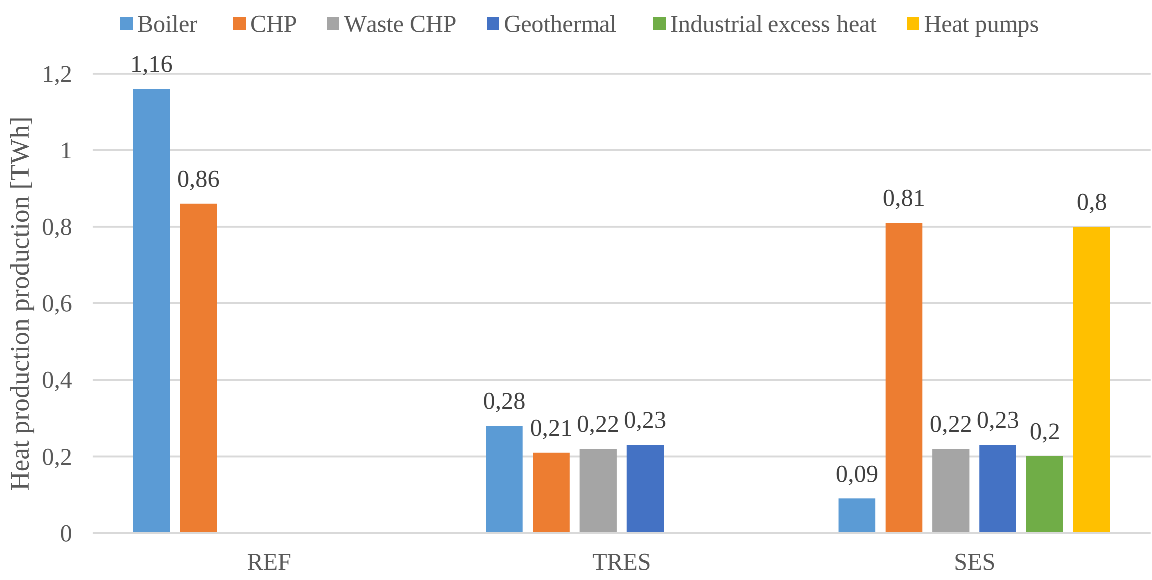

Figure 18. Heat production mix in the district heating system by scenarios (individual heating production in the REF and TRES scenarios is not included here)

5.1.3 Total annual system costs

The cost structure for each scenario is represented in Figure 19. While the TRES and the SES scenarios have approximately the same total costs and almost identical cost structure, they both significantly differ from the Reference scenario. As this scenario is heavily based on fossil fuels, variable operation and maintenance (O&M) costs (mainly fuel costs) represent 74% of the total of EUR 995 million in this case. The TRES and SES scenarios are on the other hand very investment intensive, with investment costs representing 64% and 68% of the total annual costs respectively. The reason why the SES scenario has around 1% higher total costs than TRES (about EUR 13 million) is mainly because of the very high investment costs of CSP technology, which represents by far the largest individual investment costs in the SES scenario. The impact of CSP investment cost variation on the total costs of both scenarios is analysed in Section 5.2.

Another major difference between the Reference and the two future scenarios is in the CO_2 emissions costs. While both the TRES and SES scenarios are entirely based on renewables, hence have zero emissions, the Reference scenario results in total of 3.69 Mt of CO_2 emissions each year. Note how without the CO_2 costs (representing around 11% of the total costs in the Reference scenario), total system costs of the Reference scenario are in fact 1.4% lower than in the SES scenario and around the same as in the TRES scenario. These results of cost distribution in all scenarios are in line with some other similar studies of developing renewable and smart energy systems, such as those in [37] or [22], who also determined that the total costs of renewable energy scenarios are lower or at the same level as fossil fuel scenarios and are very investment intensive.

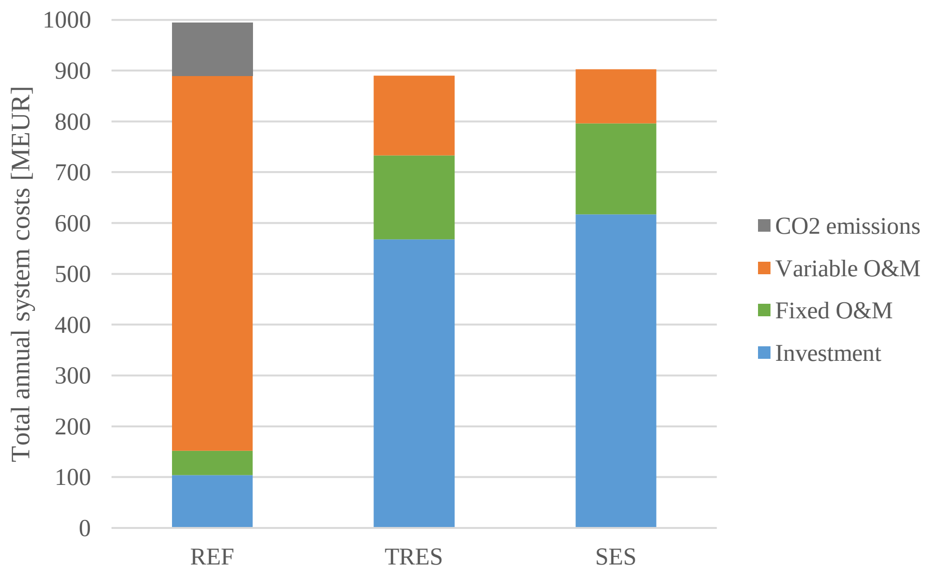

Figure 19. Total annual system cost breakdown – including investment, O&M and CO_2 emissions costs

5.1.4 Hourly electricity production

The differences in hourly electricity production between the TRES and SES scenarios, both on a winter and a summer day, are shown in Figure 20. It is important to mention that some differences in the demand between the two scenarios, although observing the very same days, are due to several influencing factors, such as different total electricity production, EV charging profile, heat pumps and electrolysers. In each of the four daily distributions, peak demand occurs during the day, more specifically around 8 in the morning. This is the time when a large amount of people starts their days, turning on the lights and various appliances, therefore high demand is expected.

Furthermore, there are three major conclusions that can be observed from Figure 20. First, the dominant unit in TRES scenario, both in winter and summer, is condensing mode power plant, generating more than 50% of electricity demand in all hours. Because this system is not able to cope with large amounts of intermittent electricity, a high power plant capacity is added. On an annual basis, this kind of hourly production results in an excessive utilization of biomass, as power plants burn only biomass. Next, CHPs play an important role in the SES scenario, especially on a winter day. The reason why this is not the case in the TRES scenario is that DH demand is much lower and CHP is set to meet only heat demand. On a summer day in the SES scenario (where CHPs balance both heat and electricity demand), CHP production is low because there are other technologies to meet the majority of the heat demand that occurs during the summer (mainly domestic hot water), primarily heat pumps. Lastly, solar technologies (CSP and PV) generate around 70% of electricity demand in each hour during the day in summer in the SES scenario. In some of these hours, CSP utilize 100% of its capacity. CSP also plays an important role on the winter day in the TRES scenario, with approximately 25% of total demand in some hours. As their capacity is lower in the TRES scenario, their impact is also much smaller.

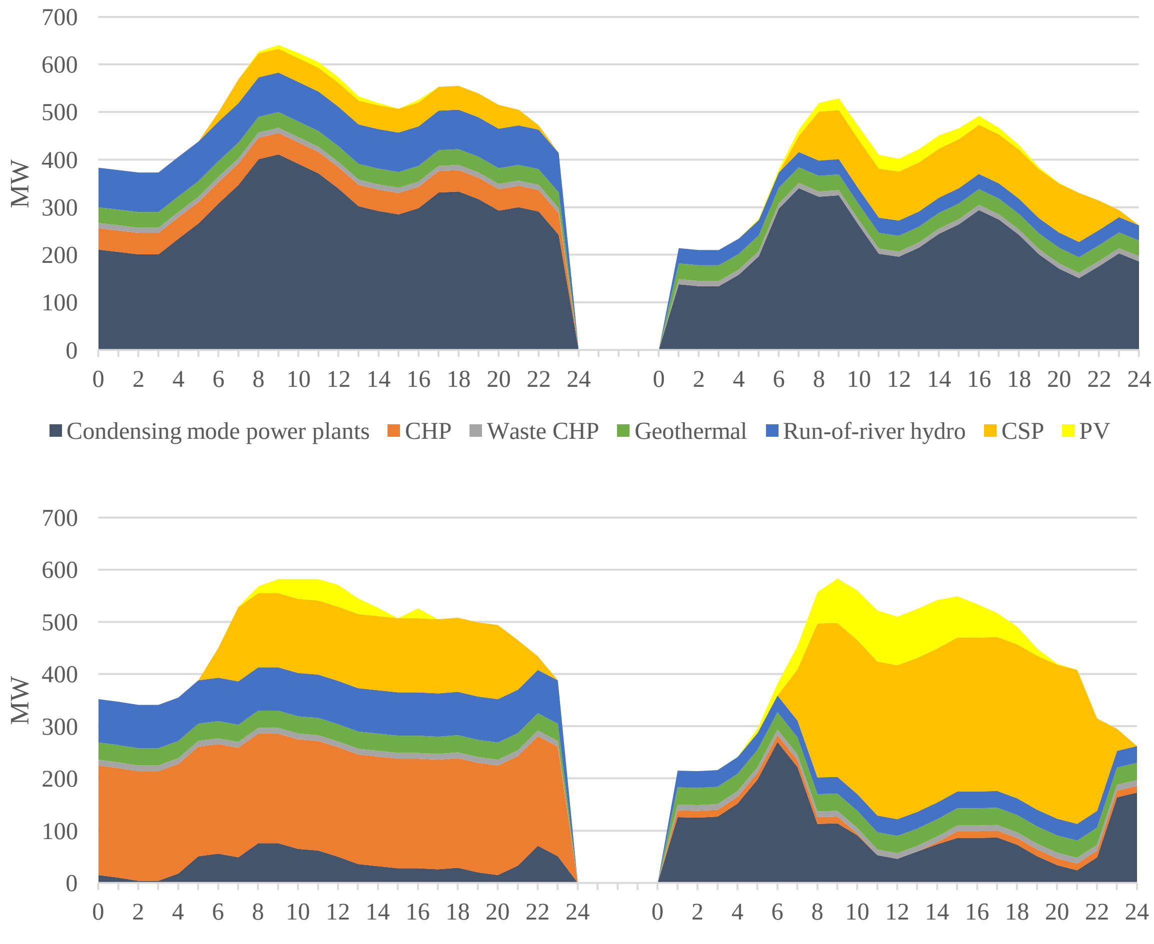

Figure 20. Hourly electricity production in the TRES scenario (upper) and the SES scenario (lower). Left side of both diagrams shows one day in mid-January and right side shows one day in mid-July

Duration curves for electricity production technologies are shown in Figure 21. This essentially shows two things – the maximum and minimum electricity generation of each technology and the number of hours in which each technology actually generates electricity. The main difference between the TRES and SES scenarios is again in condensing mode power plants – whereas in the SES scenario they are shut down for around 50% of the year, in the TRES scenario they are the major producer in almost every hour throughout the year. Maximum electricity production from condensing mode power plants in the RES scenario is 27% higher than maximum production of all the other technologies together. In the TRES scenario, CHPs show much larger duration than in TRES, which is due to the fact that they do operate in some hours during the summer, meeting the residual hot water demand that other technologies cannot meet. It is also worth noting how the duration of PV and CSP production is identical in both scenarios, however with different magnitudes. This is because distribution curves, that simulate solar radiation, are the same in both scenarios and the only difference is in capacity. Finally, geothermal and waste CHP are set to give a constant production throughout the year, whereas characteristics of hydro power plant are also the same in both scenarios.

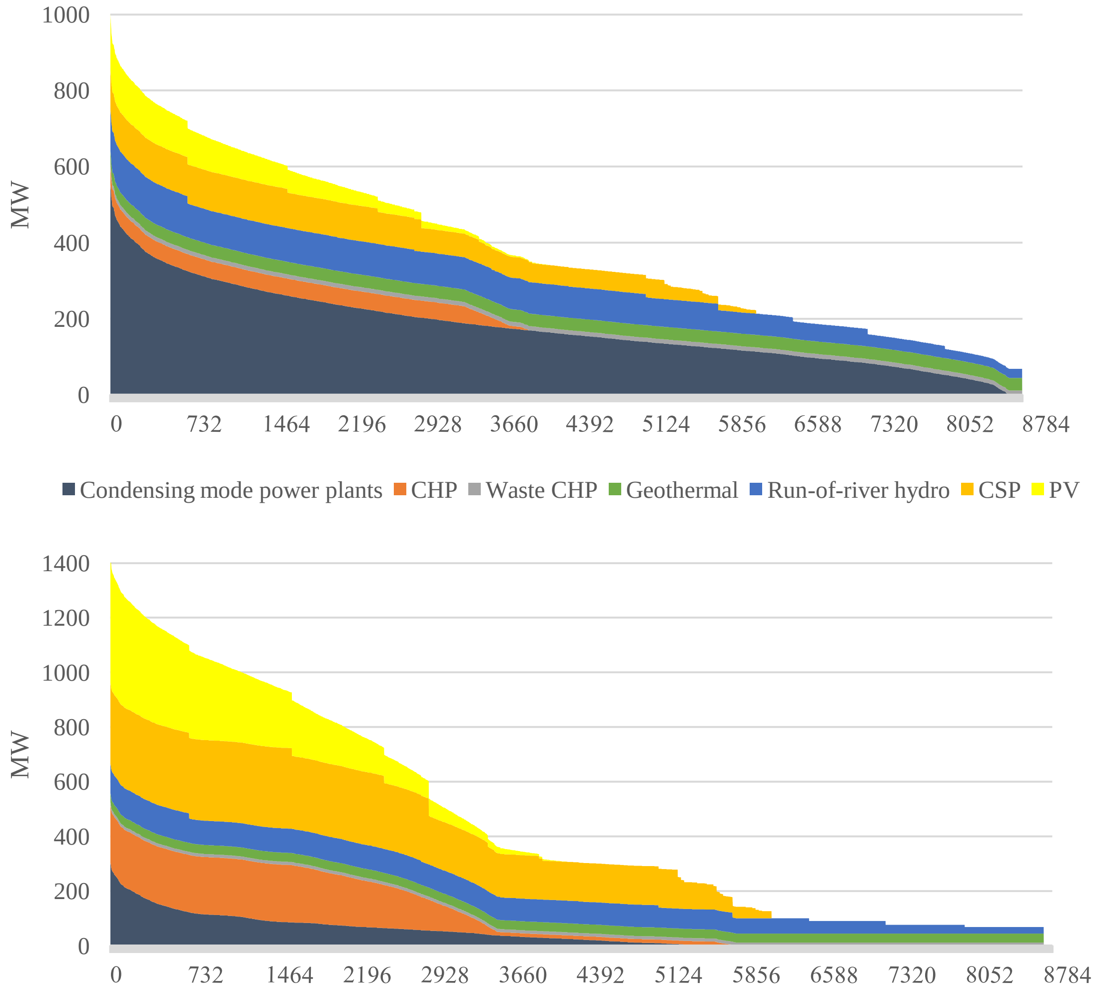

Figure 21. Duration curves for electricity production technologies in Zagreb in the TRES scenario (upper) and SES the scenario (lower) - the step along the horizontal axis (732h) corresponds to a number of hours in an average month in a leap year

So far, focusing on the three main components of the results, namely PES (with a special emphasis on biomass consumption), total system costs and electricity production mix, the differences between the TRES and SES scenarios are shown. Both scenarios are cheaper and have lower fuel consumption than the reference system, however SES performs better in terms of PES, with 5% lower total PES and 34% lower biomass consumption, while TRES is marginally cheaper, with 1% lower total annual system costs. The next section focuses on analysing what happens to some of those factors in both scenarios, when the most important variables are gradually changed.

