CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

DEPARTMENT OF ENVIRONMENTAL ENGINEERING

REVIEW OF SIMULATION METHODS FOR DISTRICT HEATING MODELING AND ASSESSMENT

BACHELOR THESIS

Karim Taha 2-EE-2021

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

BACHELOR'S THESIS ASSIGNMENT

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II. Bachelor's thesis details

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Rešerše metod pro modelování a posouzení dálkového vytápění budov

Guidelines:

In context of decarbonization of the building sector, the final project aims to research currently available methods and simulation tools for assessment of the district and neighborhood solutions. Especially methods applicable for revitalization of existing district heating should be addressed. The students will provide in-depth literature review regarding modelling concepts and methods suitable for district heating assessment, typical key performance indicators, overview of simulation tools and their application reported in literature. The literature review may be also supported by the practical demonstration of selected tools by analyzing example district or neighborhood.

Bibliography / sources:

Connolly, D., Lund, H., Mathiesen, B. V., Werner, S., Möller, B., Persson, U., ... Nielsen, S. (2014). Heat roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy, 65, 475–489. https://doi.org/10.1016/j.enpol.2013.10.035

Lund, H., Østergaard, P. A., Chang, M., Werner, S., Svendsen, S., Sorknæs, P., ... Möller, B. (2018, December 1). The status of 4th generation district heating: Research and results. Energy. Elsevier Ltd. https://doi.org/10.1016/j.energy.2018.08.206

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Assignment valid until: ____________

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

04.01.2021
Date of assignment receipt

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CVUT-CZ-ZBP-2015.1

Declaration

I hereby declare that I have prepared the bachelor's thesis work entitled "Review of Simulation Methods for District Heating Modeling and Assessment" independently under the guidance of my supervisor Ing. Vojtěch Zavřel, Ph.D., using the literature listed at the end of my bachelor's thesis in the bibliography.

In Prague …………………… ………………………………

Karim Taha

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SUMMARY

The purpose of this thesis is to review simulation tools, that may aid the future revitalization of district heating networks. The presented literature review investigates the available modeling techniques and simulation tools supporting the numerical representation of district heating. The current research identified seven of the most competent simulation tools, that were studied and compared based on their typical application reported in literature. Finally, this thesis briefly demonstrates an example of the simulation practice in one of the tools utilizing factual data of the country of reference i.e., the Czech Republic.

Keywords: District heating networks; Modeling and simulation; Decarbonization of energy sector; Thermal energy systems.

Účelem této práce je provést rešerži simulačních nástrojů, které mohou pomoci při revitalizaci současných sítí dálkového vytápění. Prezentovaná literární rešerže se zabývá možnými přístupy modelování a simulačními nástroji podporující numerickou reprezentaci systémů dálkového vytápění. Tento výzkum popisuje sedm nejvhodnějších simulačních nástrojů, které byly studovány a porovnány dlejejich typického použití popsaného v odborné literatuře. V závěru, tato práce stručně demonstruje praktický příklad simulace v jedno ze zkoumaných softwaru využívající faktografická data referenční země tj. České republiky.

Nomenclature

Abbreviations

SH	Space Heating	DAE	Differential Algebraic Equations
DHW	Domestic Hot Water	NREL	National Renewable Energy Laboratory
CHP	Combined Heat and Power	IRR	Internal Rate of Return
DHN	District Heating Network	PES	Primary Energy Saved
DCN	District Cooling Network	GHG	Green House Gases
EU	European Union	OEF	On-site Energy Fraction
CO_2	Carbon Dioxide	OEM	On-site Energy Matching
NZEB	Nearly Zero-Energy Buildings	OMC	OpenModelica Compiler
RES	Renewable Energy Sources	OME	OpenModelica Editor
VRES	Variable Renewable Energy Sources	DOE	Department of Energy
HRE 2050	Heat Roadmap Europe Scenario for 2050	BAU	Business as Usual
GDH	Generation of District Heating	kW	Kilowatt
OS	Operating System	GIS	Geographic Information System
EUI	Energy Use Intensity	LF	Load Factor
HDD	Heating Degree Day	COP	Coefficient of Performance
BL	Baseline		

Symbols

$CHP\ H_{\eta}$	Heat Efficiency in Cogeneration Production	$CHP\ E_{\eta}$	Electricity Efficiency in Cogeneration Production
$Ref\ H_{\eta}$	Efficiency in Separated Heat Generation	$REF\ H_{\eta}$	Efficiency in Separated Electricity Generation
kWh	Kilowatt-hour	$\mathrm{m_c^3}$	Conditioned Cubic Meter of Intervention
$\dot{\mathrm{Q}}_{\mathrm{loss}}$	Heat Loss in DHN		

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Thesis outline

This bachelor thesis focuses on the available methods and tools for assessing and optimizing a district heating network in terms of modeling and simulation. Chapter 1 introduces the motivation behind choosing this topic by highlighting the effects greenhouse gas emissions have on our climate, along with current efforts aimed at controlling and reducing them.

Followed by chapter 2 that depicts the conventional district heating as first-generation stage up until the latest state of the art generation. The chapter describes the motivation and goals achieved by each of the four generations in context of medium of heat carrier, energy efficiency and later on the environmental impact. The chapter ends by highlighting the importance of a district heating network in the context of the Czech Republic, supported by energy consumption and generation data obtained from several local and EU sources that unless mentioned, could be found in the bibliography.

Chapter 3 then reviews some of the most commonly used approaches in modeling of energy systems. The approaches are classified into 3 groups: computational, mathematical and physical models. In addition, some assessment and aggregation methods are described and an introduction to some of the key performance indicators that are necessary in assessing an energy system are discussed.

Chapter 4 reviews the most common modeling and simulation tools that are currently available for assessing DHN solutions. The tools were chosen based on their application in order to represent an extensive array of tools that assess energy systems of different scopes, methodologies, focuses, and technological capabilities. The tools have been summed up in a table that is attached to this thesis.

Chapter 5 discusses the application of the software tools previously mentioned in chapter 4, in practice and research. The chapter divides the applications of the tools into three categories, national and large energy system analysis, local energy system analysis, and finally map-based tools for representation of the building stock performance. Each category contains a few published research papers that tackle different aspects of the energy system with the help of one or more of the software tools reviewed in chapter 4.

Chapter 6 reviews the data published by Heat Roadmap as part of a report conducted on the Czech Republic using EnergyPLAN [1]. The purpose of this chapter however is not to get into details of the report, but rather to review the applicability of the EnergyPLAN tool for district heating modeling purposes. The focus is mainly on the data required by the tool and the methodology of how the software performs a calculation with a set of given data.

1. Introduction

In today's heavily aggravated industrial sectors around the globe, the intensity of carbon and greenhouse gas (GHG) emissions in our atmosphere have increased significantly compared to pre-industrial levels. This has had a direct effect on not only the global population's health, but also the ecosystem of our planet.

Fortunately, in recent years, and for the first time in history, a legally binding global climate change agreement that has been adopted by 196 nations from around the globe. The nations came to an agreement under the United Nations Framework Convention on Climate Change (UNFCCC) known as the Paris Agreement which aims at keeping the global average temperature below 2 °C. In addition, the EU's role has been imperative in brokering the agreement, and has established a Nationally Determined Contribution (NDC) to reduce greenhouse gas emissions by 40% by 2030 compared to 1990 and up to 85-90% by 2050 according to the European Council [2].

Most of the energy needed to cover the high heating demand in the EU comes from natural gas, coal or other oil products while only a small amount comes from green energies such as Renewable Energy Sources (RES). In recent years, the focal point in DHN has shifted towards integrating renewable energy, introducing decentralized sustainable grids into the network, and recycling industrial waste heat. It has been noticed that several studies focused on heat savings and demand and load control strategies for the future of DHN [3], [4].

This bachelor thesis is set out to highlight some of the most prominent modeling methods, key performance indicators and simulation tools that could be used for the purpose of revitalization of current DHN. The thesis also focuses a part of its review on the performance of DHN in the Czech Republic.

2. Characteristics of District Heating Networks

District heating Networks (DHN) are a set of network pipes that deliver hot water for the purpose of Surface Heating (SH) and Domestic Hot Water (DHW) from a district power plant or heating plant to consumers i.e., residential, commercial or industrial buildings. Since the 1880s when the first generation of DH was introduced, several new technologies have been integrated in order to increase the efficiency of energy and most recently to aid the decarbonization of the energy sector.

A brief history of the evolution of DHN has been depicted in this chapter, along with some of the most common RES technologies in DH. The chapter then concludes by assessing the level of DHN in context of our country of interest, the Czech Republic (CZ).

2.1 Generations of District Heating

The first generations of DHN appeared in the US and across Europe in the 1880s, where its remains could still be found in the old New York (Manhattan) and Paris. The key heat carriers used were either high pressurized steam or hot water with temperatures over 100 °C. At such high operational temperatures, the systems were considered to be highly inefficient and left a big carbon footprint as they were often fuelled by coal or oil [5]. In the 1980s the focus shifted towards Combined Heat and Power (CHP) and cogeneration systems along with control strategies that manage the consumer consumption more accurately for better regulation. Steam or hot water were still the heat carrier in place and the use of coal and fossil fuels were still at the forefront due to their high availability, operational and cost efficiency. While in the early 21st century a new third generation DH that focused on shifting towards more sustainable systems that have lower carbon emissions due to the awareness of global warming. At the time, the researchers focused most on renewable energies like solar and reducing the space heating demands using new control strategies [6].

Figure 1 below shows a typical configuration of a DH CHP plant that supplies power to the grid, and DH to residential, commercial and industrial buildings

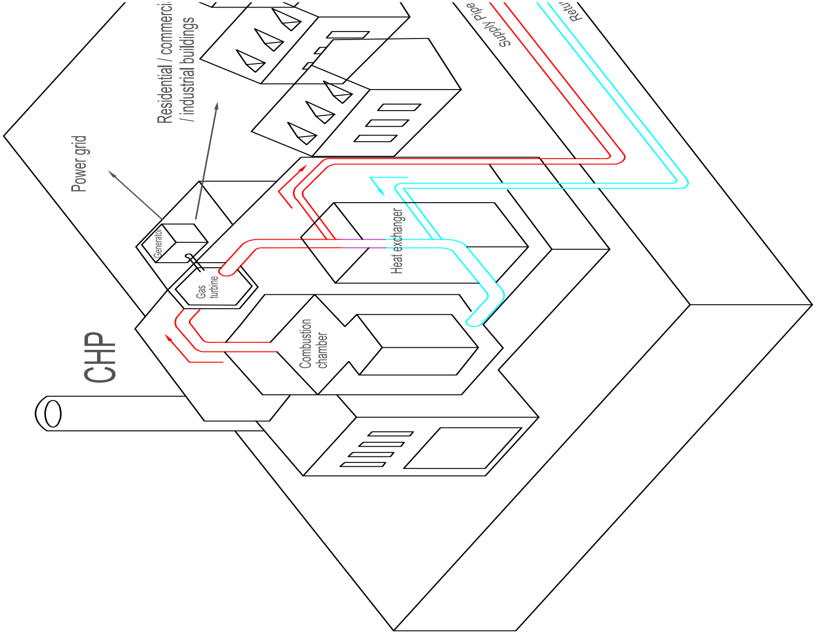


FIGURE 1. EXPLANATORY FIGURE OF A TYPICAL DH CHP PLANT

In recent years, the focus has then shifted towards a system that is more flexible in terms of sources of heat. The researchers focused on greener fuel sources such as solar thermal energy, geothermal energy, and heat pumps to enable for a more integrated large-scale district energy system [7], [8]. In this era, the smart integration of different centralized and decentralized grids is of main focus for the researchers in order to pave the way for the low-temperature smart fourth generation multi-source DH. This state of art generation DH allows the absorption from lower grade waste heat sources which were considered to be insufficient in previous generations due to its low operational temperature. This in turn increases the flexibility of sources of heat. In addition, this generation will allow the installation of less expensive distribution circuits between buildings, without the need for expensive insulation to restrict heat losses to the ground and finally, it is cost effective to retrofit in existing buildings even ones that are not currently connected to the network [9].

Figure 2 below shows a progression time-line of the district heating generations.

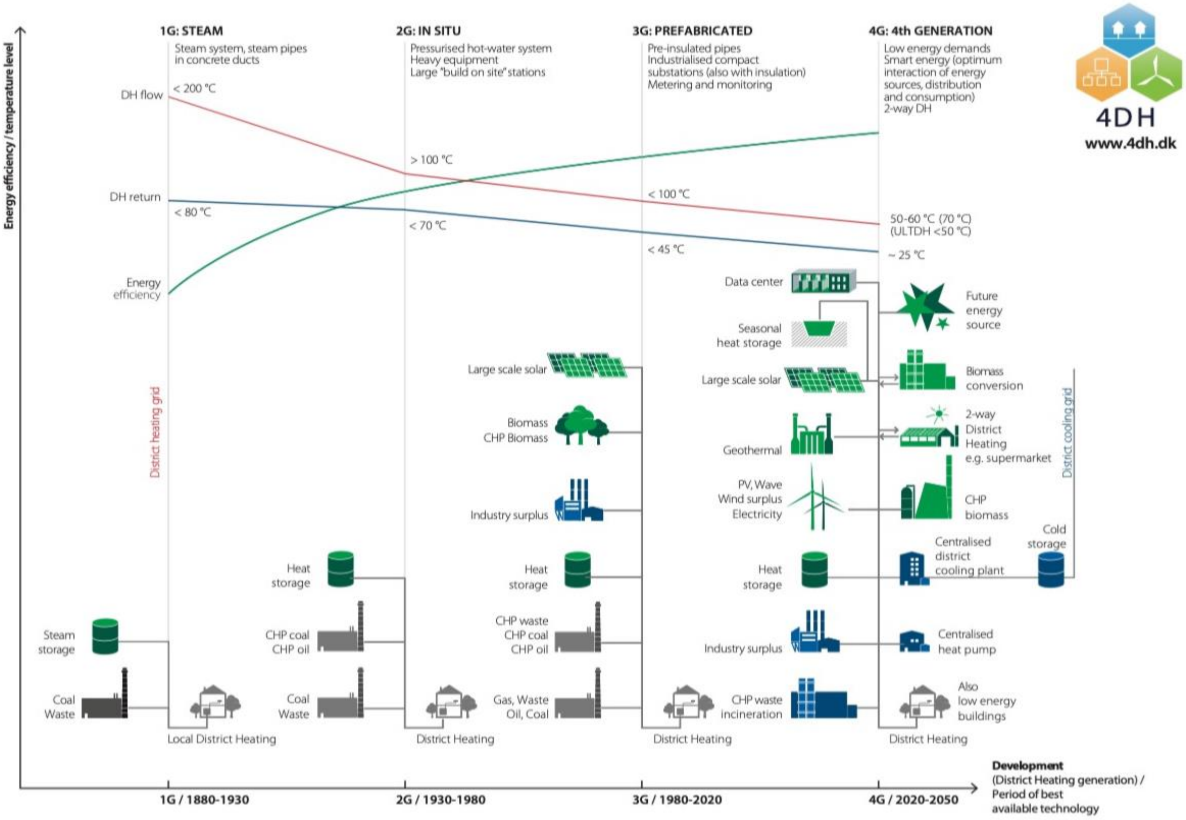


FIGURE 2. DISTRICT HEATING PROGRESSION DIAGRAM [6]

A few prominent renewable energy technologies that have been noticed throughout several studies to be the focus sources of heat for future of DHN are listed in table 1.

Technology	Overview	Challenges	Prospects	Ref.
Bioenergy	• Available from materials derived from biological sources (biomass)	• Uneconomic mass commercialization	• Policies such as ones in Denmark prove that this technology could be made mainstream	[10]–[12]
	• Could be used in rural small-scale systems as well as in industrial thermal plants	• Lack of infrastructure	• Studies have shown that the use of bioenergy in the trasnsport sector has proven to have lower greenhouse gas emissions than when used in DH	
	• As of 2016, bioenergy comprises 59.2% of renewable energy			
Industrial Waste Heat	• Technology mature	• Lack of infrastruture to connect to DH	• An intitiative from policymakers could allow this technology to cover a huge portion of Europe's heat demand	[13], [14]
	• Several studies have been published and highlighted the feasibility of enforcing the technology using long-term policies	• Quality of waste heat varies from one industrial segment to the other	• Fourth generation DH could harness the use of low energy from this technology as well as of course high energy	
Solar Thermal	• Mature technology of which most studies are aimed at improving its effeciency	• Unreliable and unpredictable source of energy that would require large scale thermal storages	• Studies focued on finding an alternative to water a storage medium for lower heat losses	[15]–[17]
	• Possibility to be centralized or decentralized	• Low grade heat source, could only work with low-temperature DHN such as the fourth generation	• Potential of use especially in small-scale decentralized energy systems in the future	
			• Large investments by countries of high solar irradiation have been noticed	
Geothermal	• Oldest technology used in DH	• Low in effeciency due to their indirect usage in heating	• A DH with supply of 50 °C could harness the maximum potential	[18], [19]
	• Possibility of using the technology in hybrid with other new technologies according to its geographic availability	• Low temperatures thus could only be harnessed in low-temperature fourth generation DH	• High density latent heat storage could mismatch the demand and supply	

TABLE 1. PROMINENT RENEWABLE ENERGY TECHNOLOGIES FOR DH

2.2 District Heating in Context of The Czech Republic

2.2.1 Heating Demands and Source Fuel Types

Space heating and domestic hot water are basic commodities in our day-to-day life that are often taken for granted. According to Heat Roadmap Europe (HRE), heating is accountable for about 56% of final energy demand in the Czech Republic which is higher than most European countries where the figure falls to about 50%. The CZ however relies on the cogeneration of heat and electricity which covers 75% of the total centrally produced heat to cover its heat demand [20], [21].

Figure 3 below shows the main fuels used in supplying heat for households in the CZ. Data obtained can be found here [22].

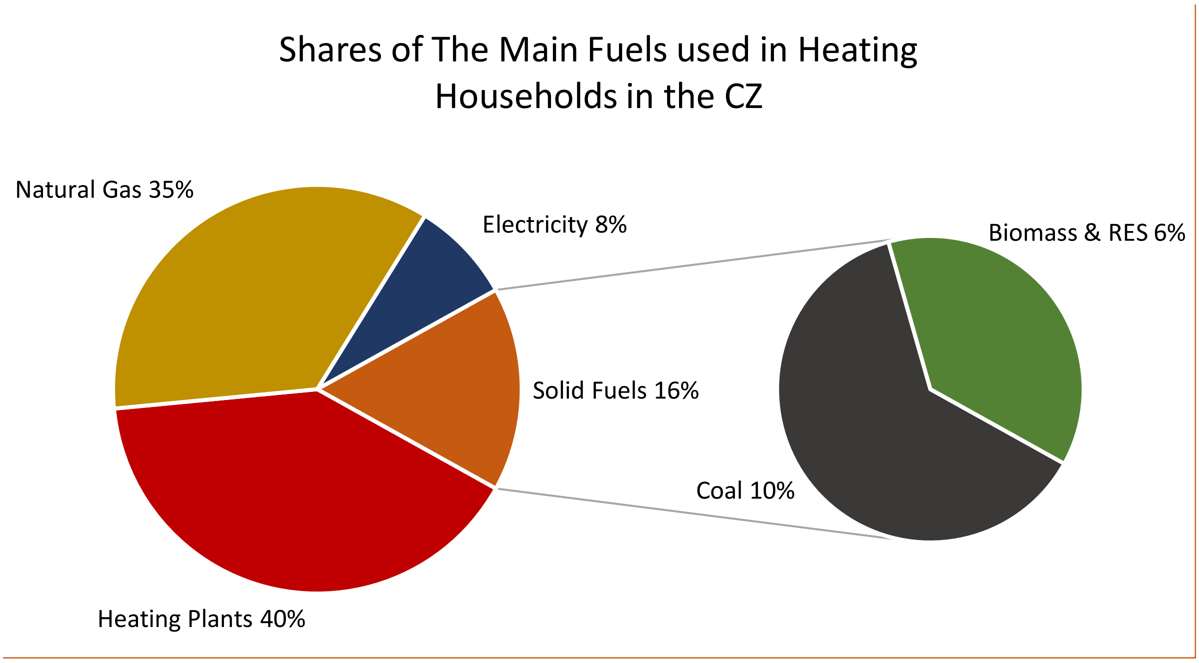


FIGURE 3. SHARE OF MAIN FUELS USED IN HEATING HOUSEHOLDS IN THE CZ IN 2015 [22]

As of 2019, DH covered 40% of the residential heat demand, followed by industry 35% and finally the services sector at 25%. The total length of the heat networks is approximately 10 000 km. Approximately 2 000 km are steam distribution lines of which 900 km of them require reconstruction [21].

2.2.2 Current and Potential Share of Technologies in DHN

According to the HRE2050 vision, the DH source shares should be compromised of a wide variety of sources in order to increase the flexibility of the system and to increase its efficiency. A few prominent energy sources such as CHP, heat pumps and various RES have proved to be some of the most anticipated technologies to be integrated on larger scale in DH by 2050. Heat pumps and CHP are expected to supply 30% and 40% of the DH heat demand, respectively [23]. It is expected that 60% of the total heat demand could be supplied using DH, where if the share is any larger than that, it would become economically inefficient [24].

Figure 4 below shows the share of sources that could be used for DH in 2050.

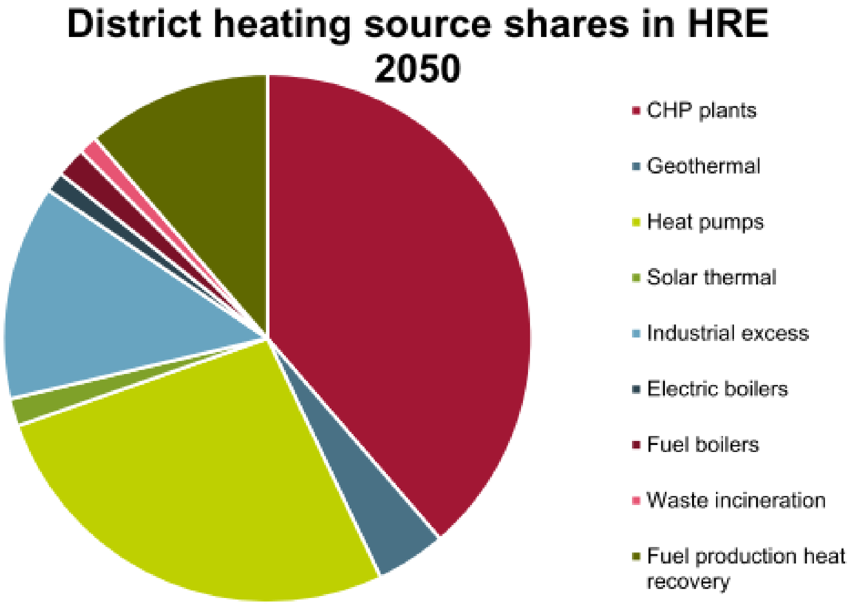


FIGURE 4. DISTRICT HEATING SOURCE SHARES IN HRE2050 [23]

Large Scale Heat Pumps and Cogeneration

It has been stated over the HRE CZ report on several occasions that heat pumps, especially large-scale ones and cogeneration should play a big role in the supply of energy to the DHN. In total, they would supply approximately 70% of the district heating demand. The reason why the researchers are very keen on heat pumps is largely due to the fact that they can integrate production from renewable energies into the heating and cooling sector due to their flexibility in working efficiently in hours of the year where variable renewables are available. In addition, this would also aid in the filling of thermal storages that would enable further integration of variable renewables. This opens the door for the use of variable renewable energies in the electricity utilisation.

The researchers however state a reduction in the cogeneration share largely due to the increase of large-scale heat pumps as they allow more flexibility in the generation of electricity and would reduce the overall demand. In addition, the integration of renewable and excess waste sources would also drive the share of CHP down. A reduction in the share of CHP would also mean a reduction in the indirect combustion of fossil fuels since their main source of fuel in the report was natural gas and biomass. When electricity is available, the use of a wide variety of het sources in the DHN could displace cogeneration while still maintaining a flexible electricity regulation [23].

Renewable Energy

The CZ in recent years has seen an increase in the investment of the renewable energy sector. According to Eurostat-SHARE tool, the data in the charts below show that the CZ has already exceeded its 2020 target of 13% renewable energy share [25]. While renewable energies such as large-scale solar thermal and geothermal are not likely to take a big share of the DH heat demand, they however, would have great potential in small, decentralized DHN that have no access to excess heat. Normally, such renewable energies take up about 5% - 10%. However, large heat pumps which would take up a share of 20% - 30% use mainly other types of renewable energy. Thus, the importance of a wide variety of RES would be deemed valuable [23], [25]. The data from figures 5 and 6 below has been retrieved from the SHARE tool by Eurostat [25]. The data show the share of renewable energy from the gross final energy consumption in the CZ, and the share of RES in heating and cooling.