5.2 Sensitivity analysis

Four key variables are identified to have the largest impact on the scenario results – discount rate, biomass price, solar technologies' investment costs and electricity production from intermittent RES. The first three variables only have the impact on the total annual system costs and this is analysed in Subsections 5.2.1, 5.2.2 and 5.2.3 respectively. Electricity production from intermittent sources apart from total costs, also influences the level of CEEP and fuel consumption. This analysis is shown in Subsection 5.2.4. and is followed by the overall conclusion of the sensitivity analysis. Each subsection gives the reasoning for choosing that particular variable, as well as the brief description of the results.

5.2.1 Impact of the discount rate

Elaborated more in details in Subsection 2.4.2, the discount rate is chosen for two reasons. The first one is the uncertainty of the value used in the main analysis (3%) and the second is the magnitude of impact it has on the total costs. As no government recommendations regarding the discount rate for renewable energy projects exist in Croatia, the choice of 3% is based on the same source as the investment cost data.

Figure 22 shows the change in total costs of all three scenarios when different discount rates are applied. It can be seen that the Reference scenario is significantly less sensitive to discount rate variations and within 10% range of rates, total costs change by only around 12%. The TRES and RES scenario, are however, much more sensitive in that sense, as investment costs represent respectively 64% and 68% of total annual costs in those scenarios. Their costs are already fairly similar for 3% discount rate, however with 0% rate, they differ by only 2 MEUR (0.03%). As the rate grows, SES gets more expensive (as it is more investment intensive) and with 10% discount rate it has 4% higher costs than the TRES scenario. This actually indicates that the difference is not significant and that as long as the same rate is applied in both scenarios, the comparison is fair and the discount rate does not have much influence on the difference between scenarios. It is however very important when estimating total costs of one scenario, as for every 1% increase in discount rate, they grow by approximately 6-7% in both scenarios.

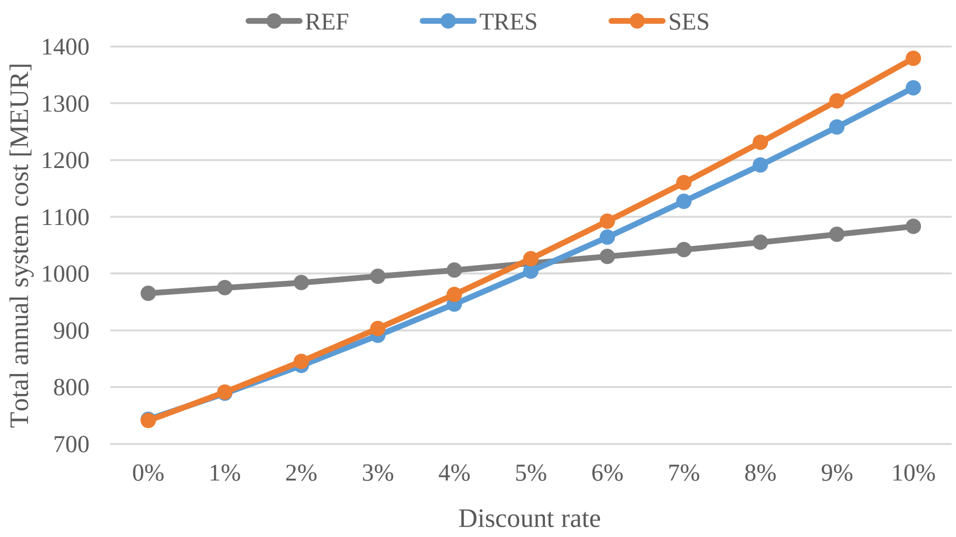

Figure 22. Total annual system costs with different discount rates in the Reference, TRES and RES scenarios (note that 3% discount rate is used in all scenarios)

5.2.2 Impact of the biomass price

Since biomass is the only fuel used in both future scenarios and biomass consumption is significantly different between them, it is relevant to compare its impact on both scenarios. It is worth emphasising here again, that EnergyPLAN does not distinguish between different types of biomass, but treats it as a single fuel. The average price of biomass used in modelling both future scenarios is 8.1 EUR/GJ and it is represented as a 0% relative change in Figure 23.

Because it utilizes more biomass, the TRES scenario is more sensitive to changes in the biomass price and for around 27% increase in the current price (approximately 10.3 EUR/GJ), TRES becomes more expensive than SES. For every 10% increase in the biomass price, total costs grow by around 1.4% in the TRES scenario and 0.9% in the SES scenario. As in any other field, it is not an easy task to predict the biomass price in the future. However, under the assumption that energy systems are going to evolve towards renewable and therefore consume more and more biomass, and knowing the important limitations of biomass availability, at this point it is more likely to expect the growth in the price.

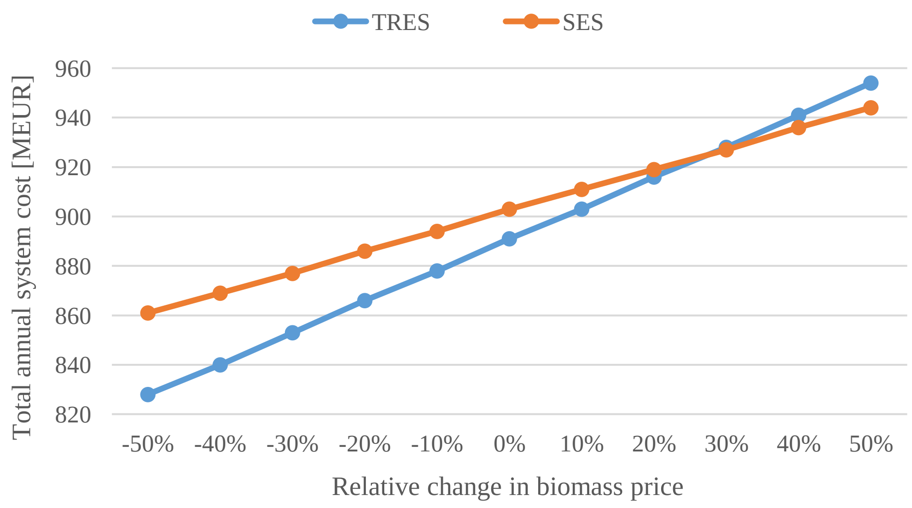

Figure 23. Total annual system costs in the TRES and SES scenario when biomass price is changed – relative change in comparison to the price used in modelling scenarios (8.1 EUR/GJ, represented as 0% relative change)

5.2.3 Impact of the solar technologies prices

CSP and PV are key renewable technologies in both the TRES and SES scenario. This is especially the case in the SES scenario, where CSP and PV are by far the largest two technologies in the system. Hence, their pricing largely influences the total costs of the system. Moreover, CSP is relatively unknown technology today, so estimating its investment costs is much more challenging than for some more conventional technologies, such as PVs.

There are three important observations from Figure 24, which shows changes in total annual system costs when CSP and PV prices gradually drop or grow. First, both scenarios are much less sensitive on PV price variations, both because there is less PVs than CSP installed in both scenarios and because PV price is already around nine times lower, so the relative change is much less significant. This leads to the second observation, which is that even for 50% PV price drop, the SES scenario is still slightly more expensive than TRES, similarly as in the case of 0% discount rate. For the case of CSP, however, already 12% lower investment cost causes that TRES and SES have the same total annual system costs, whereas with 50% decrease, SES could be potentially 4% (37 MEUR) cheaper. The problem of predicting the investment price of CSP results in a high level of uncertainty when developing systems highly based on this technology. However, if this technology continues to develop and its implementation grows, it is likely that the price is going to drop, as it has been the case with PV, whose price per unit dropped by 80% between 2008 and 2016 [69]. This problem, as well as other problems related to CSP are elaborated further in Chapter 7.

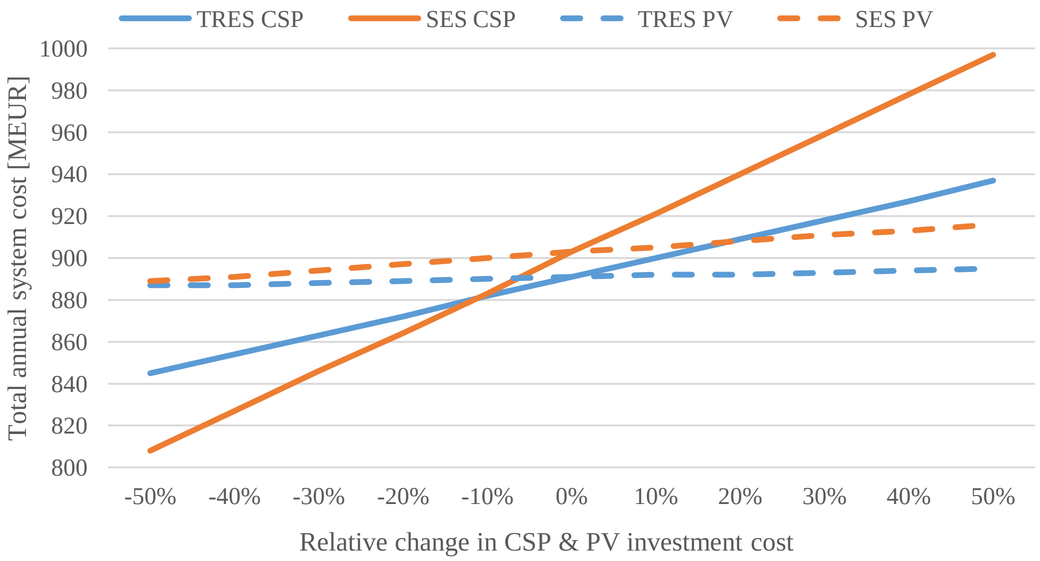

Figure 24. Total annual system costs in the TRES and SES scenario when unit investment cost of PV and CSP is changed – relative change in comparison to the costs used in modelling scenarios (0.69MEUR/unit for PV and 5.98 MEUR/unit for CSP, represented as 0% relative change – see Appendix II for more details about investment costs)

5.2.4 Impact of the increased production from intermittent RES

Both future scenarios are assumed to be closed systems, meaning there is no electricity exchange with neighbouring systems. In order for a closed system to be able to balance itself, there should be no excess electricity or electricity import demand in any hour through the year. Some researchers, however, have somewhat different approach when modelling energy systems and often it can be seen that a certain level of CEEP or import demand is allowed (usually 5% of total electricity demand), especially in systems highly based on fluctuating RES. This is under the assumption that the network infrastructure is able to cope with a certain amount of excess electricity or that it can be manually actively by, for example, shutting down wind turbines, which is something that cannot be modelled. Although a different approach is used in this thesis, it is worth investigating the implications of increased electricity production from intermittent RES on the three most important components of the results – CEEP, total costs and biomass consumption.

Figure 25 shows the changes in those three components when electricity production from PVs and CSP is increased. In every step, 100 GWh of electricity production from each technology is added (not simultaneously, but separately) in both scenarios. Electricity production of 100 GWh corresponds to 70 MW of PVs and 23 MW of CSP, for every step in both scenarios. This was found to be a logical step in this analysis, corresponding to roughly 3% of the total electricity production in both scenarios, but in 10 steps it gives a variety of insights on the behaviour of both systems.