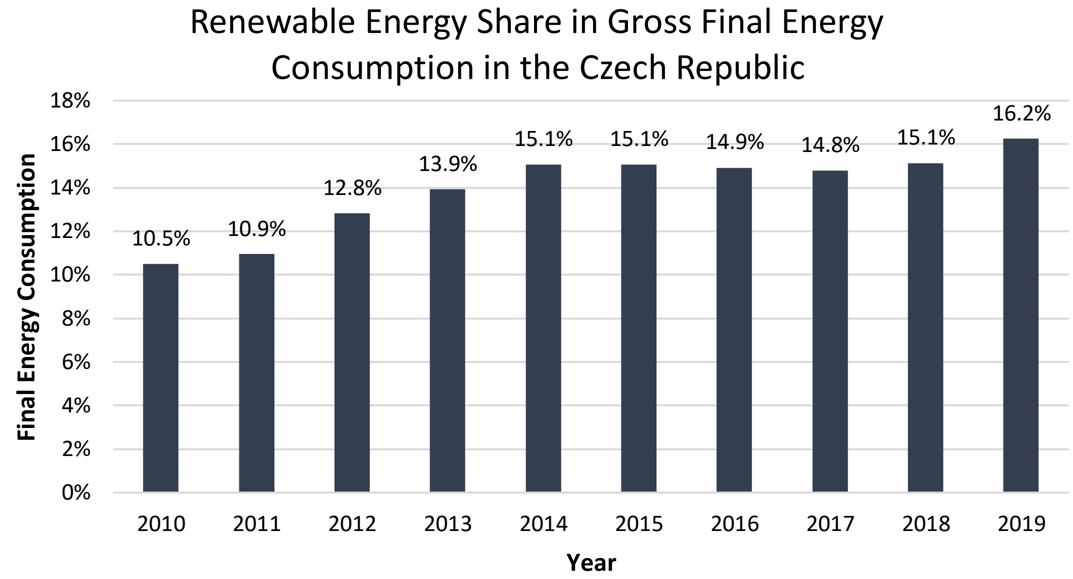


FIGURE 5. RENEWABLE ENERGY SHARE IN GROSS FINAL ENERGY CONSUMPTION IN THE CZ

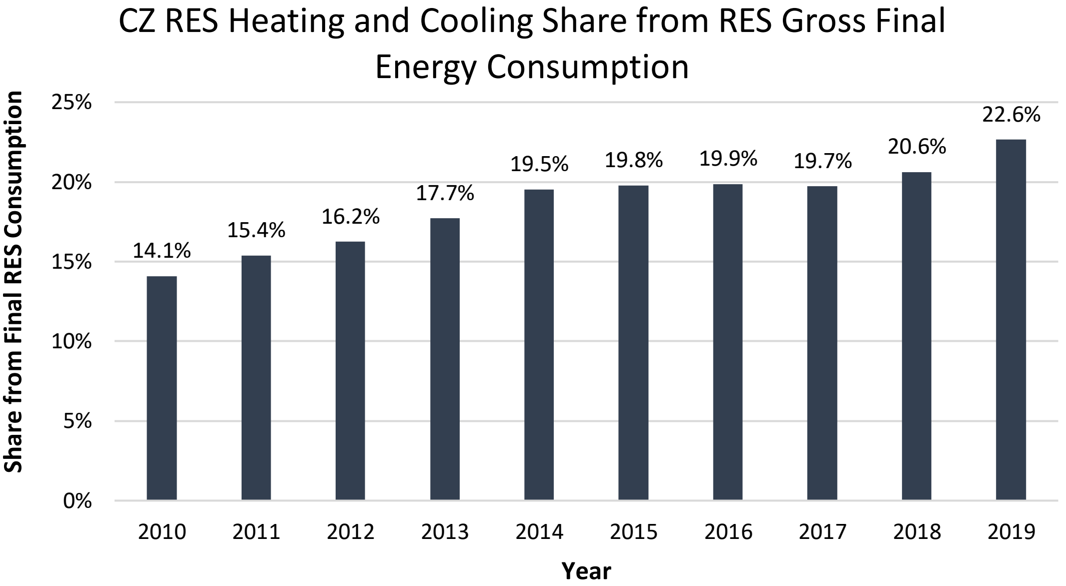


FIGURE 6. CZ RES HEATING AND COOLING SHARE FROM RES GROSS FINAL ENERGY CONSUMPTION

The share of RES in transportation from the gross final RES consumption was between 6% - 7% while electricity was approximately 14%.

3. Modeling Methods and Key Performance Indicators

This chapter discusses common modeling approaches used in DHNs by simulation tools and their associated variables. Followed by a brief introduction of assessment and aggregation methods used in DHN modeling. The chapter concludes by reviewing a few key DHN performance indicators classified into technical, economic, and environmental domains.

3.1 Modeling Approaches

This subchapter has been sourced from the research paper titled “Modeling and Simulation of Energy Systems: A Review” [26]. Energy systems can be classified into computational, mathematical and physical models. Computational models are ones where a computer executes a sequence of instructions usually in the form of one algorithm. Whereas mathematical models are series of equations that describe the behaviour of different variables and parameters of a network. In physical models on the other hand the phenomena of real-world system occur on a smaller scale or with less complexity. For our focus, we will be interested in mathematical models and can omit the remaining models.

Figure 7 below shows the classification of energy systems into 3 modeling approaches.

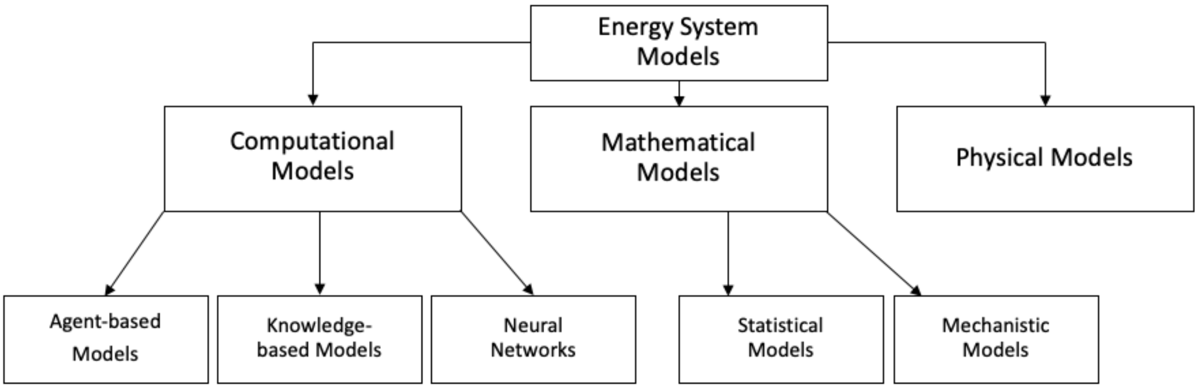


FIGURE 7. CLASSIFICATION OF ENERGY SYSTEM MODELS BY MODELING APPROACH [26]

Mathematical models can be classified into statistical models (black-box) or mechanistic models (white-box). Statistical models can be used to estimate a relationship between a dependant variable and one or more independent variables. That could be done by deriving a set of mathematical equations from input and output data. Mechanistic models on the other hand are used to engage fundamental discipline-specific theories such as fluid mechanics, thermodynamics, mass and energy balances, etc. that provide the model structure and describes the phenomena of the real-world system using generated equations.

Mathematical models can be further categorized depending on the type of data. For example, they could be discrete or continuous models according to the nature of the variables. They could be steady state or dynamic models according to whether they vary with time or not. They could be deterministic or stochastic models according to the certainty of parameters.

Most simulation tools that model district heating networks can be considered as mathematical models. This is due to their deterministic approach that contains no random variables, and the generation of outputs using equations that represent the physical behaviour of the system. In addition, variables that make up a DHN are considered as mathematical models. They either rely on statistical (e.g., demand profiles) or mechanistic (e.g., heat transfer between fluids in the system) models. Some examples of mathematical modeling variables in a DHN are listed below:

- **Demand Profiles:** Use statistical regression models to help create a mathematical equation that represents the correlation of energy consumption during different times of the day or season.
- **Weather Forecasting:** Use statistical models to predict weather conditions. Helpful in forecasting PV power or other RES availability.
- **Pipeline Networks:** Use mechanistic models that considers both the thermal and fluid dynamics of the heat transfer fluid inside the distribution pipe. Helps in assessing pressure losses in the pipe.
- **Heat Exchangers:** Use mechanistic models to simulate the heat transfer process between the heat source and the distribution network.

Note: All simulation tools reviewed in the following chapter are considered mathematical deterministic tools.

3.2 Assessment Methods

The assessment methods in energy systems are usually divided into three main sections: simulation, optimization, and equilibrium models. For our scope, we will be focused on simulation and optimization.

Simulations often evaluate different scenarios in order to understand how a system works. This is useful in identifying errors by simulating real-life systems. They are also commonly used for predicting future performances that are generated using computational, mathematical or physical representation of the system. They allow the users to understand how the system responds to different input. Simulations normally use the bottom-up approach as it provides a detailed technical description of the entire energy system. Bottom-up approach helps in generating accurate simulations for its high detail level however, this means that it is heavily data intensified and can require high computational power. Thus, aggregation methods are commonly used to simplify them [26].

Optimization models use mathematical techniques to describe real-world situations. They are used in the enhancement of systems by assessing the effect of newly integrated technologies into current systems. In our case, they are a great way of developing smart systems, and the balancing of energies due to newly introduced technologies. They are often used in DHNs to decrease heat losses, GHG emissions, or costs associated with the construction of DHNs. Among the methods used, the discrete or continuous models, neural networks, and generic algorithms are the most commonly used [27].

3.3 Methods of Aggregation

One of the key concerns besides the efficiency of technology in the DHN in the CZ, is the network distribution. Modeling the distribution network of national or even small-scale DHN is a complicated task because of the high computational time and costs required. During the last decade, two aggregation methods have been introduced which could be used for simulating and optimising the operational costs of DHNs.

Networks consist of a large number of users, pipes and long-time scales which make up the high computational costs of simulating and optimising DHN. Aggregation methods have been tested and the number of pipes could be reduced from 44 to 3 pipes, with minimal effects on the accuracy of the model [28]. Assuring the accuracy of an aggregated model lies in deciding which data from the original network is required, the complexity of the network, and finally the properties that need to be conserved [29].

Node Method

Under steady state flow conditions, the node method substitutes the existing tree structure of the system into lines and short branches. During any aggregation method, some important physical properties of the network such as water volumes, time delays and mass flows need to be preserved to maintain the level of accuracy of the system.

According to one research, any DHN with no circular loops can be considered as a network with several two-branch sub-networks (as shown below on the left side of figure 8) [30]. Each branch represents a pair of supply and return pipes. Under the physical properties mentioned above, this sub-network can be simplified into an equivalent network where there is no branching, and thus the total length of branch is reduced (as shown on right side of figure 8).

Figure 8 provides a visual explanatory for the simplification of such sub-systems.

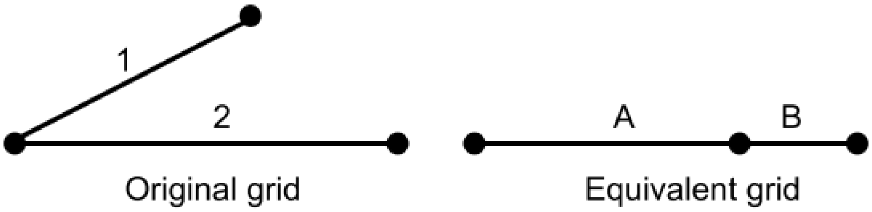


FIGURE 8. ORIGINAL (LEFT) AND EQUIVALENT (RIGHT) NETWORKS [28]

There are two main node methods, the Danish and the German Method. A brief explanation about their differences is listed below:

The Danish and German Methods

The Danish and German methods are both quite similar. They are both defined to work in steady state situations. In addition, they both have the same building blocks. They change a tree structure into a line structure while removing short branches. The German method removes a node replacing two branches with one. While the Danish removes a short branch replacing three branches with two. The Danish method in one research was able to reduce the number of pipes in a model from 44 to 3 pipes with minimal effects on the accuracy of the model [28].

Figure 9 below presents a visual representation of how each method models short branches.

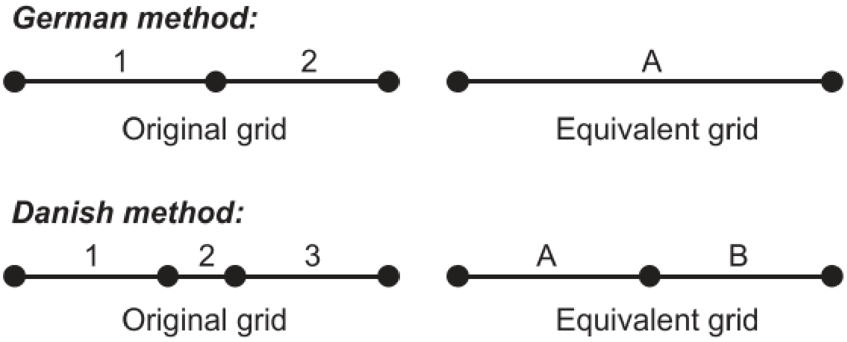


FIGURE 9. REMOVING A SHORT BRANCH [28]

The German method, unlike the Danish, is more versatile as it can model loop structures in a network. In addition, the German method accounts for both temperature and pressure fluctuations. In conclusion, both methods seem to work well at high levels of aggregation, though the German method seems to be slightly less accurate due to its higher level of aggregation [28], [30].

3.4 Key Performance Indicators

Key Performance Indicators (KPI) are the factors that are most important in assessing the performance of a DHN. The performance indicators could be classified into three domains: technical, economic, and environmental. Technical domain containing all the parameters that assess the efficiency of heat sources, the heat losses in distribution networks, and methods of assessing the end-user energy demand profiles. Whereas the economic and environmental domains assess the financial and emission-related performances.

3.4.1 Technical Domain

Technical domain KPIs take into account all the parameters that are important in assessing and optimizing the performance of a DHN. The technical domain contains an extensive selection of KPIs thus, they have been divided further into KPIs that are specific to each of the DHN components (heat source, distribution network and end-user).

1. Specific to Heat Source

Heat sources in a DHN are generally modelled based on their efficiency and heat generation. Some examples of the most usual heat sources in district heating networks are CHP plants, heat pumps, industrial waste, geothermal, etc. Thus, a couple of examples of how the efficiency of a CHP, and the performance of a heat pump are measured are listed below [31], [32]:

I. Primary Energy Saved (PES) index of a CHP heat source

$$PES = \left(1 - \frac{1}{\frac{CHP\ H\eta}{Ref\ H\eta} + \frac{CHP\ E\eta}{REF\ H\eta}}\right) \cdot 100\% \tag{1}$$

Where:

$\mathrm{CHP\ H_\eta}$ = Heat efficiency in cogeneration production
$\mathrm{Ref\ H_\eta}$ = Efficiency in separated heat generation
$\mathrm{CHP\ E_\eta}$ = Electricity efficiency in cogeneration production
$\mathrm{REF\ H_\eta}$ = Efficiency in separated electricity generation

II. Coefficient of Performance Index for Heat Pumps

The Coefficient of Performance (COP) index is usually used to assess the performance of various heat pump systems. The COP index is represented by the heat output divided by power consumption, the equation is as follows:

$$COP_{HP,act} = \frac{\dot{Q}_{sh}}{\dot{W}_{comp}} \tag{2}$$

Where:

$\mathrm{COP_{HP,act}}$ = Actual COP of heat pump
$\mathrm{\dot{Q}_{sh}}$ = Space heating load
$\mathrm{\dot{W}_{comp}}$ = Work input to the compressor

2. Specific to Distribution Network

The distribution network design depends on the scale, geographic location, type of users, heat generation source used in the network. Its main objective is supplying the heat energy to the end-user. It also has an effect on the energy consumption within the DHN, since there are often heat and pressure losses in the distribution pipe network. The modeling technique used in designing the distribution network can be either based on hydraulic or thermal equilibrium [27].

I. Hydraulic Equilibrium

The distribution network works by the transferring of heat from the supply fluid to the end-user consumption fluid. Therefore, it must be designed based on the hydraulic system.

A. Mass Flow Balance

$$\sum_{in} Q_{in} - \sum_{out} Q_{out} - \sum_{user} Q_{user} = 0 \tag{3}$$

Where:

Q_{in} = Mass flow rate entering point
Q_{out} = Mass flow rate exiting point
Q_{user} = Mass flow rate required by the user (or utility)

B. Energy balance

$$\Delta H_{ij} - (H_i - H_j) = 0 \tag{4}$$

Where:

ΔH_{ij} = Energy lost between points i and j
ΔH_i , ΔH_{ij}= Two points in the network

II. Thermal Equilibrium

Thermal equilibrium can be represented as steady-state or dynamic. Networks with low operating temperatures (70 °C or lower) can be considered as steady-state, while networks with high operating temperature (100 °C or higher) can be considered dynamic. The two main factors affecting the thermal equilibrium is the temperature drop across the users and the heat loss in the system.

A. Temperature Drop Across Users

$$Q = U \cdot \Delta T \tag{5}$$

Where:

Q = Amount of energy required by the system
U = Heat transfer coefficient
ΔT = Temperature drop across users

B. Heat losses in distribution pipe

$$\dot{\mathrm{Q}}_{\mathrm{loss}} = \mathrm{A} \cdot \mathrm{k} \cdot \Delta\mathrm{T} = \mathrm{A} \cdot \mathrm{k} \cdot (\mathrm{T}_{\mathrm{DH}} - \mathrm{T}_{\mathrm{out}}) \tag{6}$$

Where:

$\dot{\mathrm{Q}}_{\mathrm{loss}}$ = Heat losses in pipe [GWh/year]
$\mathrm{A}_{\mathrm{pipes}} = 2 \cdot \pi \cdot \frac{\bar{\mathrm{d}}}{2} \cdot \mathrm{l}$
$\bar{d}$ = Average diameter of pipes [mm]
l = Total length of network [km]
K = Average heat coefficient
$\mathrm{T}_{\mathrm{DH}} = \mathrm{T}_{\mathrm{supply}}$ and $\mathrm{T}_{\mathrm{DH}} = \mathrm{T}_{\mathrm{return}}$

3. Specific to End-User

The end-user profile is a prediction of the energy demand profile (trends) of users connected to the network. It is important to understand the end-user demand profile in order to identify the total load required for the network. There are three main user categories in a DHN:

- Residential: houses, apartments, buildings.
- Industrial: factories, plants, etc.
- Commercial: schools, shopping centres, etc.

The users have been separately categorized due to their different energy demand profiles. Residential and most commercial users utilize lower end-use temperature for heating and their demand vary significantly throughout the seasons of the year. While industrial users require a higher end-use fluid temperature, and their demand is often constant throughout the year. In order to accurately predict the energy demand profile of each user, an hourly-based time interval model would yield much higher accuracies thus improving the efficiency of the network.[27].

I. Historical Methods

As the name suggests, these methods use historical data of the demand and supply of users to model the demand profile of the system. These historical data are often easily accessible which contributes to their suitable use in measuring the heat demand profiles.

A. Heating Degree Day

The Heating Degree Day (HDD) is an index designed to quantify the heating demand in a building. When the air temperature outside falls down below a certain degree, the building needs to be heated. Thus, we can say that the HDD is derived from the outside air temperature.

$$\text{Heat Loss [kW]} = \text{Overall Heat Loss Coefficient } [\text{kW}.\text{k}^{-1}] \cdot HDD\ [k] \qquad (7)$$

HDD is a common index used to accurately find out the heating requirement of a building at a specific location. It is also commonly used in modeling small buildings when the main source of heat loss is unidentified [27].

B. Energy Use Intensity and Load Factor

Energy Use Intensity (EUI) is an index that measures the energy use relative to the buildings floor area. It is an important index that enables easier comparison of the energy efficiency in a building [33]. The Load Factor (LF) is the ratio of energy consumption over the maximum possible energy generation [27].

$$LF = \frac{Consumption\ [kWh]}{Peak\ Demand\ [kW]} * Time\ [h] \qquad (8)$$

Using both the EUI and LF, we can identify the total energy and peak heating demand required for a user.

C. Archetype Building

Archetype building is a reference building that represents a group of similar buildings in terms of construction parameters and average geometrical characteristics. The purpose of archetype building is to simplify buildings of similar typologies as their energy demand would be more or less the same. It is important not to oversimplify buildings as it could lead to inaccurate data, however, it is still important as there is no reason to characterize each building in a network. An interesting research has been conducted that assess the impact of considering different levels of detail in the characterization of building stock [34].

II. Deterministic Models

Deterministic models are simulation-based models. They are models that use the mathematical representation of the system behaviour. These simulation-based models could be categorized as complex or simple, depending on the amount of data required. The deterministic models that cover a DHN are considered complex.

These models are considered to be very accurate methods in predicting the energy demand as they would always produce the same output for an unchanged input. On the other hand, they require extensive amounts of data and are have high computational costs. Some examples of deterministic simulation-based models are reviewed in the following chapter [35], [36].

III. Energy Matching in NZEB

What has raised the importance of adopting Nearly Zero-Energy Buildings (NZEB) in the EU is the energy consumption of buildings in the European Union that accounts for around 40% of total final energy use and 36% of total CO2 emissions of the EU Member States [37]. . That is why, the EU has initiated the Energy Performance of Buildings Directive 2010/31/EU (EPBD) and the Energy Efficiency Directive 2012/27/EU which came into effect in 2003. It is an effective mean of boosting the energy performance of buildings by setting a standard for EU national governments on measuring and improving existing building stock [38].

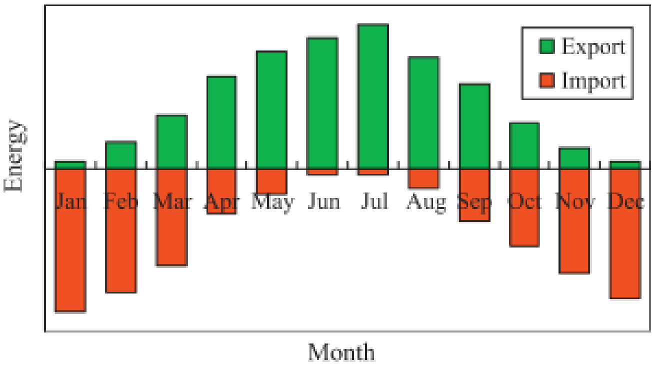


FIGURE 10. THE MONTHLY IMPORTED AND EXPORTED ENERGY FOR AN ALL-ELECTRIC BASED NZEB EQUIPPED WITH ON-SITE PV [39]

Figure 10 is a good example of a NZEB which is equipped with an on-site PV with electrical grid feed-in. The exports to the grid are significantly high during the summer months, which then compensates for the high imports during the winter months.

The legislation of the European Parliament states that all new private buildings built from 2021 and public buildings from 2019 should be NZEB [40]. However, in order to meet the EU requirement of NZEB, two major indicators need to be considered at first: On-site Energy Fraction (OEF) and On-site Energy Matching (OEM). On-site energy fraction is the proportion of the load covered by onsite generated energy. Whereas onsite energy matching is the proportion of the on-site generated energy fraction that is used instead of being exported or lost.

With that being said, the OEF factor must be significantly improved to ensure that the building is capable of sustaining its own energy compared to its load. Ideally, the OEF factor should be 1.0 or as close to it as possible, meaning no energy is imported from the grid and all energy is generated onsite. The OEF is calculated as shown below [39]:

$$\mathrm{OEF} = \frac{\int_{t1}^{t2} \mathrm{Min}[\mathrm{G(t)};\mathrm{L(t)dt}}{\int_{t1}^{t2} \mathrm{L(t)dt}};\ 0 \leq \mathrm{OEF} \leq 1 \qquad (9)$$

Similarly, the OEM factor also needs to be significantly improved to be a value of 1.0 or as close to it as possible since it represents how much of the OEF was actually used to cover the load of the building. Ideally, buildings should have both OEF and OEM values at 1.0 which would mean that the total building load is generated independently from RES and is also entirely consumed to fulfil the building's load with no exports or wastage. The OEM is calculated as shown below [39]:

$$\mathrm{OEM} = \frac{\int_{t1}^{t2} \mathrm{Min}[\mathrm{G(t)};\mathrm{L(t)dt}}{\int_{t1}^{t2} \mathrm{G(t)dt}};\ 0 \leq \mathrm{OEM} \leq 1 \qquad (10)$$

As we can see, both equations are almost identical except for the L(t) and G(t) which are the load power and on-site generated power, respectively, at an instantaneous time *t*. The variables t_1 and t_2 represent the starting and ending points of the time span, whereas dt represents the time-step.

3.4.2 Economic Domain

Another modeling key performance indicator is the economic domain that focuses on the financial cost or gain from a proposed technology to the DHN. With the main goal of reducing CO_2 emissions, the financial gain is usually not of top priority but, the cost of implementing and maintaining the new technology is. Economic domain is used mainly when calculating the profit of using RES compared to the cost of burning fuel. Examples of economic domain KPIs in a DHN are as follows [31]:

I. NPV = Net Present Value

$$\mathrm{NPV}\ (\mathrm{i}, \mathrm{N}) = \sum_{\mathrm{n}=0}^{\mathrm{N}} \frac{\mathrm{CF_n}}{(1+\mathrm{i})^{\mathrm{n}}} \quad [€] \tag{11}$$

Where:

n = time of cash flow [years]
i = discount rate
CF_n= net cash flow

II. Internal Rate of Return (IRR)

$$NPV = \mathrm{CF_1} + \frac{\mathrm{CF_1}}{1+\mathrm{i}} + \frac{\mathrm{CF_2}}{1+\mathrm{i}} + \cdots + \frac{\mathrm{CF_n}}{(1+i)^{\mathrm{n}}} = 0 \quad [€] \tag{12}$$

Where:

$\mathrm{CF_1}$= cost of investment [€]

III. Yearly depreciation rate per ton of saved CO_2e

$$\mathrm{CO_{2e\ SAVED}} = \mathrm{CO_{2e\ BEFORE\ INSTALLATION}} - \mathrm{CO_{2e\ AFTER\ INSTALLATION}}\ [\frac{€}{ton\ CO_2}] \tag{13}$$

3.4.3 Environmental Domain

Finally, the last KPI domain of modeling energy systems is the environmental domain. It measures the level of emissions a project has on the environment compared to the baseline scenario. Below are some of the examples of environmental domain KPIs in a DHN [31]:

I. Yearly Green House Gases (GHG) emissions saved

$$\mathrm{GHG_{SAVED}} = \mathrm{GHG_{Baseline}} - \mathrm{GHG_{Project}} \quad [\frac{\mathrm{ton\ CO_2}eq}{m_c^3 \cdot year}] \tag{14}$$

II. Yearly reduction of pollutant

$$\text{Reduction of pollutant} = \frac{\mathrm{CO_{2\ Baseline}}}{\mathrm{CO_{2\ Project}}}, \frac{\mathrm{PM_{Baseline}}}{\mathrm{PM_{Project}}}, \frac{\mathrm{VOC_{Baseline}}}{\mathrm{VOC_{Project}}}\ [\%] \qquad (15)$$

Where:

CO_2 = Carbon Dioxide [ppmv]
PM = Particle Matter [mg/m3]
VOC = Volatile Organic Compound [µg/m3]

4. Simulation Tools

The objective of this chapter is to describe the different simulation tools that are available to find solutions that increase the efficiency of current technology in the DHN. Such tools are focused on integrating new technologies into existing DHN in order to create scenarios where a more energy efficient, economic and environmentally friendly system is the ideal outcome.

Table of Comparison

Table of comparison of the seven chosen simulation tools. A more detailed and informative table comparing these tools can be found in the appendix.

Tool	Developer	Focus	License & Source	Release Date
EnergyPLAN	Aalborg University (DN)	Thermal Energy Systems	Free, Open-source	1999
TRNSYS	Wisconsin University (US)	Thermal and Electrical Systems	Paid, Open-source	1995
HOMER	NREL & DOE (US)	Microgrid Optimization	Paid, Closed	1993
THERMOS	Centre for sustainable energy (UK)	Thermal Energy Systems	Free, Open-source	2020
OpenModelica	Linköping University (SW) & OSMC	Modelica Computational Environment	Free, Open-source	2007
Dymola	Dassault Systemes SE (FR)	Modeling & Simulation for Automotive, Aerospace, etc.	Paid, Open-source	1978
SAM	NREL & DO (US)	Thermal Energy Systems	Free, Open-source	2006

TABLE 2. TOOL TABLE OF COMPARISON

4.1 EnergyPLAN

EnergyPLAN is a computer software developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark [35]. It is a tool that is designed to analyse technical, environmental, and economic impacts of energy solutions. It can model large-scale or individual district heating network dynamics which allows for a 100% RES model. It is a deterministic input-output model that calculates one full year on an hourly time step.

Tool Overview

The key objective of this software is to model a variety of options so that they can be compared with one another, rather than modeling one optimum solution based on defined pre-conditions. Using this methodology, it is possible to illustrate a variety of options for the energy sector. The tool's special focus is on the integration of different sectors of the energy system such as the electricity, heating and cooling, transport, and industry sectors to generate a more efficient overall energy balance. In addition, it considers a large variety of heat sources, especially ones powered by RES (i.e., on and off-shore wind power, PV, hydro, geothermal). The focus is placed on the future energy system design and how the large variety of sources may operate within the network [35], [41].