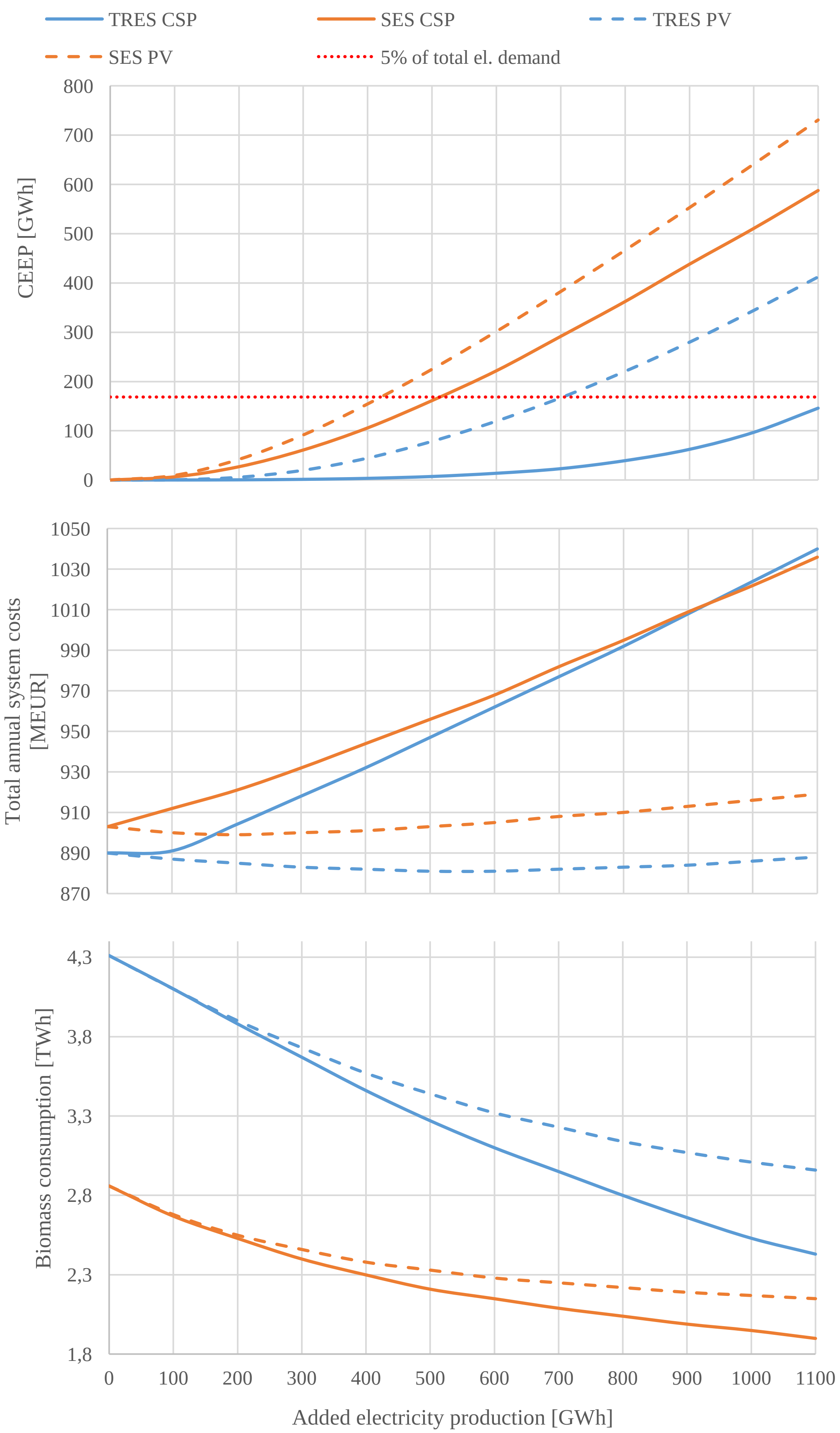

Figure 25. Impact of added electricity production from CSP and PV in the TRES and SES scenario - e.g. TRES CSP stands for added electricity production from CSP in the TRES scenario (and the rest accordingly); dashed red line in the first chart represents the value of 5% of total electricity demand

Looking at the level of CEEP, it grows as the electricity production increases in all scenarios, however it is more interesting to see how the scenarios respond differently on the two technologies. In both cases, adding 100 GWh of electricity production from PV results in more CEEP than adding the same amount of electricity from CSP: The reason for that is in the production distribution profile and installed capacity of the two technologies – while CSP generates electricity in more hours throughout the day, PV production is concentrated around fewer hours. Also, since it has a higher total capacity, it gives higher production than CSP for the same capacity utilization rate in a given hour, resulting in more hours with excess production. It is worth noting that the SES scenario is generally more sensitive than TRES, comparing both technologies. This is because it is based on intermittent electricity to a much higher extent than the TRES scenario, which has 46% of annual electricity production coming from condensing mode power plants. Overall, it can be concluded that in the TRES scenario, 700 GWh of production from PVs and more than 1,100 GWh from CSP can be added before exceeding the CEEP level of 5% of total electricity demand. In the SES scenario, this is 400 GWh for PVs and around 500 GWh for CSP.

Adding the production from CSP increases the total annual system costs in both scenarios sharply, resulting in around 17% and 15% higher costs for 1,100 GWh of added production in TRES and SES respectively. It is also interesting how at a certain level (around 950 GWh added), TRES becomes more expensive than SES. This is because at this level, more CSP production does not have much influence on decreasing condensing mode power plant production (hence decreasing the amount of fuel consumed), but only increases investment costs. For the case of PV, changes in total costs are much less significant. In fact, in both scenarios, adding up to 400 GWh of electricity from PVs actually slightly lowers the costs. For additional 1,100 GWh, SES total costs are approximately 2% higher than in the original scenario, while in TRES they are at almost the exactly same level.

Finally, adding more intermittent production expectedly reduces the level of biomass consumption. In the SES scenario, this drop is again not as sharp as in the TRES scenario and it is more sensitive to adding CSP than PV, for the very same reasons why CEEP increase in less sensitive. In the TRES scenario, it can be seen that by adding around 800 GW of production from CSP, biomass consumption drops to the sustainable level of 2.876 TWh. Looking back at the level of CEEP and total costs at that point, it can be seen that the system is still relatively stable (CEEP is less than 5% of total demand), however the system is around 10% more expensive (85 MEUR) than the system in the original SES scenario, where sustainable biomass consumption is also obtained. From that, it can be concluded that although it is possible to achieve the system with the sustainable biomass consumption in TRES scenario if a certain level of CEEP is allowed by adding more CSP, it would be more expensive than the system created in the SES scenario, which leaves it as the most optimal choice from that perspective.

The sensitivity analysis showed how the SES scenario is more sensitive to changes in PV and CSP investment costs, as well as the changes in discount rate, however the TRES scenario is more sensitive to biomass price changes and at 27% increase, is becomes more expensive than SES. Uncertainties regarding the prediction of prices are elaborated more in Chapter 7. Analysis of the impact of adding more electricity production from PV and CSP to both systems revealed that the original SES scenario is the cheapest option when the criteria of sustainable biomass consumption needs to be achieved.

5.3 Results summary

Various analyses carried out have revealed several findings and conclusions. For clarification purposes, and to make it easier to keep in mind the most important ones for the further analysis, the main findings can be summarized in the following nine points

- Both future scenarios have significantly lower PES than the Reference, however the TRES scenario utilizes 50% above sustainable level of biomass, which makes it technically unfeasible.
- Electricity production in the SES scenario is based on fluctuating RES, whereas the TRES is still largely based on condensing mode power plants (46% of the total production)
- Heat production in the SES is much more diverse than in the TRES (which is beneficial from the energy security standpoint) and it is mostly based on heat pumps and CHPs, while in the TRES the largest share is from heat-only boilers.
- The cost structure in both future scenarios is significantly different than in the Reference, having investment costs as the major cost component instead of variable operating costs, but total costs in the TRES and SES differ by only 1%.
- Hourly electricity productions over a typical winter and summer day illustrate the main differences in the two scenarios – the TRES is mostly based on stable production from condensing mode power plants, whereas the SES is largely based on intermittent electricity from PV and CSPs
- Unlike the Reference scenario, both future scenarios show a fairly high sensitivity on changes in the discount rate, because of being much more investment intensive.
- If the biomass price increases by 30%, with all the other variables remaining constant, the TRES becomes more expensive than the SES.
- If the CSP price drops by around 15%, the TRES becomes more expensive than the SES
- In case of adding 800 GWh or more of CSP production in the TRES scenario, its biomass consumption becomes sustainable, while CEEP is below the level of 5% of total electricity production. However, in that case scenarios becomes around 100 MEUR more expensive than the original SES scenario.

The next chapter deals with identifying what policy changes need to be introduced in Zagreb and Croatia in order to successfully implement the identified technical changes in Zagreb's energy system.

6 Implementation analysis

So far, the focus of this work has been on identifying the differences between a smart energy system and a traditional renewable energy system in Zagreb from a technical and economic perspective, i.e. characteristics of the energy systems and the total annual costs. This chapter gives a brief description of some key factors to consider in the implementation stage of developing a future energy system in Zagreb, representing the third step of the Choice awareness theory presented in Section 2.1 (public regulation proposals).

The assumption in this chapter is that the implementation differences in developing a smart energy system vs. a traditional renewable energy system in Zagreb are not as explicit as the technical and economic. Moreover, differences are in some aspects marginal or even non-existing, especially in the early stage of the implementation. Therefore, this chapter analyses the elements that need to be considered in developing a new energy system in general, focusing on stakeholders that need to addressed, policy and public regulation frameworks to be changed and infrastructure requirements. Where relevant, however, the differences between the two scenarios are emphasised and their implications on the overall conclusions are discussed.

6.1 Stakeholders to be addressed

As defined by Lund [41], a radical technological change requires addressing stakeholders related to the issue at hand, especially if it significantly influences their business activities or if they have an impact on decisions in the implementation stage. Following the framework presented in Figure 6, the most important stakeholders are placed into six main groups, based on their roles in the decision making process and helps to understand how they influence (or are influenced in) that process. The general description of each group is given in Section 2.6 and Figure 26 gives an overview of the specific stakeholders in each category.

Policy makers
Ministry of Economy, Entrepreneurship and Crafts
Ministry of Construction and Physical Planning
Ministry of Environment and Energy

Coordination bodies
Center for Monitoring Business Activities in the Energy Sector and Investments (CEI)
Croatian Regulatory Energy Agency (HERA)

Infrastructure owners
HEP
City of Zagreb

Funding allocators and payers
Environmental Protenction and Energy Efficiency Fund
Citizens

Policy implementers
North-West Croatia Regional Energy Agency
City adminitrative bodies

Policy advisors
Energy Institute Hrvoje Požar (EIHP)
University of Zagreb

Figure 26. Overview of the main stakeholders with their general roles – the level of power decreases from the top to the bottom of the list

Policy makers. Ministries in Croatia are in charge of designing and implementing policies and regulations within their area, synchronizing them with the EU requirements and being the supreme regulation body when it comes to policy implementation. Their main role is, however, the final decision making on internal or external proposals. Three ministries are identified to be important for the energy sector in Croatia and Zagreb – namely Ministry of Economy, Entrepreneurship and Crafts (short: Ministry of Economy), Ministry of Construction and Physical Planning and Ministry of Environment and Energy.

The Ministry of Economy sees the energy sector as one of the three key areas within their scope (next to industry and trade). They control investments and innovations in this sector and set development goals as a part of the industrial strategy they design every five years. The Ministry is also in charge of all domestic and international trade markets and harmonisation of Croatian markets with EU directives across different sectors. Moreover, they are in charge of allocating governmental funds for investments in the energy sector [101].

The Ministry of Construction and Physical Planning performs administrative tasks in the field of buildings, construction and planning, as well preparing and implementing EU-funded projects in this area. Within the scope of this work, the Ministry is especially important because it is in charge of efficiency of buildings on the national level and all the strategic documents related to energy renovations. The most important here is the "Long-Term Strategy for Mobilising Investment in the Renovation of the National Building Stock of the Republic of Croatia" [102], which outlines the plans for investments in energy refurbishments by the year 2050.

The Ministry of Environment and Energy, established in 2016, is in charge of designing acts and laws in the energy sector, defining the national energy strategy, national energy efficiency action plans and reporting on the current state of the energy sector in Croatia. They are also supervising the performance of the Environmental Protection and Energy Efficiency Fund (EPEEF), another key stakeholder [103], elaborated later in this section.

Understanding the role of each ministry, it can be concluded that they could have a large influence the dynamics of implementing a new energy system in Zagreb. Hence, it is crucial that they recognize and define renewable energy and energy efficiency as a strategic path for the sustainable development of the country by defining clear and ambitious plans towards 2050, supporting investments in the energy sector, ensuring funds for their implementations and reducing existing barriers that slow down both the policy making and the actual implementation.

Coordination bodies. The Centre for Monitoring Business Activities in the Energy Sector and Investments (CEI) was founded in 2012 and has a task to manage and supervise the implementation of the Croatian energy strategy, as well as to support public investments in the energy sector [104]. Croatian Regulatory Energy Agency (HERA) supervises business activities in the energy sector, regulates energy prices and coordinates energy markets [105]. Both institutions are also included in making proposals for new energy policies or adjustments in the existing ones, with the main goal to monitor investments in the sector cohesively and make them transparent for the public. As such, CEI does not have a large executive power, but serves more as a support in designing investment strategies in the sector.

Infrastructure owners. As already mentioned when describing the existing energy system in Section 4.1, HEP is the major Croatian energy company and the owner of all the large energy facilities in the country, including the two CHP plants in Zagreb [53]. Next to ministries, they are the most powerful stakeholder, as this transition largely influences their business activities. It is therefore extremely important that HEP's future business plans focus on transforming the two plants into being biomass and/or waste fuelled, expanding the DH network and investing in large-scale PV, CSP and hydro projects.

The City of Zagreb is the owner of the gas network, all the road infrastructure and waste treatment facilities. As they decide on how the waste is being collected and treated, they are the key stakeholder in developing the waste CHP plant. Because they are involved in major construction projects in Zagreb, they are also an important player in expanding the DH network. The city also has a significant labour force, skilled and experienced in performing various infrastructure projects in the city [106]. As the majority of the energy infrastructure is not under the city's ownership, its interest might be low, however its support can strengthen the implementation process.