Much like all input-output energy system models, EnergyPLAN requires extensive amounts of data to accurately represent an output. However, unlike most models of its category, it does not require high computational power nor and the simulations are completed in a very short time [42].

User Interface

As shown below in figure 11, the EnergyPLAN model is designed in a series of tab sheets where the main categories are the demand, supply, balancing and storage, cost and output.

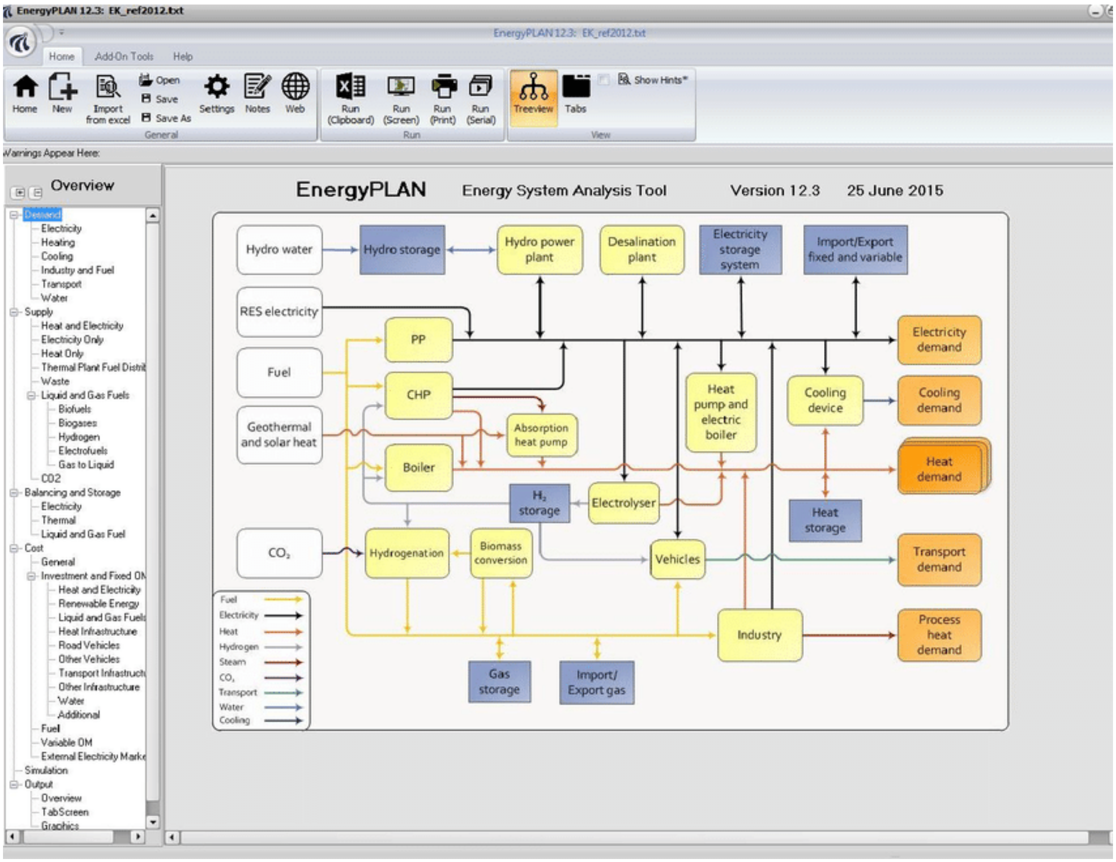


FIGURE 11. ENERGYPLAN USER INTERFACE [43]

License and Compatibility

EnergyPLAN is a free software that requires no payment to be used for its full potential. The developers also have a variety of training sessions, forums and existing models of many countries already available on their website. They also offer workshops for PhD's; however, those are only available for their registered clients for a small fee. The software is only available for Windows OS. However, could be used on a Mac OS using a Windows simulation environment.

4.2 TRNSYS

TRNSYS is a simulation software that was developed by the University of Wisconsin and has been commercially available to the public since 1995 [44]. This tool breaks down an energy system into separate components which allow for easy modification and high accuracy results. However, this means that it is highly dependable on the data quantity and high computational costs. Therefore, TRNSYS is often used in small-scale building level or energy systems where there is a limited number of buildings, as this would yield high accuracy results with a fair amount of data required and computational cost. Much like other building level simulation tools, they could be scaled up for use at a local (community) scale [45].

Tool overview

TRNSYS is a graphically based and modular software environment. It was originally used to perform transient dynamic simulations of the behaviour of a solar hot water system. Nowadays, most researches have been using TRNSYS to assess the performance of thermal or electrical energy systems even at a state or district scale [46]–[49]. The reason why they have recently been used for assessing thermal or electrical systems is for the thorough library that is filled with components that are usually needed in assessing such systems. The thermal library contains components ranging from solar and wind systems, CHP, heat exchanger, district network, thermal storage, hydronics pumps, building physics, etc.

In addition to the library, it offers users to create their own components written in Fortran, C, C++, or any other programming language given that can be compiled into a DLL file. That combined with its open-source allowed it to become a prominent tool in the assessment of energy systems [49].

User Interface

The main benefit of the interface is that you can control exactly which component you would like to use and how you would like it to be connected to the system. Moreover, you can also watch every individual component in live simulation to see how it performs, thus making it simpler to spot any inconsistencies in your system that would require modification. Figure 12 shows us an example of a typical TRNSYS graphical scheme.

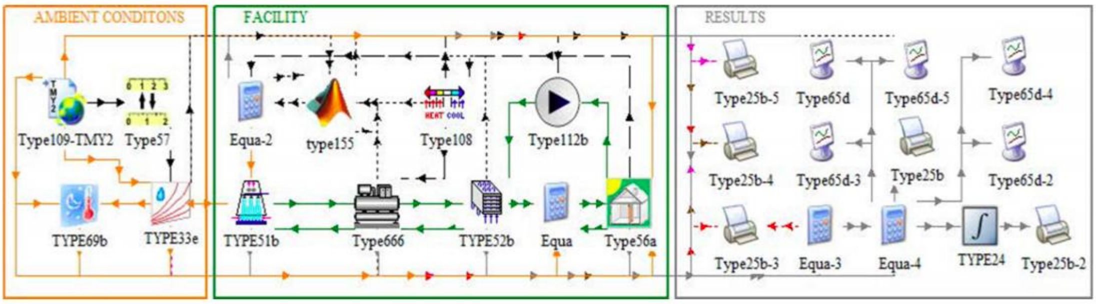


FIGURE 12. SCHEMATIC ARRANGEMENT OF THE TRNSYS MODEL [47]

License and Compatibility

TRNSYS unlike EnergyPLAN is not a freeware. For a single user commercial license, it would cost you \$5060, while for an educational license \$2530. However, with that package you get access to several other TRNSYS software's, live-taught online training as well as in person training sessions. The software is only compatible on Windows OS. However, could be used on a Mac OS using a Windows simulation environment.

4.3 HOMER

HOMER is an acronym for Hybrid Optimization Model for Multiple Energy Resources. It is a simulation tool that was developed by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) in 1993. According to the developers there are over 3 million model runs that have been simulated using HOMER. The software is divided into two tools, the original product HOMER Pro and the newly introduced HOMER Grid. HOMER Pro is essentially a simulation tool that is focused on large scale models, according to the user's desired combination of components and input data. Whereas HOMER Grid is a tool that optimizes the value of behind-the-meter modeling that is focused on a commercial scale, solar and storage, and value stacking [50]

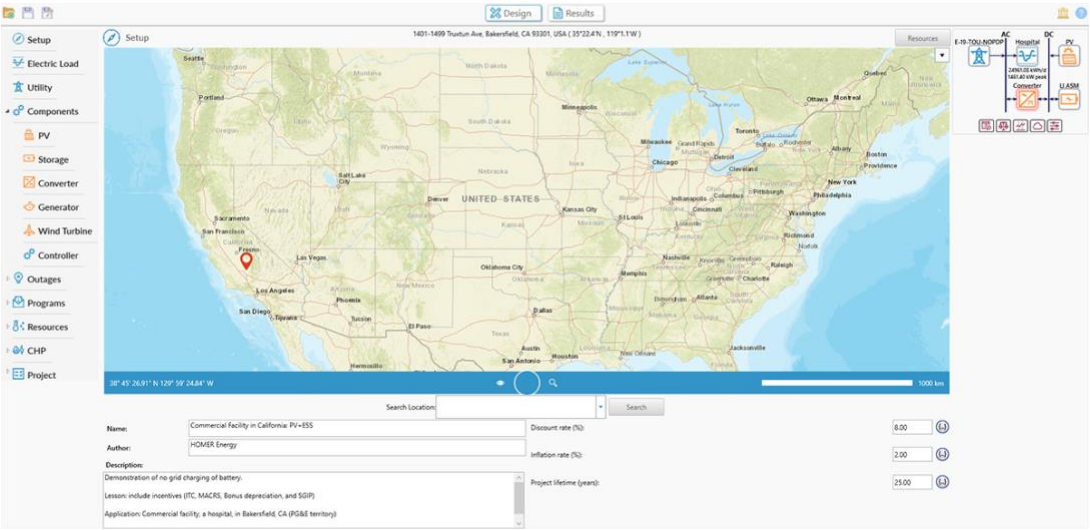
Tool Overview

HOMER simulates and optimises stand-alone and grid-connected energy systems using technologies such as PV arrays, wind turbines, hydro power, biomass power, fuel cells, batteries, etc. The tool considers both the electric and thermal (individual or district heating network) loads for a 1-year time period using a minimum time step of 1 minute. The tool uses energy storage as well as load management to ensure the availability of energy at all times using off-peak prices when available for a cost-efficient system.

Another cost-effective solution that HOMER uses, is the optimization function. It works by finding the least cost combination of equipment by analysing all possible combinations. The user is only required to enter a few details such as the desired search location, electric and thermal load and cost of the available RES (e.g., cost of kW for solar photovoltaic panels) [50]. Some of the researches conducted using HOMER for socio-economic, or hybrid system analysis could be found here [51], [52].

User Interface

It has an extremely easy layout for you to navigate through, entering your data or using samples provided by the developers in the simplest way possible. It could provide you with data of available local resources for your location. Similar to EnergyPLAN, it has a tab sheet interface that categorises the components of the energy system separately as shown in figure 13 below.



1401-1499 Truxtun Ave, Bakersfield, CA 93301, USA (35°22.4'N , 119°1.1'W)

38° 45' 26.91" N 129° 59' 24.84" W

Name: Commercial Facility in California: PV+ESS

Author: HOMER Energy

Description:
Demonstration of no grid charging of battery.
Lesson: include incentives (ITC, MACRS, Bonus depreciation, and SGIP)
Application: Commercial facility, a hospital, in Bakersfield, CA (PG&E territory)

Discount rate (%): 8.00

Inflation rate (%): 2.00

Project lifetime (years): 25.00

FIGURE 13. HOMER GRID HOMEPAGE INTERFACE [50]

License and Compatibility

The license cost for HOMER Pro standard license without any addition models is $42/month for a one user license, for an academic facility $21/month and $6/month for students. HOMER energy also offers their potential clients a custom configuration, where you do not have to buy a package, but only the models you know you are going to use [50]. HOMER software's are native only to the Windows OS. However, just like the previously mentioned software's, the tool could be run using a Windows OS simulation environment.

4.4 THERMOS

THERMOS is an acronym for Thermal Energy Resource Modeling and Optimisation System. It is a project that is coordinated by the Centre for Sustainable Energy; however, a variety of experts from environmental agencies and universities including Aalborg university the developers of EnergyPLAN are contributing to the project. The project is currently still under development and is expected to be completed in June 2020 [53]. The main aim of this project is to accelerate the development of low carbon DHNs across European countries.

Tool Overview

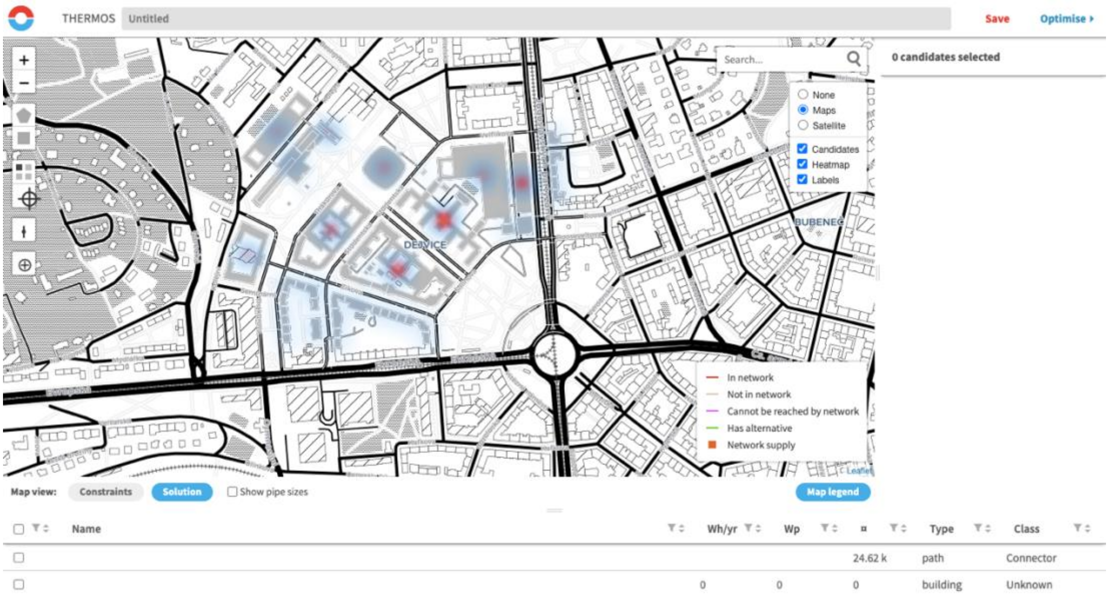
THERMOS aims to enable faster upgrades, modifications and expansion of current DHNs in terms of environmental and economic solutions. The software will be able to perform complex deductions using algorithms. THERMOS will be able to suggest energy design concepts for thermal energy networks, use of different RES according to availability, waste heat from industrial sector, differentiate between different end-users (i.e., residential, industrial, commercial), heat storage options, and network planning for future scenarios [53].