Funding allocators and payers. The Environmental Protection and Energy Efficiency Fund (EPEEF) is the central funding collector and co-financing allocator for energy efficiency and renewable energy projects in Croatia. The most important activity of the fund today is co-financing energy renovation projects in private and public buildings in Croatia. The fund is not financed from the national annual budget, but collects resources from various fees paid by the citizens and companies through their utility bills, as well from local budgets, donations or profits from international projects [107]. In order to implement the project of developing a new energy system in Zagreb successfully, the activities of this fund need to focus primarily on how to support citizens in renovating their homes and investing in small-scale renewable energy projects, i.e. develop concrete and easily accessible, but fair co-funding measures.

Policy implementers. Although the list of stakeholders that can be a part of this category could be much longer, there are the two main organizations that need to be addressed because of the scope of their influence, namely North-West Croatia Regional Energy Agency (REGEA) and City administrative bodies.

REGEA is a local energy agency, with a primary focus on developing local energy plans and implementing concrete projects in renewable energy and energy efficiency field in the region. The agency is also an expert in ensuring international and the EU funding for energy projects, which makes it important collaborator in the implementation stage [108].

City administrative bodies refer to several city offices within three areas of expertise – planning and development; economy; construction and utilities. Similarly as REGEA, they work on implementing development projects on the city level, but are also a link to the city executives and policy makers, hence an important stakeholder to consider [106].

Policy advisors. This group of stakeholders has the two main roles that make them relevant to include in this analysis. Firstly, as research and education institutions, they make sure to follow the most recent technology trends and put them in the Croatian context, investigate different small-and large scale solutions to find the optimal ones and transfer their knowledge to students and other citizens. Moreover, they are often included in developing local and national energy strategies and reports, policy public regulation proposals and are in some way public opinion-makers. They have worked on several major strategic documents in the past, e.g. EIHP developed *National heating and cooling efficiency potential* [54], while the University worked on creating the *Low carbon development strategy* [109], both described later in Section 6.2. Secondly, through various research projects, they have worked on some actual implementations (so far those are rather small projects), so their experience and expertise can be of a great value when it comes to larger projects as well. To conclude, although research institutions do not have much of the direct executive power, with their expertise and recommendations they advise and collaborate with stakeholders that do.

6.2 Current policies

As an EU country, Croatia aims to design its energy policies in accordance to the EU regulations and to follow the official EU goals. Two strategic documents that define the EU 2050 energy goals are Energy Roadmap 2050 [110] and Heat Roadmap 2050 [111]. The former outlines the EU goals to cut greenhouse gas emissions in the EU by 80-95% by 2050 and what the implications of that are to the energy system. The latter is a comprehensive study on the future European heating system and is partially based on the Stratego project, mentioned several times in this thesis. Both studies set ambitious goals on a large-scale level, however they also put a strong emphasis on the importance of national, regional and local plans to follow those goals. Heat Roadmap even goes a step further by analysing future heating systems of five EU member countries.

Table 4 shows the most important energy policies in Croatia and Zagreb divided into three main categories: strategic documents; research studies and reports; and legal acts. Whereas a *Low carbon development strategy* [112] deals with long-term (2050) goals on the national level, a long-term energy strategy for the city does not exist. Moreover, it can be seen that in all three categories, policies on a city level are rather humble and none of them deals with long-term energy goals. This especially goes for the strategic documents, where the only existing document is SEAP [14], which does not focus on the period beyond the year 2020 and where the main focus is on energy efficiency measures in different sectors.

Also, there is a missing link between national and local level policies, both from the regulation and the strategic perspective. As argued by Thellufsen & Lund [113] coordination of different level of energy planning is crucial for the future systems to be feasible and sustainable. Hence, the national strategy needs to take a closer look at the potential and resources of different local authorities, whereas local plans need to consider its surrounding and the overall national goals. That is the reasons why the future scenarios in this work are modelled in such a way that they do not generate excessive amount of electricity that the rest of the country needs to handle and they do not overexploit national resources for own needs.

Another insight noted both when reviewing the existing policies and modelling the Zagreb's energy system is a lack of relevant data and information needed for analyses. Although sectoral fuel consumption data can be found in the city's SEAP [14], more detailed data on the fuel use and technical characteristics of the energy plants and DH network would be helpful for future researchers and policy makers. Also, a system containing the historic hourly electricity network data, such as hourly power load, on a city or at least a regional level is another factor that would enable better research in the future. A good example of such a system is the one provided by the Danish TSO, Energinet.dk for the Danish electricity market [114].

Finally, none of the official legal acts related to energy requires from local authorities to create their energy strategies, neither sets a legal framework for that. As described in Section 6.1 when introducing the stakeholders, the decision making process in Croatia can be characterized as a top-down, hence the high level policies are the first place where the changes need to take place.

Table 4. Overview of the main policies related to energy system development in Zagreb and Croatia

Document type	**Document name**	**Level of application**	**Description**	**Ref**
STRATEGIC DOCUMENTS	*National renewable energy action plan*	National	National version of the EU 20-20-20 goals, defines national 2020 goals	[115]
	National energy efficiency action plan	National	Short term energy efficiency measures for the period 2017-2019 (new document every 2 years)	[116]
	Low-carbon development strategy	National	Defines national goals for 2030 and 2050, RES to have 68% share in 2050, EVs 75%, 92% of the buildings refurbished	[109]
	SEAP Zagreb	Local	Defines CO_2 reduction measures until 2020 in transport, buildings and public lightning sector	[14]
	City of Zagreb 2020 development strategy	Local	Development strategy of the city where energy and environment are one of the six key focuses	[117]
RESEARCH STUDIES & REPORTS	*Energy in Croatia – annual report*	National	Comprehensive annual statistical report on energy production and consumption in Croatia	[118]
	National heating & cooling efficiency potential/National cogeneration potential	National /Local	Define potential for district heating, energy efficiency in the building sector and CHP/cogeneration plants for the entire country, however with detailed analyses on a local level	[54], [119]
	Study on RES potential in Zagreb	Local	Describes renewable technologies with a natural potential in Zagreb, however without much capacity estimations	[85]
LEGAL ACTS – Energy general	*Energy act;* *Act on RES and highly efficient cogeneration*	National	Regulation in energy production, consumption, policy and strategic planning/Defines measures for incentives for RES and Cogeneration	
LEGAL ACTS – Electricity	*Electricity market act*	National	Regulation on business activities in the field of electricity production, distribution, supply and electricity market	

Heating	*Heat market act;* *Act on heat production, distribution and supply*	National	Regulation on business activities in the heating sector – production, distribution and supply	[120]
Energy Efficiency	*Act on energy efficiency;* *Act on efficient use of energy in district use*	National	Regulation on energy efficiency, energy audits and design of local and national strategies for improving energy efficiency	
Fossil fuels	*Act on oil and oil products market* *Gas market act*	National	Regulation on business activities in producing, distributing, storing and trading oil and gas respectively	

6.3 Infrastructure requirements

This section outlines some of the main additional infrastructure requirements not mentioned so far, but important to consider in the implementation stage. First, the land/area requirements for PV and CSP are elaborated, followed by the EV charging infrastructure and lastly, DH network expansion is discussed.

6.3.1 Area requirements for solar technologies

Following the supply side design presented in Subsection 4.2.3, it can be seen that the solar technologies (PV and CSP) are by far the most robust technologies in the SES scenario and among the most robust in the TRES scenario. In respect to that, it is worth it to look into the total area that is required to install such a high capacities of PV and CSP and analyse how realistic is that in a relatively small and densely populated place such as Zagreb.

The United States National Renewable Energy Laboratory (NREL) gives estimations of the total area required to install a PV and a CSP facility in acres per MW (1 acre=4,047 m^2). The total area is all land enclosed by the site boundary and not just the solar collector surface [121]. Using their estimations and knowing the capacity of the two technologies in each scenario, Table 5 is obtained. As expected, area requirements are proportional to the capacities, meaning the required area in the SES scenario is around 3 times higher than in the TRES scenario. As for the PVs, a majority of them can be installed on the roofs of the buildings throughout the city. In France, for example, a new legislation from 2015 says that all new buildings in commercial zones must be covered by plants or solar panels [122]. CSP plants can be installed on free non-used agricultural and construction land in and around the city. The calculated area seems reasonable in both scenarios and should not represent a large issue in the actual implementation stage.

Table 5. Total area requirements for installing estimated capacities of PV and CSP in TRES and CSP scenarios – based on per MW requirements from [121]

	TRES	**SES**
Area requirements for PV [km^2]	4.83	16.30
Area requirements for CSP [km^2]	4.17	11.94
Total [km^2]	**9.00**	**28.24**

Apart from land requirements, introducing large amounts of fluctuating electricity into the system will require interventions in the distribution network. This is thoroughly discussed by Lund in his article on electric grid stability in designing sustainable energy systems [123]. This issue is not in the focus of this thesis, however it is important to emphasise it for future researchers and decision makers.

6.3.2 EV charging infrastructure & adoption incentives

When modelling the transport demand in Subsection 4.2.2, it was calculated that around 380,000 EVs are to be introduced in Zagreb in both scenarios (the current number deducted by the estimated drop in the number of vehicles, further deducted by the number of vehicles that are not electrified). Such a significant shift in the vehicle fleet clearly requires equally serious changes in the city infrastructure. Apart from that, adopting EVs from the citizens' side requires from the city (and the country) to introduce a series of policy changes and incentives.

The charging stations need to be planned in such a way that it does not require from the citizens to change their driving and parking behaviour. Hence, public parking lots, garages, shopping centres, business centres and other locations with many regular visitors need to be equipped with a sufficient amount of charging stations. The billing system for that service needs to be developed as well, although nowadays many cities (including Zagreb [123]) offer free charging for EVs as an incentive measure. When a larger share of vehicles is electric, this kind of incentive is not needed anymore. Although it seems obvious that cities must not overlook developing the EV charging infrastructure, the study in [124] shows that despite many cities in the UK actively support the implementation of EVs, only two cities, namely London and Birmingham, have made significant efforts in developing more advanced infrastructure for those vehicles. Tesla, on the other hand, installs its EV superchargers at conventional gas stations [125]. Apart from mentioning the importance of planning the EV charging infrastructure in the city, this thesis does not dig deeper into that topic, however it is an important area for future studies.

As for the incentives, the pioneer and the best practice example in implementing EVs is Norway. Apart from being excluded from paying the value added tax (VAT) and purchase tax, which adds up to 50% to the cost of a vehicle in Norway, EV owners have access to free ferry tickets, free tunnels, free parking and charging and are allowed to use bus lanes [126]. Some of those measures could be adopted in Zagreb as well. In the long run, however, this measures need to be phased out and can only serve as incentives until EVs become more affordable and a certain level of penetration is achieved.

6.3.3 DH network expansion

While the TRES scenario does not include it, DH network expansion represents one of the largest infrastructural changes in the SES scenario. As it is assumed that the share of DH rises up to 100% until 2050, this means the piping system needs to connect the DH plants and every single building and house in the city. The current DH network in Zagreb is 260 km long and supplies around 28% of the households (approximately 86,000 households). It is however a fairly old system with high heat and water losses, therefore requires renovation in any case. This means that an entirely new system in the entire city needs to be built.

Estimating the exact length of the new network requires more detailed geographical mapping of the city, but knowing that the total length of the existing natural gas distribution network is 2,864 km and that around 80% of the city has access to natural gas [85], it can be concluded that the new network will be 2,500-3,500 km long. In Aalborg for example, a city around four times smaller than Zagreb in terms of population, the DH network that supplies close to 100% of households is around 1,400 km long [70]. This will require large-scale construction works, both in public places in the city and in private homes. The Stratego project [111] emphasises that every local authority needs to develop a master plan for their new heating system and after having the master plan, the individual projects can be planned in details. They also emphasise that every new implementation needs to be divided into logical periodical steps, i.e. the individual projects should be done one at the time. Ideally, the project of connecting the consumers to the network should be carried out simultaneously with the project of renovating their homes to implement energy efficiency measures. This is also a design issue, as the DH network needs to be dimensioned according to a new peak heat demand, i.e. the peak demand after implementing energy efficiency measures, in order to avoid building a costly network designed for much higher peaks. Also, two construction works are reduced to one, again benefiting the citizens' convenience.

6.4 Key policy recommendations

After presenting the existing stakeholders and their roles, current policies and the additional requirements needed to be considered in the implementation stage, the general policy recommendations can be made. The first step towards the implementation is to define a long-term (2050) master plan for the city energy system, followed by a series of more short term plans (e.g. for every 5 years) and specific plans divided by sectoral segments (i.e. a heat plan, transport plan etc.). This should include the collaboration of all the mentioned stakeholders, but the plan itself should be primarily created by research institutions and policy implementers – REGEA and the City administrative bodies. The following are general recommendations related to specific sectors, based both on the technical analysis, as well the stakeholder and policy analysis:

- Energy efficiency & heating:
    - All new buildings must obtain at least B level energy performance certificate and be connected to the DH grid in order to go in line with the projected 52% drop in heat demand and 100% share DH.
    - All the existing buildings that do not meet energy efficiency requirements need to be renovated (same reason as the previous point) – if achieving at least 50% savings, EPEEF provides co-funding (in line with the existing policy).
    - In case of the TRES scenario, fossil fuel boilers should not be allowed to be installed as individual heating solutions, but only small-scale heat pumps and solar thermal – this is the main technical measure implemented in the individual heating sector (see Subsection 4.2.3).
- Electricity:
    - Create a new system for supporting the development of small private PV projects (and other renewables) in order to foster achieving a high level of electricity production from renewables.

    - HEP, as the major energy infrastructure owner and operator, needs to focus their future business activities on developing large scale PV, CSP and biomass power plants.
    - To maintain and monitor the sustainable biomass consumption, develop a better understanding of the available biomass resources in Croatia and plan the biomass power plants accordingly – research institutions should carry out a study that determines the exact sustainable amount of biomass that can be used for energy purposes annually.
- Transport:
    - Subsidise buying electric vehicle until the technology becomes affordable.
    - Develop a plan of building the EV charging infrastructure throughout the entire city (e.g. charging units in all public parking lots, garages, shopping centres and business centres).
    - In order to implement the important step of the SES scenario, plan for the implementation of electric fuels (SES scenario), as soon as they reach the commercial stage of development.
- Industry:
    - Based on the industry demand modelling presented in Subsection 4.2.2, it is important to introduce requirements for the industry sector to implement the energy efficiency measures and transfer from fossil fuels to biogas and electricity.
    - Industrial excess heat plays an important role in the heating sector in the SES scenario, hence a collaboration between the industries and the DH operator to utilize waste heat from the industry to the DH grid should be established, by developing a business model beneficial for both.

Note how none of the proposed measures is not particularly specific, which is due to the scope of the study presented in this thesis, which is fairly broad and includes all different components of the energy system. Therefore, the proposed policy measures are only general guidelines for the decision makers how to successfully implement the identified technical measures.

7 Discussion

The results and observations made so far are based on a series of data, assumptions and estimations, of which some are very specific to this study. Thus, it is essential to further elaborate on implications of such considerations on the results of the study, the scope of their impact, as well as on the additional limitations not thoroughly accounted for so far. This chapter aims to provide such a discussion, by critically reviewing the most important issues and suggesting future work needed to address them.

7.1 System design & scenario differences

For the sake of simplicity, all scenarios modelled in this work are assumed to be isolated energy systems, i.e. no electricity import and interconnections with the neighbouring areas are included, which is not the situation in reality. Instead, all the electricity import is modelled as a single natural gas-fuelled condensing mode power plant, assumed to be within the system boundaries. The reasoning behind that assumption is elaborated in Subsection 4.1.1. It is however, worth mentioning that the total PES obtained in the Reference scenario, does not represent the actual fuel consumption in Zagreb, but rather the consumption needed to meet Zagreb's heat and electricity demand. A similar method in modelling the electricity import was used by Østergaard et al. [22] in their study on the renewable energy scenario of Aalborg Municipality.

Using the isolated system approach in modelling future scenarios, gives an opportunity to develop a system that does not depend on its neighbouring areas in terms of importing or exporting electricity. For example, if a system has a high electricity export, it requires from neighbouring areas to utilize that electricity and does not leave them the flexibility to develop according to the same pattern of implementing high amounts of electricity from fluctuating RES. Moreover, Østergaard [127] discusses that such a situation puts a system operator in a poor bargaining situation as well, as there are no alternatives to exporting/selling electricity in hours where there is electricity excess or buying when there is electricity import demand. In practice, however, future energy systems of neighbouring areas need to be coordinated and also in line with the overall national goal. This is a potentially interesting area for a future research and has already been addressed by Thellufsen & Lund in their two studies on the roles of local and national energy systems in the renewable energy integration [113] and interconnectivity in renewable energy systems [128].

Furthermore, several assumptions are made to make conceptual difference between the TRES and SES scenarios, most focused on the technologies that interconnect different energy sectors. For example, large-scale heat pumps are not included in the TRES scenario, however small-scale, individual heat pumps are. This is because this technology is feasible for individual households already today and it is expected to play an important role in the future, regardless of the scenario. Excluding individual heat pumps from the TRES scenario and replacing them with, for example, biomass boilers, would certainly result in even higher biomass consumption in that scenario and lower potential to implement intermittent RES. That situation is not analysed in this work, however could be an interesting aspect to compare. The same goes for many other technologies, such as electrofuels, industrial excess heat or DH expansion. Including each of this technologies in the TRES scenario individually, would give valuable observations about the system behaviour and potentially present the next step towards finding an optimal solution.

7.2 Technology & resources feasibility

One of the most important resources utilized in both future scenarios is biomass. While it can be a perfect substitute for fossil fuels, its main limitation is availability, so it must be used in a sustainable way, i.e. exploited resources need to be renewed. The European Commission has issued non-binding recommendations regarding biomass sustainability criteria that apply to all energy installations of at least 1 MW of thermal or electric power [129]. Biomass consumption is also one of the main technical characteristics used to compare the scenarios in this thesis and ultimately, it represents the major difference between the two scenarios. Determining the sustainable level of biomass utilization for energy purposes is a rather challenging task. In this thesis, the total amount available on the national level [130] is used, scaled-down using the population ratio. This in turn, means that a certain amount of biomass is available per Croatian citizen, regardless of where the biomass resources are actually located. This might seem as an unfair distribution, especially considering the fact that many Croatian citizens own and use their own wood.

Another issue is the actual total level of biomass available for energy purposes on the national level. Some researchers [130] suggest up to 40% higher potential than used in this work, whereas others [131] use 60% lower values in their analyses. This indicates that the accurate level is still to be determined and both the researchers and the decision makers need to make a consensus regarding using it in all the future work.

The energy system developed in the SES scenario utilizes just below the assumed sustainable level of biomass. In the case of an extremely dry year (i.e. lower production from hydro power plants), or in an extremely cloudy year (i.e. lower production from CSP and PV), the biomass consumption necessarily increases, which makes the system unsustainable. The opposite conditions (i.e. extremely wet or sunny year), might result in lower biomass consumption. As there are no large capacities of neither solar technologies nor hydro power plants installed in Zagreb today, it is hard to compare historic annual production values in order to predict the future. However, the weather conditions used in distributions curves of the model correspond to historically average weather conditions, therefore it is assumed to be a fair representations of the average conditions in the future.

Continuing on CSP technology, its feasibility needs to be discussed from two perspectives – development stage and area requirements. CSP is the key technology in both scenarios, however it is still in an early development stage, with 4.8 GW of the total installed capacity worldwide (PV total installed capacity was 227 GW in the same period) [132]. Viebahn et al. [132] assessed the potential role of CSP in the future and in one of their scenarios, electricity from CSP reaches 15% of the total global electricity demand in 2050, which is a result of a substantial drop in the technology price. Moreover, in their report on cost analysis of CSP [132], IRENA predicts that the CSP capital costs could decrease between 17% and 40% already by 2020, the latter in a case of more aggressive deployment. As the adoption rate heavily depends on the price, the future development is hard to predict, however looking at the trends of the PV technology, whose price has dropped by more than 60% since 2009 and is expected to decrease further [133], optimistic predictions for the CSP are realistic as well.

As calculated in Subsection 6.3.1, area requirements for CSP are 14.17 km^2 in the TRES scenario and 11.94 km^2 in the SES scenario, which represents 1.4% and 4.4% of the total area of the city, respectively. Hence, it is not certain whether this area is actually available in the city and if so, whether it meets all the requirements for installing a CSP system. This issue is something worth investigating in the future, as it was outside of the scope of this thesis. Moreover, if the area within the city is insufficient, the alternatives should be considered, e.g. a collaboration with a neighbouring area able to lend a non-used land. Of course, as discussed in Section 7.1, that would be possible only if a neighbouring area does not have the same business ambitions.

Another important assumption made in modelling the SES scenario is that electrofuels account for around 28% of the total transport energy demand in 2050. Producing electrofuels includes the hydrogeneration of CO_2, which in a 100% renewable system is available only from combusting biomass. In such a system, it might not be possible to capture enough CO_2 to produce biofuels, so it would need to be captured from air, which is a much more expensive procedure. The same issue was raised by authors in [36]. The method of producing electrofuels are not elaborated in details in this thesis, but Ridjan et al. [134] provide an overview and comparison of different pathways of producing electrofuels. The availability of CO_2 and its balance, as well as the optimal location of hydrogeneration and co-electrolysis facilities in Zagreb, are not in the focus of this work, hence this represent an interesting area for future research.

7.3 Uncertainties in future estimations

Many forecasts regarding future trends were included in modelling both the scenarios, especially their demand side. They range from estimating future energy demand by sector, forecasting weather conditions to future technology price and penetration. There are, however, two assumptions that are especially interesting, important for the analysis and might intrigue future researchers to investigate them further. Those transport demand and technology price in the year 2050.

Although it is assumed that all the vehicles in the city switch to either electricity or electrofuels, the total number of vehicles is only 10% less than in the reference year. This sector is currently experiencing major innovations, with the ever growing number of large tech companies and start-ups being included in developing innovations in the field of electric and autonomous vehicles, with Tesla as a leader. Hence, there is a possibility that in a rather short time period (10-20 years), a completely new technology enters the market and potentially disrupt the entire sector.

Because of the level of uncertainty in such a dramatic scenario, this possibility is not accounted for in this work, but it is important to raise the awareness that certain technologies and events may result in the transport energy demand modelled in Subsection 4.2.2 being largely over or underestimated. This is a field that will certainly be largely represented in the future research. Also, the impact of the technologies that are already well-known, but their applications in the transport sector are new, should also be assessed. Authors in [28] identified seven promising emerging alternative technologies that could cause changes in the transport sector, of which four are highly applicable to the city level. This includes delivery drones in commercial supply chains, 3D printing that could reduce the need for transport of manufactured parts, catenary vehicles, which could use the electricity directly, without a need for large batteries and car sharing, which would increase the efficiency of the public transportation sector. Those technologies should not be neglected in the future research on the future urban transport sector.

Furthermore, as explained in Subsection 2.4.2, 2050 technology costs are taken from the EnergyPLAN cost database [56], therefore this work goes in line with the majority of studies that used EnergyPLAN to model energy scenarios. However, it is worth emphasising how this is another area where a high degree of uncertainty is present, due to a broad range of estimation alternatives available. For clarity purposes, all costs are presented in Appendix II, so the reader is able to asses each individual cost.

7.4 Limitations in policy & public regulation

The implementation analysis, developed in Chapter 6, provides an overview of the most important stakeholders and the current policy framework, as well as the key policy recommendations. The analysis and the recommendations are rather general and do not include all the necessary steps needed to be considered in the actual implementation stage. They were not in the main focus of the thesis, although the collaboration between the relevant stakeholders and efficient policy strategies are the two most important things in implementing technical solutions. Hence, they need to be discussed more thoroughly in the future work, where researchers could analyse the implications of different policy measures on the technical results of the scenarios. For example, what happens if the Government does not subsidise EVs at all – how does that reflect on the results of the energy system model. Also, what if the state decides not to stop using fossil fuels and encourages building natural gas plants in the country. Many other policy interventions could be analysed as well.

Both the TRES and the SES scenario are 100% renewable, therefore both have zero CO_2 costs, whereas the Reference scenario has 105 MEUR of CO_2 costs. This represent significant savings, but apart from that, the analysis of some external cost savings when implementing a renewable energy system should be carried out. This includes other environmental costs (apart from CO_2), such as NO_x costs, currently the most worrisome pollutant in cities [135], as well as the savings in health costs related to air pollution. Moreover, renewable energy and energy efficiency bring a large job creation opportunity, which has not been addressed in this work. Also, existing companies and jobs could largely benefit from being included in all different aspects of developing a new system – from planning, engineering and developing new business models to the component manufacturing and installation.

Finally, an important and significant change such as new energy system development, requires citizen participation in different aspects. This should include capacity buildings to raise awareness about the benefits of renewable energy, implementation of energy-related topics into the education system to a much larger extent and providing an opportunity to participate in decision making and investing in their own projects.

After the various issues not addressed in the main analysis have been discussed in this chapter, the next Chapter gives an overview of the main conclusions gathered from the analyses, with the main purpose to provide a clear answer to the research question and the related subquestions.

8 Conclusion

In this thesis, two approaches in developing a 100% renewable energy system in a city are examined, namely a traditional renewable energy system and a smart energy system. The former is the system where each energy sector is developed independently, without a cross-sector integration, while the latter includes various technologies that enable interaction between heating, electricity and transport sector. The main part of the work deals with modelling the two systems, using the city of Zagreb as a case, and analysing their technical and economic performance. The thesis also looked into some implementation requirements when developing a new energy system, all with the main goal of answering the following research question:

Using the city of Zagreb as a case, what are the differences in a smart energy system approach vs a non-integrated renewable energy system approach from a technical, economic and implementation perspective?

The analysis revealed that a smart energy system is a preferable option for Zagreb's energy system, due to three main reasons: lower PES and sustainable biomass consumption, the same level of costs as the traditional renewable energy system and higher energy security due to more diverse energy production mix and lower dependence on a certain technology. More details on the results, explaining the main conclusion, can be summarized as follows:

- The current energy system in Zagreb is highly centralized and entirely based on fossil fuels, imports 75% of electricity annually, meets 34% of heat demand from DH and generates 3.69 Mt of CO_2.
- The major differences between a traditional renewable energy system (TRES scenario) and a smart energy system (SES scenario) are:
  - TRES utilizes 4.31 TWh of biomass, which is 50% above the sustainable level, while the SES scenario has a just below sustainable level of biomass consumption (2.86 TWh)
  - The smart energy system is able to utilize much larger shares of electricity production from intermittent solar technologies (PV, CSP) – 49% of the total production in the SES and 20% in the TRES
  - One of the reasons for that is that the SES has a 100% share of DH, with CHPs and heat pumps as the main technologies (34% of total heat each), which increases its flexibility
  - The smart energy system is marginally more expensive (1%), but both systems have investment costs as the major component of the total annual costs
  - The SES scenario requires 28.2 km^2 (35 m^2/capita) of area for solar technologies, while TRES requires only 9 km^2 (11 m^2/capita)
  - Sensitivity analysis shows that a 30% increase in biomass price or 15% drop in CSP investment cost makes the SES scenario cheaper than the TRES
  - The TRES can reach the level of sustainable biomass consumption if 800 GWh of electricity from CSP is added (having below 5% CEEP), but in that case it is 100 MEUR per year more expensive than the TRES

- The largest implementation differences in the two future scenarios are the DH expansion and the integration of electrofuels (both requiring additional policy regulations and robust infrastructural actions), while other technical differences should not represent any further implementation challenges

These results are, however, based on a series of assumptions and forecasts, which all contribute to the level of uncertainty in the accuracy of the results. The main factors here are definitely the future weather condition forecasts, which could significantly influence the production from intermittent RES, as well as the future technology prices, which are the main basis for the economic results and could be the main decision factor. Moreover, some of the main technologies implemented in the scenarios are still in a very early development stage (e.g. CSP and electrofuel) and it is still hard to estimate their potential. None of those uncertainties, as discussed in Chapter 7, should cause significant differences in the general results and the overall conclusion of this work – that smart energy systems are more sustainable, consume less fuel, contribute to energy security and have the same costs as non-integrated renewable energy systems.