As of today, the tool only offers data for the four partner pilot cities (Granollers, Spain. Islington, UK. Jelgava, Latvia. Warsaw, Poland). However, a built in OpenStreetMap feature allows users to generate data according to their chosen geographic area selected. There is also the possibility to upload your own GIS data.

Even with a demo of the tool that is freely accessible, the information and research focus on the tool is still limited as it is still under development [53]. Only a few researches have been found that were mostly conducted by the developers themselves [54]–[56]

User Interface

THERMOS is a map-based web tool that can be operated by any local energy planner. Figure 14 below shows a screenshot of the THERMOS application version 5.



☐	Name	Wh/yr	Wp	¤	Type	Class
☐				24.62 k	path	Connector
☐		0	0	0	building	Unknown

FIGURE 14. CTU IN PRAGUE'S HEATMAP USING THERMOS WEB SOFTWARE

License and Compatibility

THERMOS is a free open-source software that requires absolutely no license to use. They also offer the opportunity to enrol for a certificate program to become a THERMOS Trainer free of charge. All that is required is to complete a set of tasks and exercises that are free of charge as well [53]. The tool is accessible on any computer device that has access to the internet through a web browser, regardless of what OS you use.

4.5 Modelica-Based

Modelica is a high-level declarative programming language for describing mathematical behaviours. It was developed in 1997 as part of an international effort to unify modeling languages to allow for easier exchange of models and model libraries [57]. Later on, several Modelica based simulation environments have been developed for a wide variety of engineering purposes [58]. Of which, only one is free to use and has been chosen to be part of this review, the OpenModelica simulation tool. A second paid Modelica-based simulation environment has been chosen to be reviewed called Dymola. The tools were chosen based on their relevance to our topic.

4.5.1 OpenModelica

OpenModelica was developed in 2007 by Linköping University and Open Source Modelica Consortium (OSMC) which is a group of universities, companies, individuals and institutes. The tool is an open-source and is intended for industrial and academic use. The goal of the tool is to create a free comprehensive Modelica-based simulation environment for research, teaching and industrial usage.

Tool Overview

OpenModelica allows users to benefit from the open-source Modelica libraries and models. In addition, it offers the opportunity for its users to build ring networks and bi-directional flow in a robust way, which an important factor to consider when developing a multi-source closed district heating network [59].

The advanced interactive OpenModelica Compiler (OMC) is basically the Modelica language compiler. It translates Modelica to C code with a symbol table with definitions of components. These definitions could be predefined, user-defined, or from libraries [60]. OMC is basically the brain of the entire system; it unites all the different components and process them to be simulated.

User Interface

OpenModelica connection Editor (OME) is a highly advanced tool that provides users with a friendly graphical environment for model creation. Its graphical interface which can be seen below in figure 15, is much similar to TRNSYS's interface in terms of enabling easy modifications to any component in the network.

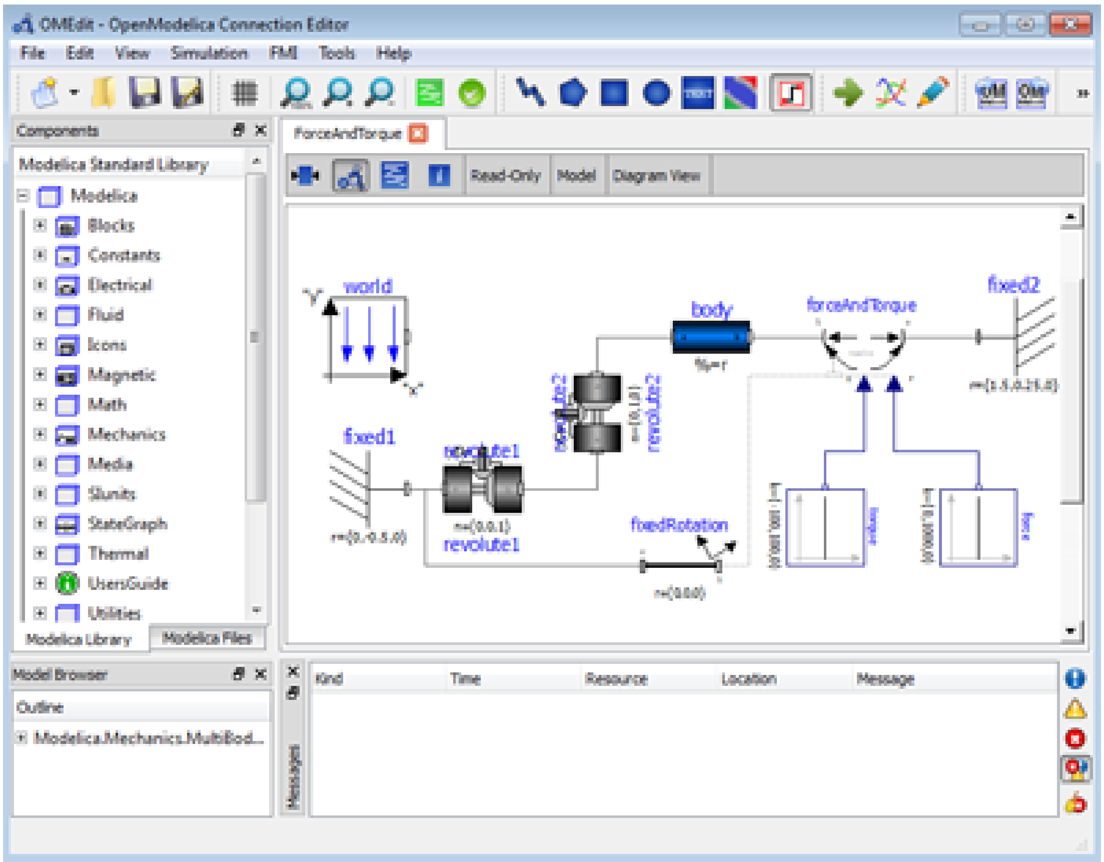


FIGURE 15. OME GRAPHICAL INTERFACE [60]

License and Compatibility

As discussed above, it is an open-source tool. The tool is supported by Windows, Linux and Mac OS. Also, they have instructions on how to download the software and run it on each of those OSs on their website [60].

4.5.2 Dymola

Dymola was initially designed by Hilding Elmqvist for his PhD thesis at the Lund Institute of Technology in 1978 [61]. However, in 2006 it was acquired by the Dassault Systemes. It is a commercial modeling and simulation environment. Just like the previously reviewed tools, they are built to describe dynamic behaviour of a system in a mathematical equation or algorithms.

Tool Overview

Dymola with its multi-engineering capabilities grants users the ability to model and simulate any physical component that can be described by differential algebraic equations (DAE). The software is used in a comprehensive variety of engineering fields, especially in the automotive, aerospace and energy efficiency sectors. Since DHN and its components fall under this category, it could be used for modeling or network design purpose [62].

User Interface

The Dymola interface also offers a tabs feature that enables the users to rapidly switch between the class, coding or documentation layer. Dymola offers users to view a plot or analyse the performance of their model, or even show an animation of the models in work.

Figure 16 shows an example of a coupled energy grid system in Hamburg, showing electricity generation at the top and its connection to a DHN.

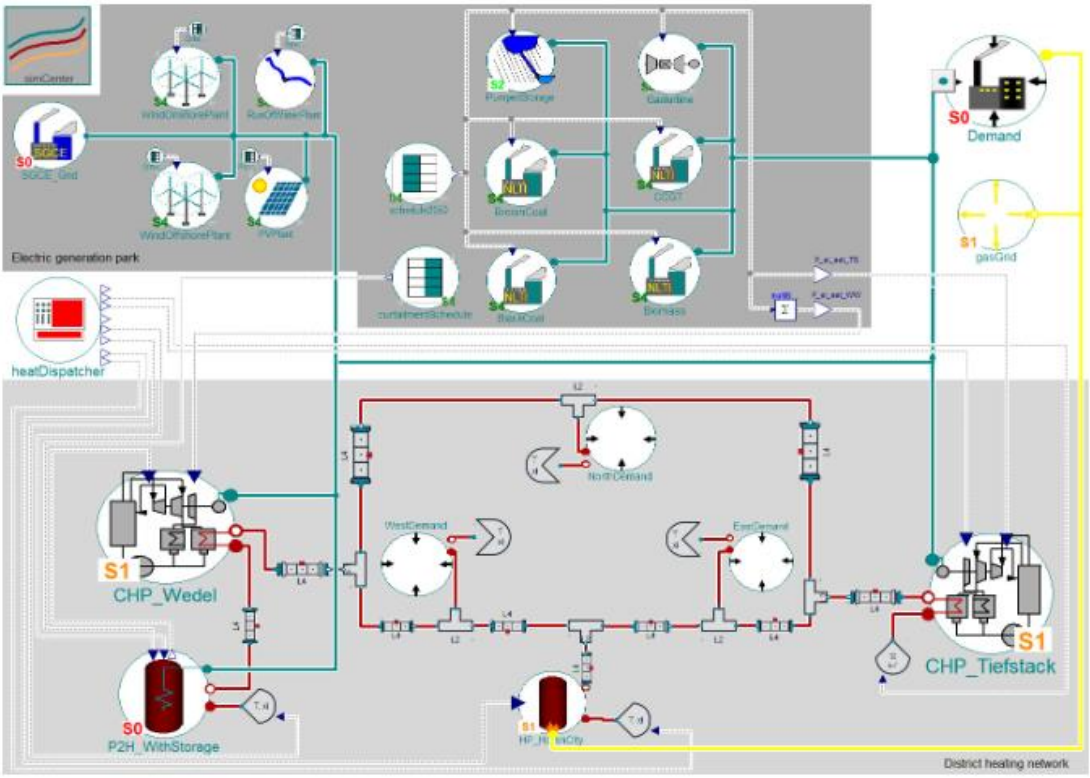


FIGURE 16. DYMOLA MODEL OF ELECTRICITY GENERATION AND DISTRICT HEATING NETWORK [63]

License and Compatibility

Dassault Systemes offers a variety of free webinars, tools and libraries for the Modelica users. The exact figure of how much a license of Dymola costs is not publicly mentioned but is available upon request. Dymola is currently supported by Windows and Linux OS.

4.6 System Advisor Model

SAM was developed in 2006 by the National Renewable Energy Laboratory (NREL) in partnership with the US DOE. It is a performance and financial model. It is focused on facilitating decision making for people in the renewable energy sector to help researchers, project managers and technology developers to increase the efficiency of grid-connected systems [64].

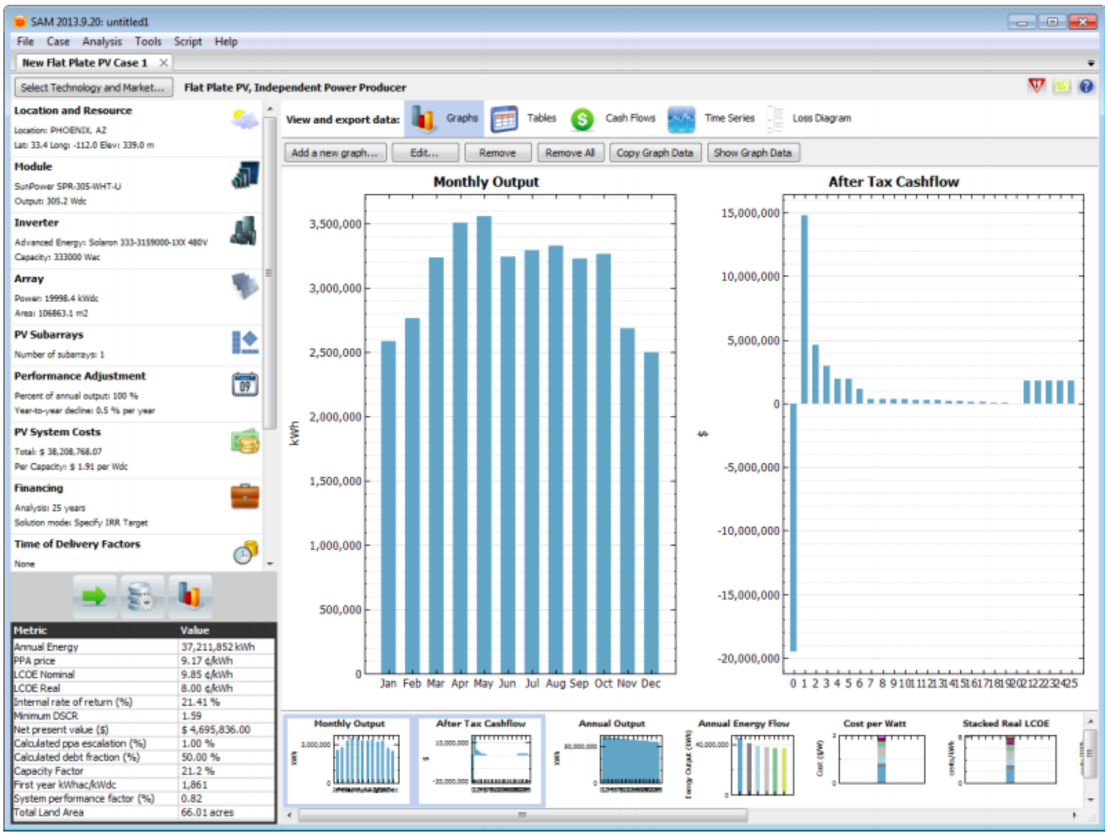
Tool Overview

SAM is comprised of two models, technology and financial models. The technology model focuses on optimizing the energy design model by providing the user with the RES availability of a location. Some of the technologies included are PV, solar thermal, battery storage, and most importantly concentrated solar. Concentrated solar is the process of a field containing concentrated mirrors focused on sunlight on a receiver to heat a fluid in order to deliver heat to a steam-driven power cycle for the generation of electricity. Some research papers that focused on concentrated solar and SAM in district heating scale applications can be found here [65], [66]

The financial model of SAM is thoroughly focused on encouraging and enabling consumers to rely on RES for the purpose of meeting their heat and electricity demand independently while making a revenue out of the excess heat generated. SAM users could enter their heat demand, as well as their location using the weather data file and the software can automatically provide them with the capability of their location in generating a RES [64].