Finally, new policies must primarily be focused on banning fossil fuels, developing an energy efficiency improvement programme, developing large-scale RES projects, promoting implementation of small-scale, individual RES projects and providing incentives for EVs. The crucial implementation step, regardless of the scenario chosen, is engaging the relevant stakeholders to build an institutional and policy framework suitable for implementing radical changes in the energy system.

9 References

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10 Appendix

10.1 Appendix I – Distribution curves

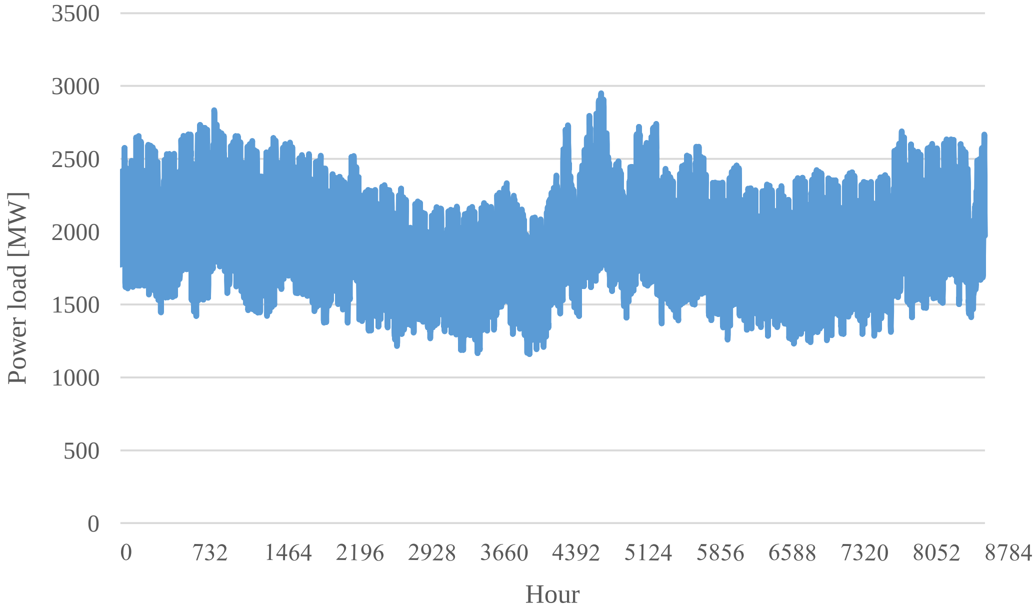

Figure 27. Hourly electricity load in Croatia in 2015 - the step along the horizontal axis (732h) corresponds to a number of hours in an average month in a leap year

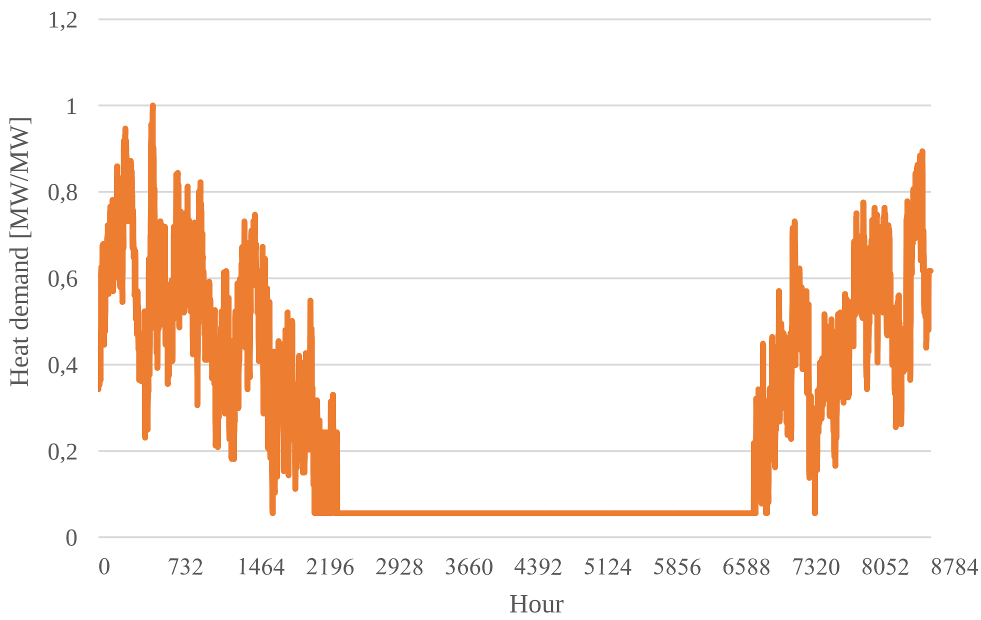

Figure 28. Annual heat demand based on the total heat demand (individual + DH) - the step along the horizontal axis (732h) corresponds to a number of hours in an average month in a leap year (values are normalised, i.e. each hourly value is divided by the maximum annual value)

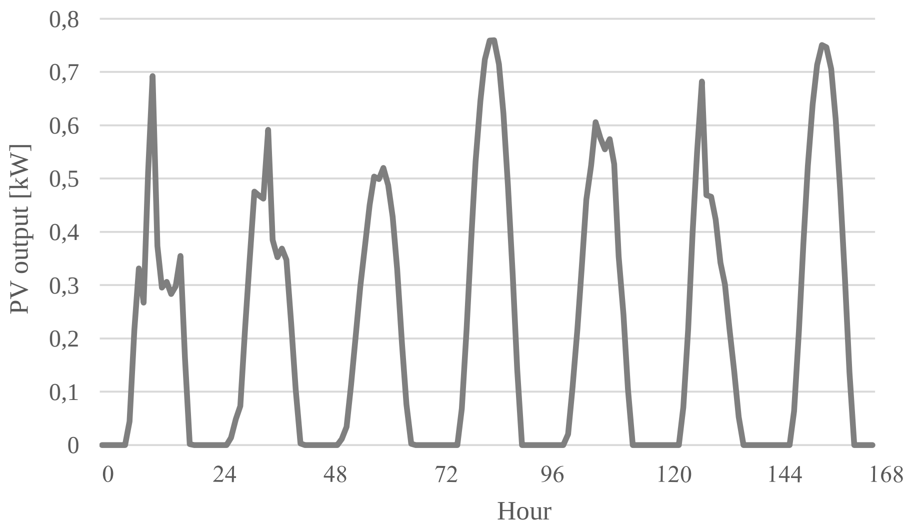

Figure 29. PV output for one week in August for 1 kW PV panel with the following characteristics: 35° inclination of the surface, 30° orientation of the inclined plane (south/south-west), 20% reflection factor from the ground, 0.4%/°C temperature coefficient of power, 45°C nominal operating cell temperature, 10% aggregated losses from module to grid, 1367 W/m² solar constant – the step along the horizontal axis (24 h) corresponds to one day

10.2 Appendix II – Costs & CO_2 content in fuels

Table 6. Costs and unit sizes in the SES scenario

Technology	**Size**	**Investment [M€/year]**	**Depreciation time [years]**	**O&M [M€/year]**
CHP	210 MW	9.5	25	6.3
Thermal storage	5 GWh	1.0	20	0.1
Waste CHP	0.31 TWh	4.5	20	5.0
HP – DH grid	120 MW	20.0	25	7.0
DH boilers	239 MW	0.9	35	0.3
Condensing power plants	271 MW	14.0	27	8.5
PV	510 MW	23.7	20	3.5
CSP	295 MW	118.6	20	70.6
Run-of-river hydro	170 MW	28.6	30	11.2
Geothermal power plant	33 MW	8.9	20	4.7
Geothermal – DH grid	0.23 TWh	3.3	25	1.4
Industrial excess heat	0.2 TWh	0.4	30	0.1
Individual heat pumps	15,000 units	11.9	20	2.6
Individual solar thermal	0.07 TWh	18.9	30	4.5
Gasification plant	16 MW	0.7	15	1.3
CO_2 hydrogeneration	400 MW	13.4	15	4.8
Chemical synthesis plant	51 MW	1.9	20	1.0
Heat savings	52%	174.6	20	0
Electricity savings	50%	73.7	10	0
DH network	2.36 TWh	318.0	40	91.9
EV charging infrastructure	421,000 EVs	56.6	20	37

Table 7. Costs and unit sizes in the TRES scenario

Technology	**Size**	**Investment [M€/year]**	**Depreciation time [years]**	**O&M [M€/year]**
CHP	45 MW	2.0	25	1.4
Thermal storage	0.75 GWh	1.0	20	0.1
Waste CHP	0.31 TWh	4.5	20	5.0
DH boilers	234 MW	0.8	35	0.3
Condensing power plants	271 MW	14.0	27	8.5
PV	151 MW	7.0	20	1.0
CSP	295 MW	41.4	20	24.6
Run-of-river hydro	103 MW	28.6	30	11.2
Geothermal power plant	33 MW	8.9	20	4.7
Geothermal – DH grid	0.23 TWh	3.3	25	1.4
Individual heat pumps	103,000 units	79.9	20	17.8
Individual solar thermal	0.3 TWh	18.9	30	4.5
Gasification plant	16 MW	0.7	15	1.3
Heat savings	52%	174.6	20	0
Electricity savings	50%	73.7	10	0
EV charging infrastructure	380,000 EVs	56.6	20	37

Table 8. Fuel costs used in the Reference (2015) and the future scenarios (2050) [EUR/GJ]

	Fuel oil	**Diesel**	**Petrol**	**Natural gas**	**LPG**	**Biomass**
2015	11.9	15	16.1	9.1	17	6.2
2050	16.1	20	20.6	12.2	22.1	8.1

Table 9. CO_2 content in fuels

Fuel type	**Fuel oil/Diesel/Petrol**	**Natural gas**	**LPG**	**Waste**
CO_2 content [kg/GJ]	**11.9**	15	16.1	9.1

10.3 Appendix III – EnergyPLAN outputs

10.3.1 Reference scenario output

Input _Zg_ref_2015.txt — **The EnergyPLAN model 12.4**

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	2.93	Fixed imp/exp.	0.00
Electric heating + HP	0.00	Transportation	0.09
Electric cooling	0.00	Total	3.02

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.04	0.00	1.99	2.03
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.04	0.00	1.99	2.03

Wind	0 MW	0.00 TWh/year	0.00	Grid
Photo Voltaic	0 MW	0 TWh/year	0.00	stabili-
Wave Power	0 MW	0 TWh/year	0.00	sation
River Hydro	0 MW	0 TWh/year	0.00	share
Hydro Power	0 MW	0 TWh/year		
Geothermal/Nuclear	0 MW	0 TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0.39	0.45	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	144	166	0.39	0.45	
Heat Pump	0	0			3.00
Boiler		696		0.95	
Condensing	510		0.35		

Heatstorage: gr.2: 1 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.00	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.00

Regulation Strategy:	Technical regulation no. 1
CEEP regulation	00000000
Minimum Stabilisation share	0.00
Stabilisation share of CHP	0.00
Minimum CHP gr 3 load	0 MW
Minimum PP	0 MW
Heat Pump maximum share	0.50
Maximum import/export	0 MW
Distr. Name :	Hour_nordpool.txt
Addition factor	0.00 EUR/MWh
Multiplication factor	2.00
Dependency factor	0.00 EUR/MWh pr. MW
Average Market Price	227 EUR/MWh
Gas Storage	0 GWh
Syngas capacity	0 MW
Biogas max to grid	0 MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0.80	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:		0.000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	3.25	0.03	0.00
Household	0.00	0.28	2.91	0.59
Industry	0.00	0.28	0.29	0.00
Various	0.00	0.00	0.00	0.00

Output

District Heating: Demand / Production / Balance; Electricity: Consumption / Production / Balance; Exchange

	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Payment Imp Million EUR	Payment Exp Million EUR
January	567	0	0	12	166	0	0	389	0	0	358	10	0	0	0	0	0	0	0	0	0	144	225	100	0	0	0	0	0	0
February	480	0	0	10	166	0	0	304	0	0	365	10	0	0	0	0	0	0	0	0	0	144	232	100	0	0	0	0	0	0
March	366	0	0	8	162	0	0	197	0	0	340	10	0	0	0	0	0	0	0	0	0	140	210	100	0	0	0	0	0	0
April	95	0	0	2	73	0	0	20	0	0	315	10	0	0	0	0	0	0	0	0	0	63	262	100	0	0	0	0	0	0
May	38	0	0	1	37	0	0	0	0	0	298	10	0	0	0	0	0	0	0	0	0	32	277	100	0	0	0	0	0	0
June	38	0	0	1	37	0	0	0	0	0	306	10	0	0	0	0	0	0	0	0	0	32	285	100	0	0	0	0	0	0
July	38	0	0	1	37	0	0	0	0	0	363	10	0	0	0	0	0	0	0	0	0	32	342	100	0	0	0	0	0	0
August	38	0	0	1	37	0	0	0	0	0	346	10	0	0	0	0	0	0	0	0	0	32	324	100	0	0	0	0	0	0
September	38	0	0	1	37	0	0	0	0	0	320	10	0	0	0	0	0	0	0	0	0	32	298	100	0	0	0	0	0	0
October	153	0	0	3	100	0	0	50	0	0	310	10	0	0	0	0	0	0	0	0	0	87	234	100	0	0	0	0	0	0
November	387	0	0	8	165	0	0	214	0	0	328	10	0	0	0	0	0	0	0	0	0	143	196	100	0	0	0	0	0	0
December	540	0	0	11	166	0	0	362	0	0	351	10	0	0	0	0	0	0	0	0	0	144	218	100	0	0	0	0	0	0
Average	231	0	0	5	98	0	0	128	0	0	333	10	0	0	0	0	0	0	0	0	0	85	259	100	0	0	0	0	Average price	
Maximum	927	0	0	20	166	0	0	696	0	46	501	21	0	0	0	0	0	0	0	0	0	144	476	100	0	0	0	0	(EUR/MWh)	
Minimum	38	0	0	1	37	0	0	0	0	0	197	0	0	0	0	0	0	0	0	0	0	32	88	100	0	0	0	0	227	204
TWh/year	2.03	0.00	0.00	0.04	0.86	0.00	0.00	1.12	0.00	0.00	2.93	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	2.27		0.00	0.00	0.00	0.00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV	Wave	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Net	CO2 emission (Mt): Total	CO2 emission (Mt): Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	-	0.00	0.00	0.00	0.00	0.00
Oil	-	-	0.19	-	0.12	-	-	-	-	-	-	-	-	-	-	-	-	3.25	0.28	0.28	4.11	0.00	4.11	1.10	1.10
N.Gas	0.05	-	1.73	-	1.06	6.49	-	-	-	-	-	-	-	-	-	-	-	0.14	2.91	0.29	12.68	0.00	12.68	2.59	2.61
Biomass	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.59	0.00	0.59	0.00	0.59	0.00	0.00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
H2 etc.	-	-	0.00	-	0.00	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-0.06	-	-	-	-	-	-	0.06	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	0.05	-	1.92	-	1.16	6.49	-	-	-	-	-0.06	-	-	-	-	-	-	3.44	3.78	0.57	17.38	0.00	17.38	3.69	3.71

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Output specifications _Zg_ref_2015.txt The EnergyPLAN model 12.4

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Storage MW	Gr.2 Balance MW
January	12	0	0	12	0	0	0	0	0	0	0	0	0	0
February	10	0	0	10	0	0	0	0	0	0	0	0	0	0
March	8	0	0	8	0	0	0	0	0	0	0	0	0	0
April	2	0	0	2	0	0	0	0	0	0	0	0	0	0
May	1	0	0	1	0	0	0	0	0	0	0	0	0	0
June	1	0	0	1	0	0	0	0	0	0	0	0	0	0
July	1	0	0	1	0	0	0	0	0	0	0	0	0	0
August	1	0	0	1	0	0	0	0	0	0	0	0	0	0
September	1	0	0	1	0	0	0	0	0	0	0	0	0	0
October	3	0	0	3	0	0	0	0	0	0	0	0	0	0
November	8	0	0	8	0	0	0	0	0	0	0	0	0	0
December	11	0	0	11	0	0	0	0	0	0	0	0	0	0
Average	5	0	0	5	0	0	0	0	0	0	0	0	0	0
Maximum	20	0	0	20	0	0	0	0	0	0	0	0	0	0
Minimum	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0.04	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Storage MW	Gr.3 Balance MW
January	555	0	0	166	0	0	389	0	0	0
February	470	0	0	166	0	0	304	0	0	0
March	359	0	0	162	0	0	197	0	0	0
April	93	0	0	73	0	0	20	0	0	0
May	37	0	0	37	0	0	0	0	0	0
June	37	0	0	37	0	0	0	0	0	0
July	37	0	0	37	0	0	0	0	0	0
August	37	0	0	37	0	0	0	0	0	0
September	37	0	0	37	0	0	0	0	0	0
October	150	0	0	100	0	0	50	0	0	0
November	379	0	0	165	0	0	214	0	0	0
December	528	0	0	166	0	0	362	0	0	0
Average	226	0	0	98	0	0	128	0	0	0
Maximum	908	0	0	166	0	0	696	0	0	46
Minimum	37	0	0	37	0	0	0	0	0	0
Total for the whole year TWh/year	1.99	0.00	0.00	0.86	0.00	0.00	1.12	0.00		0.00

	RES specification RES1 Wind MW	RES2 Photo ' MW	RES3 Wave I MW	RES 4-7 :r MW	Total MW
January	0	0	0	0	0
February	0	0	0	0	0
March	0	0	0	0	0
April	0	0	0	0	0
May	0	0	0	0	0
June	0	0	0	0	0
July	0	0	0	0	0
August	0	0	0	0	0
September	0	0	0	0	0
October	0	0	0	0	0
November	0	0	0	0	0
December	0	0	0	0	0
Average	0	0	0	0	0
Maximum	0	0	0	0	0
Minimum	0	0	0	0	0
Total for the whole year TWh/year	0.00	0.00	0.00	0.00	0.00

Own use of heat from industrial CHP: 0.00 TWh/year

ANNUAL COSTS (Million EUR)		
Total Fuel ex Ngas exchange =		317
Uranium =	0	
Coal =	0	
FuelOil =	28	
Gasoil/Diesel=	156	
Petrol/JP =	65	
Gas handling =	49	
Biomass =	20	
Food income =	0	
Waste =	0	
Total Ngas Exchange costs =		412
Marginal operation costs =		8
Total Electricity exchange =		0
Import =	0	
Export =	0	
Bottleneck =	0	
Fixed imp/ex=	0	
Total CO2 emission costs =		105
Total variable costs =		843
Fixed operation costs =		48
Annual Investment costs =		104
TOTAL ANNUAL COSTS =		995

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Individual MW	Transport MW	Indu. Var. MW	Demand Sum MW	Biogas MW	Syngas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Storage MW	Sum MW	Import MW	Export MW
January	382	332	642	815	4	33	2207	0	0	0	0	0	0	2207	2207	0
February	299	332	662	689	4	33	2019	0	0	0	0	0	0	2019	2019	0
March	195	324	601	526	4	33	1683	0	0	0	0	0	0	1683	1683	0
April	21	145	749	136	4	33	1088	0	0	0	0	0	0	1088	1088	0
May	1	74	791	54	4	33	956	0	0	0	0	0	0	956	956	0
June	1	74	814	54	4	33	979	0	0	0	0	0	0	979	979	0
July	1	74	977	54	4	33	1142	0	0	0	0	0	0	1142	1142	0
August	1	74	927	54	4	33	1092	0	0	0	0	0	0	1092	1092	0
September	1	74	852	54	4	33	1017	0	0	0	0	0	0	1017	1017	0
October	51	201	669	220	4	33	1177	0	0	0	0	0	0	1177	1177	0
November	212	330	560	556	4	33	1694	0	0	0	0	0	0	1694	1694	0
December	356	332	623	775	4	33	2123	0	0	0	0	0	0	2123	2123	0
Average	126	197	739	332	4	33	1431	0	0	0	0	0	0	1431	1431	0
Maximum	681	332	1361	1332	4	33	3172	0	0	0	0	0	0	3172	3172	0
Minimum	1	74	251	54	4	33	697	0	0	0	0	0	0	697	697	0
Total for the whole year TWh/year	1.11	1.73	6.49	2.91	0.03	0.29	12.57	0.00	0.00	0.00	0.00	0.00	0.00	12.57	12.57	0.00

RES Share: 3.4 Percent of Primary Energy 0.0 Percent of Electricity 0.0 TWh electricity from RES

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10.3.2 TRES scenario output

Input _Zg_TRES_2050.txt

The EnergyPLAN model 12.4

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	2.04	Fixed imp/exp.	0.00
Electric heating + HP	0.42	Transportation	0.91
Electric cooling	0.00	Total	3.37

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.04	0.00	0.86	0.90
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.04	0.00	0.86	0.90

				Grid stabilisation share
Photo Voltaic	151 MW	0.22	TWh/year	0.00
CSP Solar Power	103 MW	0.44	TWh/year	0.00
River Hydro	170 MW	0.63	TWh/year	0.00
Photo Voltaic	0 MW	0	TWh/year	0.00
Hydro Power	0 MW	0	TWh/year	
Geothermal/Nuclear	33 MW	0.29	TWh/year	

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0.39	0.45	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	45	56	0.40	0.50	
Heat Pump	0	0			3.00
Boiler		210		0.95	
Condensing	680		0.47		

Heatstorage: gr.2: 0 GWh gr.3: 1 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.00	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.09

Regulation Strategy: Technical regulation no. 1
CEEP regulation 00000000
Minimum Stabilisation share 0.00
Stabilisation share of CHP 0.00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 1.00
Maximum import/export 0 MW

Distr. Name : Price_DKV_2003.txt
Addition factor 0.00 EUR/MWh
Multiplication factor 1.00
Dependency factor 0.00 EUR/MWh pr. MW
Average Market Price 250 EUR/MWh
Gas Storage 0 GWh
Syngas capacity 16 MW
Biogas max to grid 0 MW

Fuel Price level:

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	60	2	0.90	
Hydro Turbine:	60		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	

CAES fuel ratio: 0.000

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	0.00	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.00	0.00	0.14	0.14
Various	0.00	0.00	0.00	0.00

Output

	District Heating: Demand Distr. heating MW	DH Production: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Electricity Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Electricity Production: Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Balance: Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp (Million EUR)	Exp
January	252	0	80	12	56	0	0	103	0	0	250	101	144	0	0	0	0	127	0	33	11	45	280	100	0	0	0	0	0	0
February	214	0	80	10	54	0	0	70	0	-1	255	104	121	0	0	0	0	126	0	33	11	43	267	100	0	0	0	0	0	0
March	163	0	80	8	46	0	0	32	0	-3	238	105	87	0	0	0	0	150	0	33	11	36	200	100	0	0	0	0	0	0
April	42	0	46	2	7	0	0	0	0	-13	220	100	15	0	0	0	0	172	0	33	11	5	114	100	0	0	0	0	0	0
May	17	0	27	1	0	0	0	0	0	-11	208	105	0	0	0	1	1	181	0	33	11	0	89	100	0	0	0	0	0	0
June	17	0	27	1	0	0	0	0	0	-11	214	104	0	0	0	0	0	156	0	33	11	0	119	100	0	0	0	0	0	0
July	17	0	27	1	0	0	0	0	0	-11	254	101	0	0	0	0	0	133	0	33	11	0	178	100	0	0	0	0	0	0
August	17	0	27	1	0	0	0	0	0	-11	241	105	0	0	0	0	0	123	0	33	11	0	180	100	0	0	0	0	0	0
September	17	0	27	1	0	0	0	0	0	-11	223	102	0	0	0	0	0	135	0	33	11	0	147	100	0	0	0	0	0	0
October	68	0	56	3	17	0	0	1	0	-9	217	103	8	0	0	0	0	160	0	33	11	13	111	100	0	0	0	0	0	0
November	172	0	80	8	49	0	0	35	0	0	229	104	57	0	0	0	0	137	0	33	11	39	171	100	0	0	0	0	0	0
December	240	0	80	11	56	0	0	92	0	0	245	101	137	0	0	0	0	148	0	33	11	45	247	100	0	0	0	0	0	0
Average	103	0	53	5	24	0	0	28	0	-7	233	103	47	0	0	0	0	146	0	33	11	19	175	100	0	0	0	0	Average price (EUR/MWh)	
Maximum	413	0	80	20	56	0	0	210	0	86	350	313	236	0	0	57	56	325	0	33	11	45	564	100	0	0	0	0		
Minimum	17	0	27	1	0	0	0	0	0	-116	138	0	0	0	0	0	0	24	0	33	11	0	0	100	0	0	0	0	252	245
TWh/year	0.90	0.00	0.47	0.04	0.21	0.00	0.00	0.24	0.00	-0.06	2.04	0.90	0.42	0.00	0.00	0.00	0.00	1.28	0.00	0.29	0.09	0.17	1.54		0.00	0.00	0.00	0.00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	PV	CSP	Hydro	PV	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
N.Gas	-	-	-	-	-	-	-	-	-	-	-0.14	-	-	-	-	-	-	-	-	0.14	0.00	0.00	0.00	0.00	0.00
Biomass	0.05	-	0.42	-	0.26	3.27	-	-	0.31	-	0.18	-	-	-	-	-	-	-	-	0.14	4.62	0.00	4.62	0.00	0.00
Renewable	-	-	-	-	-	-	0.36	-	-	-	-	-	0.22	0.44	0.63	-	0.30	-	-	-	1.94	0.00	1.94	0.00	0.00
H2 etc.	-	-	-	-	0.00	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-0.36	-	-	-	-	-	-	0.36	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	0.05	-	0.42	-	0.26	3.27	0.36	-	0.31	-	-0.32	-	0.22	0.44	0.63	-	0.30	0.36	-	0.29	6.57	0.00	6.57	0.00	0.00

27-August-2017 [13:23]

Output specifications _Zg_TRES_2050.txt The EnergyPLAN model 12.4

District Heating Production

Gr.1

	District heating MW	Solar MW	CSHP MW	DHP MW
January	12	0	0	12
February	10	0	0	10
March	8	0	0	8
April	2	0	0	2
May	1	0	0	1
June	1	0	0	1
July	1	0	0	1
August	1	0	0	1
September	1	0	0	1
October	3	0	0	3
November	8	0	0	8
December	11	0	0	11
Average	5	0	0	5
Maximum	20	0	0	20
Minimum	1	0	0	1
Total for the whole year TWh/year	0.04	0.00	0.00	0.04

Gr.2

	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW
January	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00

Gr.3

	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW
January	240	0	80	56	0	0	103	0	145	0
February	203	0	80	54	0	0	70	0	326	-1
March	155	0	80	46	0	0	32	0	420	-3
April	40	0	46	7	0	0	0	0	646	-13
May	16	0	27	0	0	0	0	0	718	-11
June	16	0	27	0	0	0	0	0	718	-11
July	16	0	27	0	0	0	0	0	718	-11
August	16	0	27	0	0	0	0	0	718	-11
September	16	0	27	0	0	0	0	0	718	-11
October	65	0	56	17	0	0	1	0	666	-9
November	164	0	80	49	0	0	35	0	361	0
December	229	0	80	56	0	0	92	0	146	0
Average	98	0	53	24	0	0	28	0	525	-7
Maximum	393	0	80	56	0	0	210	0	750	86
Minimum	16	0	27	0	0	0	0	0	0	-116
Total for the whole year TWh/year	0.86	0.00	0.47	0.21	0.00	0.00	0.24	0.00		-0.06