User Interface

In the latest version of SAM, the developers have enhanced the tool furthermore to allow it to be as user friendly as possible. As seen in figure 17 below, the tool divides the functions into categories. The tool also provides the users with charts of the monthly and annual output, cost per watt, energy flow etc.



Location and Resource
Location: PHOENIX, AZ
Lat: 33.4 Long: -112.0 Elev: 339.0 m

Module
SunPower SPR-305-WHT-U
Output: 305.2 Wdc

Inverter
Advanced Energy: Solaron 333-3159000-1XX 480V
Capacity: 333000 Wac

Array
Power: 19998.4 kWdc
Area: 106863.1 m2

PV Subarrays
Number of subarrays: 1

Performance Adjustment
Percent of annual output: 100 %
Year-to-year decline: 0.5 % per year

PV System Costs
Total: $ 38,208,768.07
Per Capacity: $ 1.91 per Wdc

Financing
Analysis: 25 years
Solution mode: Specify IRR Target

Time of Delivery Factors
None

Metric	Value
Annual Energy	37,211,852 kWh
PPA price	9.17 ¢/kWh
LCOE Nominal	9.85 ¢/kWh
LCOE Real	8.00 ¢/kWh
Internal rate of return (%)	21.41 %
Minimum DSCR	1.59
Net present value ($)	$ 4,695,836.00
Calculated ppa escalation (%)	1.00 %
Calculated debt fraction (%)	50.00 %
Capacity Factor	21.2 %
First year kWhac/kWdc	1,861
System performance factor (%)	0.82
Total Land Area	66.01 acres

FIGURE 17. MONTHLY OUTPUT OF ELECTRICITY GENERATION FOR A PHOTOVOLTAIC SYSTEM ON SAM SOFTWARE [64]

License and Compatibility

SAM is a free open-source tool that requires no license to operate it to its maximum potential. It is supported by Windows, Mac and Linux OS with annual improvement updates.

5. Applications of the Simulation Tools in Practice and Research

There are two main applications of the aforementioned energy system simulations: energy planning and energy design. Energy planning is usually conducted on regional or national scale by the policy makers in developing long-term scenarios that tackle desired objectives such as, reducing GHG/CO_2 emissions, supporting new technology etc. The stakeholders in interest are typically public policy-makers, municipalities, etc.

Energy design is usually conducted on a local energy system scale, typically a house, building, group of buildings. The stakeholders in interest are typically building developers or consumers looking to find new innovative solutions for a more efficient energy system to reduce their energy bill, etc.

5.1 Regional and National Energy System Analysis

National scale energy system assessment has proved to be an essential research field for energy optimization as well as the relief of GHG emissions in energy planning. The reason being that cities are areas with the highest concentration of the country's population, thus, they are the largest energy consumer groups [67]. National energy systems typically involve municipal and large utility companies as stakeholders and investors of interest. Typical goals involve improving the DHN by lowering the supply and return temperatures, integration of RES, reduction of GHG.

5.1.1 IDA's Energy Vision 2050

The IDA's energy vision 2050 research was commissioned by The Danish Society of Engineers, IDA and Aalborg University, the main developers of the EnergyPLAN tool. Needless to say, the development of the tool was tailored to fit and meet the requirements and challenges this research has to offer. The purpose of the research is to create a 100% renewable, intelligent integration of the heat, electricity, gas and transport sectors of Denmark while also considering the hourly variations in the demand and supply of energy. Different scenarios were created to show how the energy system might transform and the difference in impact when fuels such as fossils (DEA Fossil) versus wind power (DEA Wind) are used for the years 2035 and 2050.

The aim of the research was to study the transition to an integrated smart energy system, which its reliability has been proven throughout the research. In addition, a conversion to a fully renewable energy system is possible and is even within economic reach. Not only that, but there is also potential to create more jobs and reduce health and environmental related effects.

The IDA's main conclusion is that we have to switch from a sectoral term to a cross-sectional thinking. Such a conclusion was achieved by realizing the amount of waste heat that is lost while the demand for it is still required. By making use of such heat loss the total energy demand would be allowed to go down, while still leaving room for our individual electricity demand to increase.

EnergyPLAN was used to assist the strategy of energy planning in a technical and economic analysis by comparing the benefits and limitations of different energy systems by looking at an energy system as a whole. For e.g., electricity smart grids were coordinated with the utilization of renewable energy to find uses other than electricity production such as DH and DC. The tool also was able to develop a 100% renewable energy strategy for Denmark for electricity, heat, industry and transport [23].

5.1.2 Zero Carbon Energy System in South East Europe in 2050

This research was conducted by a number of universities such as, Technical University of Denmark, Aalborg University, University of Zagreb, etc. Much similar to the previous research, this study also adopted the concept of smart energy systems. EnergyPLAN has been picked as the most suitable tool for the purpose of this research as it is able to combine different energy sectors together, utilizing all the available resources.

The aim of the research is to present the transitioning steps for the South East EU countries in order to achieve a 100% renewable energy system. This paper compared to other similar research papers following the same topic stands out due to its introduction of using sustainable biomass in order to achieve a 100% renewable energy system. The researchers have emphasized that only sustainable biomass can be considered carbon-neutral.

The outcome of the research states that the biomass consumption of the model was 725.94 PJ for the entire region, which is in line with its potential. The findings also state that several in order to increase the security of supply, a wide variety of energy sources are needed to be used with every individual energy share not exceeding 30%. The main technologies with highest shares are wind turbines and photovoltaic with 28.9% and 22.5% respectively. Followed by hydro power, concentrated solar power, biomass and geothermal energy sources.

The researchers have proven that such an energy system is possible, and even feasible. Their findings show that the system is highly financially beneficial, saving up to 20 billion euros for the year 2050 compared to the base year [68].

5.1.3 Technical and Economic Analysis of a Grid Tied PV Plant

This research conducted by Ege University conducts a technical and economic analysis on the introduction of building PV power plants at four random points in Kars and Mersin, Turkey. The goal of this paper is to increase the reliance of RES in order to increase the share of renewable energy in the world primary energy consumption, which was 2.8% as of 2015. This in turn would assist countries in achieving lower CO_2 emissions in order to reduce the global warming effects and clean our environment.

The findings of this research show that an IRR value close to 10% is achievable using the suggested PV plants location. Such a quick feasibility analysis was conducted using SAM tool by adding the cost values and weather data of the technology and location [69].

5.1.4 An Automated Approach to Building and Simulating Dynamic District Heating Networks

The purpose of this research was to use computer-aided design tools in order to create a model that can successfully predict the heat propagation and temperature distribution in a localised case study. The research was conducted on Sweden's district heating network, as it is a rather large and complex one that accounts for 50% of the total heat demand of the country.

A dynamic model was developed using OpenModelica's while methods for modeling, simulation and visualization of results were developed using Matlab. The combination of OpenModelica and Matlab was a successful one, with the authors describing the accuracy of the model as "an acceptable degree" of predicting such a complicated system.

The output of this research proved that this combination of tools is beneficial for complex large-scale DHN. The model proved that it has the capacity to predict bi-directional and reversing flows in complex ring structures which without the model is a difficult task for the heat providers to predict [70].

5.1.5 Dynamic Simulation of District Heating Networks

The following is a master's thesis that was conducted by Rickard Hägg at Lund University. The purpose of the research is to simulate a large DHN model that has a good representation network that also allows for easier switching between simulation and optimization. The author was able to implement a new pipe model which was achieved using the SpatialDistribution operator from the Modelica library that enabled the simulation of large DHN of up to 100 consumers.
Dymola was used as the simulation environment as it is a Modelica run tool, and the results show that the model was able to simulate such large DHN which included both pressure and heat losses of pipes [71].

5.2 Local Energy System Analysis

Local energy systems typically fall under energy design as they are conducted on significantly smaller scales i.e., building, neighbourhood, as compared to energy planning tools. They also focus on optimizing current systems by introducing a few new technologies e.g., installation of PV panels for domestic electricity consumption etc. instead of major changes in a large energy system.

Local energy systems could be modelled using simulation engines or using tailor made algorithms. The models could represent a small-scale neighbourhood or buildings' performance. Below are a few scientific research papers as a reference:

5.2.1 Optimum Design and Operation of an HVAC Cooling Tower for Energy and Water Conservation

The Miguel Hernandez University of Elche in Spain using TRNSYS have conducted this research aimed at optimizing the use of energy and water consumption in HVAC cooling systems.

The researchers used several different cooling tower configurations by shuffling six drift eliminators and two water distribution systems. TRNSYS was able to formulate an ideal optimized configuration that would reduce the use of energy up to 10.8% per story, and water consumption up to 4.8%. When these results are implemented on an entire neighbourhood or district, it would make a significant improvement to the environment and economy [47].

5.2.2 Optimal Sizing of a Hybrid System of Renewable Energy for Lighting Street

A joint research by students from different universities in the Middle East (such as University of Technology (Baghdad), Sohar University and Baghdad University) that is aimed at using hybrid renewable energy systems to supply enough electricity for streetlights in isolated areas that are located far away from the grid. For this research, they have taken a 10km street in Salalah, Oman as the focus of their research. In their research they compared four different models using homer, PV, wind, diesel or hybrid PV/wind/battery system. According to HOMER's calculations, the hybrid PV/Wind/Battery system proved to be the cheapest as well as the cleanest form of energy to light the street [51].

5.3 Map-based Building Stock Performance Analysis

Map-based building stock tools are quite useful in planning and optimizing the heating network of a specific area of interest. The tools usually could suggest a distribution network that connects buildings in a nodded set of paths. In addition, they could also give an estimate of the buildings heat demand using the building's accurate geometric parameters.

5.3.1 A combined spatial and technological model for the planning of district energy systems

A research done by the Imperial College London mixes the optimal technology types for local energy generation. Using THERMOS's OpenStreetMap, a spatial framework was achieved providing the best distribution network structure. The research incorporated a variety of heat sources to provide the internal and external power demands and describe their benefits when combining with different components (such as heat pumps and CHP) to satisfy the emission targets [72].

6. EnergyPLAN: Tool Practice

EnergyPLAN has been chosen as the tool of practice for this segment of the thesis for its focus on district heating and cooling purposes. The focus of this chapter however revolves around the type of data required to run a simulation on the tool. This includes some sources of how and where to look for the data, as well as the format of the data required by the tool.

In order to get some logical results while navigating the tool, a set of data published by the Heat Roadmap as part of a report on the Czech Republic using EnergyPLAN is used [1]. Whereas most of the information regarding the technical parameters of the tool are sourced from the “Finding and inputting data into EnergyPLAN” [73].

The data published by Heat Roadmap for the Czech Republic included a 2010 baseline (BL) year as well as a 2050 Business as Usual (BAU) however, only the Czech Republic 2010 BL data (moving forward will be referred to as CZ-BL-2010) will be used for this section. The details of the report are overlooked since the motive of this chapter is to review the tool.

6.1 Type of Data Required

In this section, we will be explaining what each tab of the EnergyPLAN tool represents and where could the data be found. Firstly, let us start with the data that EnergyPLAN typically requires [73]:

1. The total annual production/demand [TWh/year]
2. The capacity of the unit installed [MW]
3. The hourly distribution of the total annual production/demand
    - The hourly distribution data is in the form of a text file
    - Must contain 8784 data point rows, one for each hour of the year
    - Typically placed in the distributions folder, however the text file could be manually selected
    - The data points are usually between 0-1, representing 0-100%

Demand Tab

Firstly, the demand tab contains a lot of information that can be found from the country’s energy balance sheet. The energy balance sheet for the Czech Republic has been obtained from the IEA through filtering their World Energy Balances Microsoft excel sheet[74].

Figure 18 below shows the heat energy balance of the CZ as a sample of the information that could be extracted from the energy balance sheet of a country. The energy balance sheet has proved to be a reliable source of extracting information for EnergyPLAN as it indicates the energy consumed for each sector of the energy system.