RES specification

	RES1 Photo MW	RES2 CSP S MW	RES3 River MW	RES 4-7 MW	Total MW
January	13	32	83	0	127
February	22	32	73	0	126
March	25	39	85	0	150
April	29	53	89	0	172
May	35	59	88	0	181
June	36	65	56	0	156
July	37	65	32	0	133
August	34	65	24	0	123
September	25	65	46	0	135
October	19	59	82	0	160
November	12	35	89	0	137
December	9	32	108	0	148
Average	25	50	71	0	146
Maximum	145	103	108	0	325
Minimum	0	0	24	0	24
Total for the whole year TWh/year	0.22	0.44	0.63	0.00	1.28

Own use of heat from industrial CHP: 0.00 TWh/year

ANNUAL COSTS (Million EUR)

Total Fuel ex Ngas exchange =		148
Uranium =	0	
Coal =	0	
FuelOil =	0	
Gasoil/Diesel=	3	
Petrol/JP =	0	
Gas handling =	1	
Biomass =	144	
Food income =	0	
Waste =	0	
Total Ngas Exchange costs =		0
Marginal operation costs =		9
Total Electricity exchange =		0
Import =	0	
Export =	0	
Bottleneck =	0	
Fixed imp/ex=	0	
Total CO2 emission costs =		0
Total variable costs =		157
Fixed operation costs =		165
Annual investment costs =		568
TOTAL ANNUAL COSTS =		891

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
February	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
March	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
April	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
May	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
June	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
July	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
August	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
September	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
October	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
November	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
December	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
Average	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	16	16	0	16	0	0	0	0	0	0	0
Total for the whole year TWh/year	0.00	0.00	0.00	0.00	0.00	0.14	0.14	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00

RES Share: 100.0 Percent of Primary Energy 157.5 Percent of Electricity 3.4 TWh electricity from RES 27-August-2017 [13:24]

10.3.3 SES scenario output

Input _Zg_SES_2050.txt — **The EnergyPLAN model 12.4**

Electricity demand (TWh/year):		Flexible demand	0.00
Fixed demand	2.04	Fixed imp/exp.	0.00
Electric heating + HP	0.05	Transportation	0.90
Electric cooling	0.00	Total	3.00

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0.04	0.00	2.32	2.36
Solar Thermal	0.00	0.00	0.00	0.00
Industrial CHP (CSHP)	0.00	0.00	0.00	0.00
Demand after solar and CSHP	0.04	0.00	2.32	2.36

Photo Voltaic	510 MW	0.73 TWh/year	0.00	Grid
CSP Solar Power	295 MW	1.26 TWh/year	0.00	stabili-
River Hydro	170 MW	0.63 TWh/year	0.00	sation
River Hydro	0 MW	0 TWh/year	0.00	share
Hydro Power	0 MW	0 TWh/year		
Geothermal/Nuclear	33 MW	0.29 TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0.39	0.45	
Heat Pump	0	0			3.00
Boiler		0		0.90	
Group 3:					
CHP	210	263	0.40	0.50	
Heat Pump	120	360			3.00
Boiler		215		0.95	
Condensing	481		0.47		

Heatstorage: gr.2: 0 GWh gr.3: 5 GWh
Fixed Boiler: gr.2: 0.0 Per cent gr.3: 0.0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0.00	0.00
Gr.2:	0.00	0.00
Gr.3:	0.00	0.09

Regulation Strategy:	Technical regulation no. 2
CEEP regulation	00000000
Minimum Stabilisation share	0.00
Stabilisation share of CHP	0.00
Minimum CHP gr 3 load	0 MW
Minimum PP	0 MW
Heat Pump maximum share	1.00
Maximum import/export	0 MW
Distr. Name :	Price_DKV_2003.txt
Addition factor	0.00 EUR/MWh
Multiplication factor	1.00
Dependency factor	0.00 EUR/MWh pr. MW
Average Market Price	250 EUR/MWh
Gas Storage	0 GWh
Syngas capacity	16 MW
Biogas max to grid	0 MW

Fuel Price level:

Capacities Storage Efficiencies	MW-e	GWh	elec.	Ther.
Hydro Pump:	0	0	0.90	
Hydro Turbine:	0		0.90	
Electrol. Gr.2:	0	0	0.80	0.10
Electrol. Gr.3:	0	0	0.80	0.10
Electrol. trans.:	0	0	0.80	
Ely. MicroCHP:	0	0	0.80	
CAES fuel ratio:	0.000			

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0.00	0.00	0.00	0.00
Household	0.00	0.00	0.00	0.00
Industry	0.00	0.00	0.14	0.14
Various	0.00	0.00	0.00	0.00

Output

	District Heating: Demand Distr. heating MW	DH Production: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Electricity Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Electricity Production: Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Balance: Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million EUR	Exp Million EUR
January	660	0	127	12	229	257	0	33	0	2	250	101	107	42	0	0	0	215	0	33	11	183	58	100	0	0	0	0	0	0
February	559	0	127	10	206	211	0	11	0	-6	255	104	87	55	0	0	0	236	0	33	11	165	57	100	0	0	0	0	0	0
March	427	0	127	8	150	138	0	0	0	4	238	105	57	84	0	0	0	284	0	33	11	120	36	100	0	0	0	0	0	0
April	110	0	62	2	26	23	0	0	0	-3	220	103	13	97	0	0	0	339	0	33	11	21	28	100	0	0	0	0	0	0
May	44	0	27	1	7	9	0	0	0	0	208	107	4	116	0	0	0	373	0	33	11	5	13	100	0	0	0	0	0	0
June	44	0	27	1	7	9	0	0	0	0	214	107	4	113	0	0	0	361	0	33	11	5	28	100	0	0	0	0	0	0
July	44	0	27	1	8	8	0	0	0	0	254	103	3	92	0	0	0	341	0	33	11	6	61	100	0	0	0	0	0	0
August	44	0	27	1	8	8	0	0	0	0	241	106	3	89	0	0	0	324	0	33	11	7	65	100	0	0	0	0	0	0
September	44	0	27	1	8	8	0	0	0	0	223	104	4	88	0	0	0	314	0	33	11	6	54	100	0	0	0	0	0	0
October	179	0	81	3	50	48	0	0	0	-3	217	103	21	92	0	0	0	315	0	33	11	40	33	100	0	0	0	0	0	0
November	451	0	127	8	180	134	0	0	0	1	229	104	56	75	0	0	0	231	0	33	11	144	46	100	0	0	0	0	0	0
December	629	0	127	11	229	238	0	22	0	1	245	101	92	65	0	0	0	228	0	33	11	184	48	100	0	0	0	0	0	0
Average	269	0	76	5	92	91	0	6	0	0	233	104	38	84	0	0	0	297	0	33	11	74	44	100	0	0	0	0	Average price	
Maximum	1080	0	127	20	262	360	0	215	0	318	350	296	155	356	0	0	0	840	0	33	11	210	307	100	0	0	0	0	(EUR/MWh)	
Minimum	44	0	27	1	0	0	0	0	0	-269	138	-176	0	0	0	0	0	24	0	33	11	0	0	100	0	0	0	0	246	240
TWh/year	2.36	0.00	0.67	0.04	0.81	0.80	0.00	0.05	0.00	0.00	2.04	0.91	0.33	0.74	0.00	0.00	0.00	2.61	0.00	0.29	0.09	0.65	0.39		0.00	0.00	0.00	0.00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	PV	CSP	Hydro	Hydro	Solar.Th	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
N.Gas	-	-	-	-	-	-	-	-	-	-	-0.14	0.00	-	-	-	-	-	-	-	0.14	0.00	0.00	0.00	0.00	0.00
Biomass	0.05	-	1.62	-	0.05	0.82	-	-	0.31	-	0.17	-	-	-	-	-	-	-	-	0.14	3.17	0.00	3.17	0.00	0.00
Renewable	-	-	-	-	-	-	0.36	-	-	-	-	-	0.73	1.26	0.63	-	0.07	-	-	-	3.04	0.00	3.04	0.00	0.00
H2 etc.	-	-	-	-	0.00	0.00	-	-	-	-0.52	-	0.52	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-0.36	-	-	-	-	-	0.36	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Total	0.05	-	1.62	-	0.05	0.82	0.36	-	0.31	-0.52	0.03	0.16	0.73	1.26	0.63	-	0.07	0.36	-	0.29	6.21	0.00	6.21	0.00	0.00

27-August-2017 [13:24]

Output specifications _Zg_SES_2050.txt The EnergyPLAN model 12.4

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Storage MW	Gr.2 Balance MW
January	12	0	0	12	0	0	0	0	0	0	0	0	0	0
February	10	0	0	10	0	0	0	0	0	0	0	0	0	0
March	8	0	0	8	0	0	0	0	0	0	0	0	0	0
April	2	0	0	2	0	0	0	0	0	0	0	0	0	0
May	1	0	0	1	0	0	0	0	0	0	0	0	0	0
June	1	0	0	1	0	0	0	0	0	0	0	0	0	0
July	1	0	0	1	0	0	0	0	0	0	0	0	0	0
August	1	0	0	1	0	0	0	0	0	0	0	0	0	0
September	1	0	0	1	0	0	0	0	0	0	0	0	0	0
October	3	0	0	3	0	0	0	0	0	0	0	0	0	0
November	8	0	0	8	0	0	0	0	0	0	0	0	0	0
December	11	0	0	11	0	0	0	0	0	0	0	0	0	0
Average	5	0	0	5	0	0	0	0	0	0	0	0	0	0
Maximum	20	0	0	20	0	0	0	0	0	0	0	0	0	0
Minimum	1	0	0	1	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0.04	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00

	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Storage MW	Gr.3 Balance MW	RES specification RES1 Photo MW	RES2 CSP S MW	RES3 River MW	RES 4-7 MW	Total MW
January	648	0	127	229	257	0	33	0	313	2	43	90	83	0	215
February	549	0	127	206	211	0	11	0	974	-6	73	90	73	0	236
March	419	0	127	150	138	0	0	0	2089	4	86	112	85	0	284
April	108	0	62	26	23	0	0	0	1376	-3	98	152	89	0	339
May	43	0	27	7	9	0	0	0	1377	0	117	168	88	0	373
June	43	0	27	7	9	0	0	0	1377	0	120	185	56	0	361
July	43	0	27	8	8	0	0	0	1377	0	124	185	32	0	341
August	43	0	27	8	8	0	0	0	1377	0	115	185	24	0	324
September	43	0	27	8	8	0	0	0	1377	0	83	185	46	0	314
October	175	0	81	50	48	0	0	0	1580	-3	66	168	82	0	315
November	443	0	127	180	134	0	0	0	1626	1	40	101	89	0	231
December	617	0	127	229	238	0	22	0	1418	1	30	90	108	0	228
Average	264	0	76	92	91	0	6	0	1356	0	83	143	71	0	297
Maximum	1060	0	127	262	360	0	215	0	5000	318	489	295	108	0	840
Minimum	43	0	27	0	0	0	0	0	0	-269	0	0	24	0	24
Total for the whole year TWh/year	2.32	0.00	0.67	0.81	0.80	0.00	0.05	0.00		0.00	0.73	1.26	0.63	0.00	2.61

Own use of heat from industrial CHP: 0.00 TWh/year

ANNUAL COSTS (Million EUR)		
Total Fuel ex Ngas exchange =		99
Uranium =	0	
Coal =	0	
FuelOil =	0	
Gasoil/Diesel=	3	
Petrol/JP =	0	
Gas handling =	1	
Biomass =	96	
Food income =	0	
Waste =	0	
Total Ngas Exchange costs =		0
Marginal operation costs =		7
Total Electricity exchange =		0
Import =	0	
Export =	0	
Bottleneck =	0	
Fixed imp/ex=	0	
Total CO2 emission costs =		0
Total variable costs =		107
Fixed operation costs =		179
Annual Investment costs =		617
TOTAL ANNUAL COSTS =		902

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	0	0	0	0	0	16	16	0	16	26	0	-51	0	26	27	1
February	0	0	0	0	0	16	16	0	16	33	0	-51	0	18	21	3
March	0	0	0	0	0	16	16	0	16	51	0	-51	0	0	10	10
April	0	0	0	0	0	16	16	0	16	59	0	-51	0	-8	18	25
May	0	0	0	0	0	16	16	0	16	71	0	-51	0	-19	20	39
June	0	0	0	0	0	16	16	0	16	69	0	-51	0	-17	20	38
July	0	0	0	0	0	16	16	0	16	56	0	-51	0	-5	22	27
August	0	0	0	0	0	16	16	0	16	54	0	-51	0	-3	23	26
September	0	0	0	0	0	16	16	0	16	53	0	-51	0	-2	21	23
October	0	0	0	0	0	16	16	0	16	56	0	-51	0	-4	13	18
November	0	0	0	0	0	16	16	0	16	46	0	-51	0	6	8	2
December	0	0	0	0	0	16	16	0	16	39	0	-51	0	12	13	1
Average	0	0	0	0	0	16	16	0	16	51	0	-51	0	0	18	18
Maximum	0	0	0	0	0	16	16	0	16	216	0	-51	0	51	51	165
Minimum	0	0	0	0	0	16	16	0	16	0	0	-51	0	-165	0	0
Total for the whole year TWh/year	0.00	0.00	0.00	0.00	0.00	0.14	0.14	0.00	0.14	0.45	0.00	-0.45	0.00	0.00	0.16	0.16

RES Share: 100.0 Percent of Primary Energy 125.2 Percent of Electricity 4.0 TWh electricity from RES

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