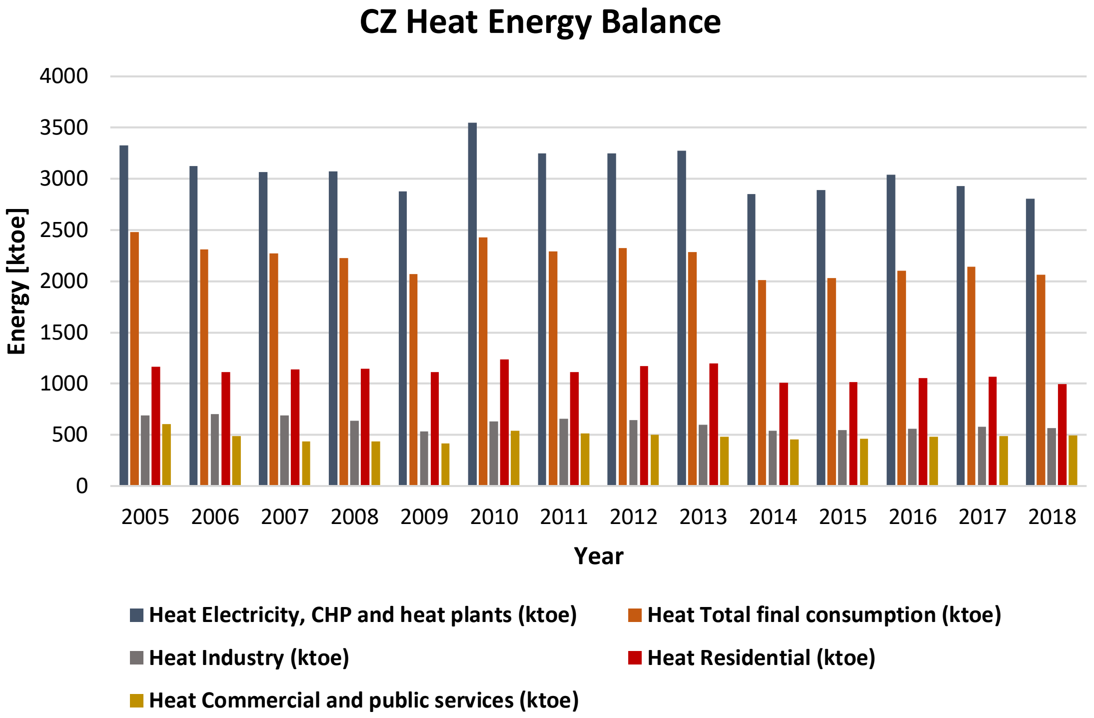


FIGURE 18. CZECH REPUBLIC HEAT ENERGY BALANCE SHEET [74]

EnergyPLAN divides the DH into 3 groups, group 1 represents DHN with no CHP, group 2 represents DHN with small CHP which are CHP plants that cannot operate without a heat load, and finally group 3 represents DHN with large CHP which are CHP plants that do not need a heat load to generate electricity. Unfortunately, the energy balance sheet would not be sufficient to measure the annual heat distribution of a whole country, which is why the Heating Degree Day (HDD) as shown in figure 19 below is necessary.

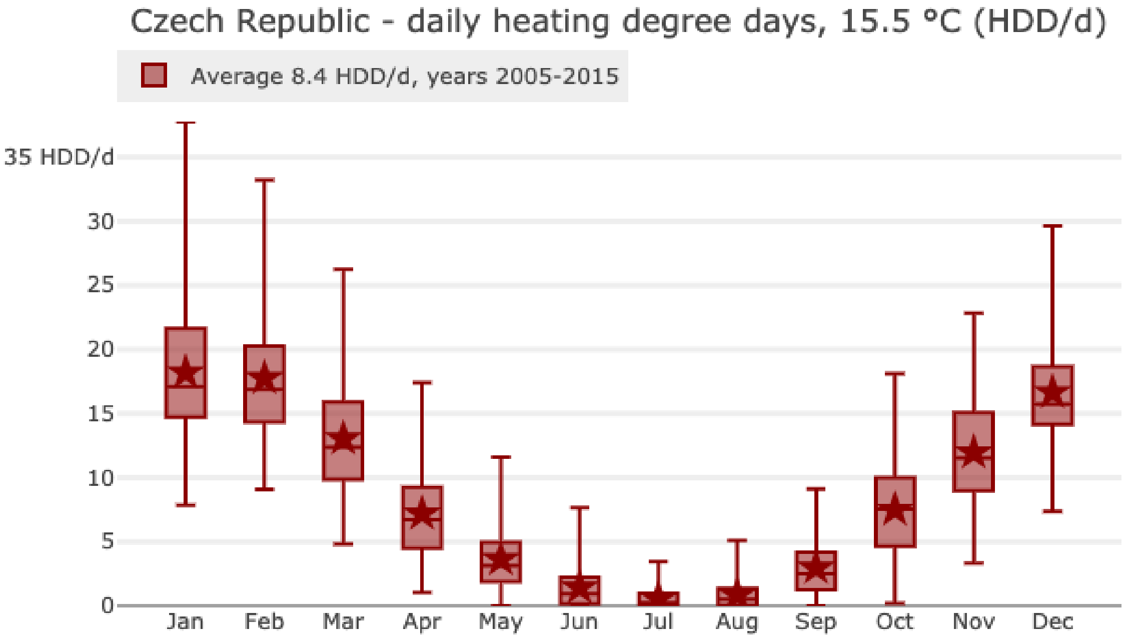


FIGURE 19. THE CZECH REPUBLIC HDD DATA PLOT [75]

Figure 20 below shows the heat demand tab of EnergyPLAN with CZ-BZ-2010 data entered.

Total Heat Demand* : 88.39 **Demand Per Building* :** 15000 kWh/year **Indv. heated households:** 4090 1000-Units

Individual Heating:

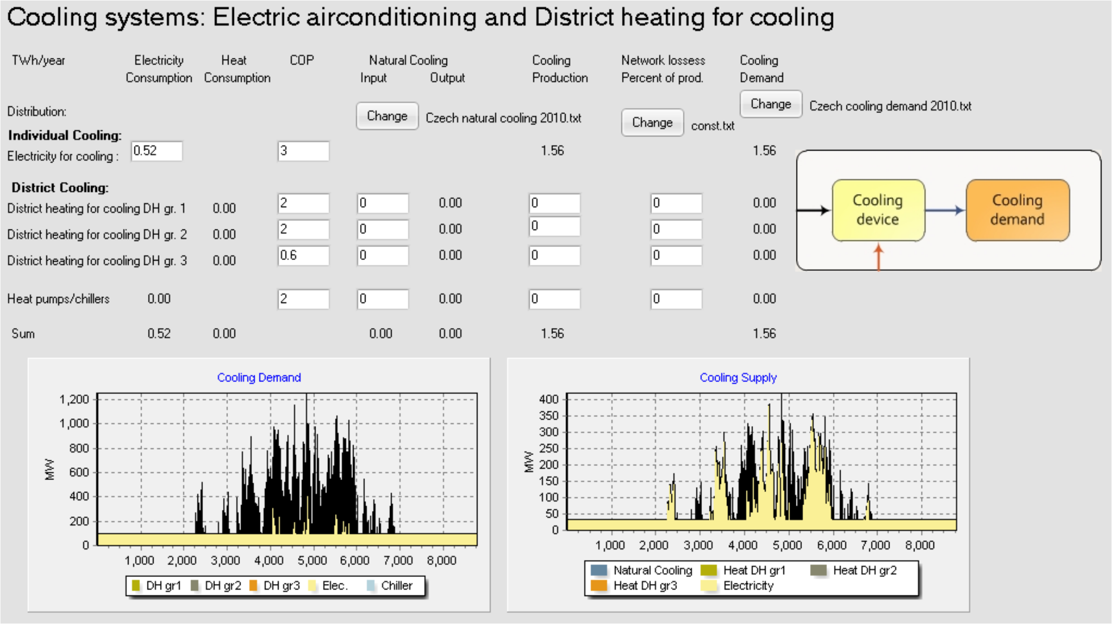
TWh/year	Fuel Input	Efficiency Thermal	Heat Demand	Efficiency Electric	Capacity Limit*	Estimated Electricity Production	Heat Storage* (Days of heat demand)	Solar Thermal Share*	Solar Thermal Input	Solar Thermal Output	Resulting Fuel Consumption*
Distribution:			Heat Czech heat demand 2010.txt							Solar Czech solar thermal 2010.txt	
Coal boiler :	6.92	0.65	4.50				0	0	0	0.00	6.92
Oil boiler :	0.52	0.8	0.42				0	0.9	0.1	0.05	0.45
Ngas boiler :	44.43	0.85	37.77				0	0.9	0	0.00	44.43
Biomass boiler :	13.79	0.65	8.96				0	0.9	0	0.00	13.79
H2 micro CHP :		0.5	0	0.3	1	0.00	0	1	0	0.00	0.00
Ngas micro CHP :		0.45	0	0.45	0.5	0.00	0.3	0.9	0	0.00	0.00
Biomass micro CHP :		0.5	0	0.3	1	0.00	0	1	0	0.00	0.00
Heat Pump :			3.91	3	1	-1.30	1	1	0	0.00	
Electric heating :			5.8		1	-5.80	0	1	0	0.00	
Total Individual:			61.35			-7.10				0.05	65.59

District Heating:

	Group 1:	Group 2:	Group 3:	Total:	Distribution:
Production:	0	0	31.81	31.81	Change Czech district heat demand 2010.txt
Network Losses:	0.15	0.15	0.15		
Heat Demand:	0.00	0.00	27.04	27.04	

FIGURE 20. HEAT DEMAND TAB

It is important to note that EnergyPLAN also takes into consideration the cooling demand as it is a commodity that has been on the rise in recent years due to the warmer temperatures around the globe. Thus, making it essential for energy planning. Figure 21 below shows the EnergyPLAN cooling demand inputs (negligible) for CZ-BL-2010.



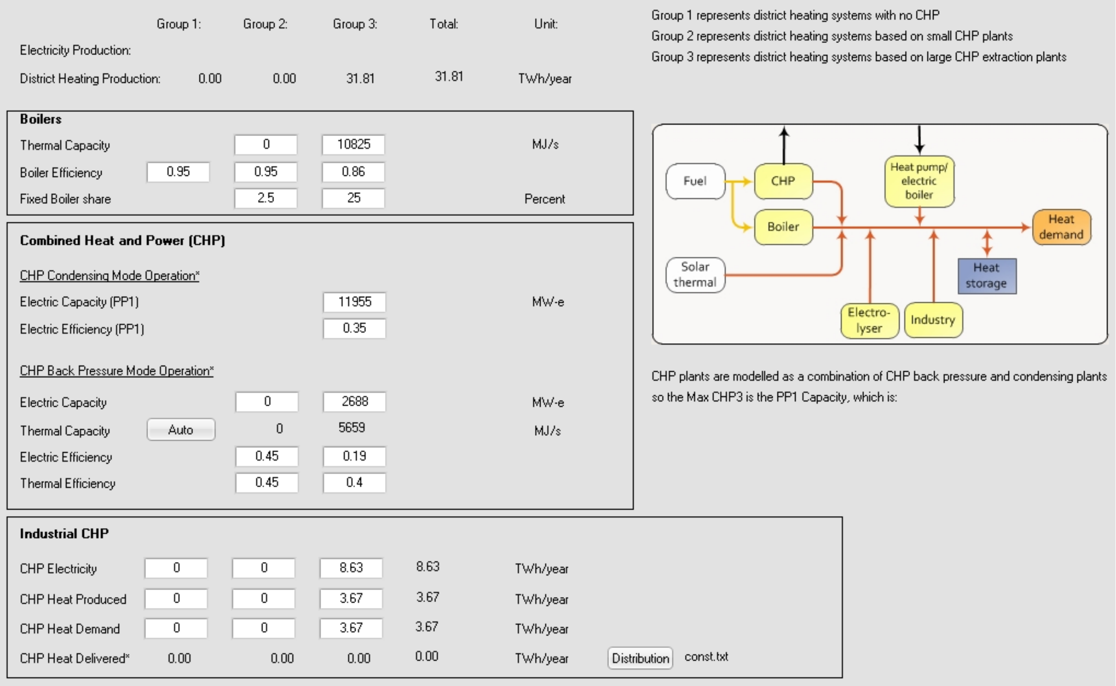
Cooling systems: Electric airconditioning and District heating for cooling

TWh/year	Electricity Consumption	Heat Consumption	COP	Natural Cooling Input	Natural Cooling Output	Cooling Production	Network lossess Percent of prod.	Cooling Demand
Distribution:				Change	Czech natural cooling 2010.txt		Change const.txt	Change Czech cooling demand 2010.txt
Individual Cooling:								
Electricity for cooling :	0.52		3			1.56		1.56
District Cooling:								
District heating for cooling DH gr. 1		0.00	2	0	0.00	0	0	0.00
District heating for cooling DH gr. 2		0.00	2	0	0.00	0	0	0.00
District heating for cooling DH gr. 3		0.00	0.6	0	0.00	0	0	0.00
Heat pumps/chillers	0.00		2	0	0.00	0	0	0.00
Sum	0.52	0.00		0.00	0.00	1.56		1.56

FIGURE 21. COOLING DEMAND TAB

Supply Tab

Figure 22 shows the breakdown of the electricity supply by technologies such as boilers, CHP in condensing mode and back pressure mode, and industrial CHP. The reason why this tab is of importance is to measure the efficiency of the different types of CHP plants in order for the tool to be able to balance the production of electricity and heat during the fluctuating demands across the year. Also, this is the input that lets the tool know what kind of CHP plants are available in the scope of your research and their efficiency.



	Group 1:	Group 2:	Group 3:	Total:	Unit:
Electricity Production:					
District Heating Production:	0.00	0.00	31.81	31.81	TWh/year

Group 1 represents district heating systems with no CHP
Group 2 represents district heating systems based on small CHP plants
Group 3 represents district heating systems based on large CHP extraction plants

Boilers

	Group 1	Group 2	Group 3	Unit
Thermal Capacity		0	10825	MJ/s
Boiler Efficiency	0.95	0.95	0.86	
Fixed Boiler share		2.5	25	Percent

Combined Heat and Power (CHP)

CHP Condensing Mode Operation*

	Group 2	Group 3	Unit
Electric Capacity (PP1)		11955	MW-e
Electric Efficiency (PP1)		0.35	

CHP Back Pressure Mode Operation*

		Group 2	Group 3	Unit
Electric Capacity		0	2688	MW-e
Thermal Capacity	Auto	0	5659	MJ/s
Electric Efficiency		0.45	0.19	
Thermal Efficiency		0.45	0.4	

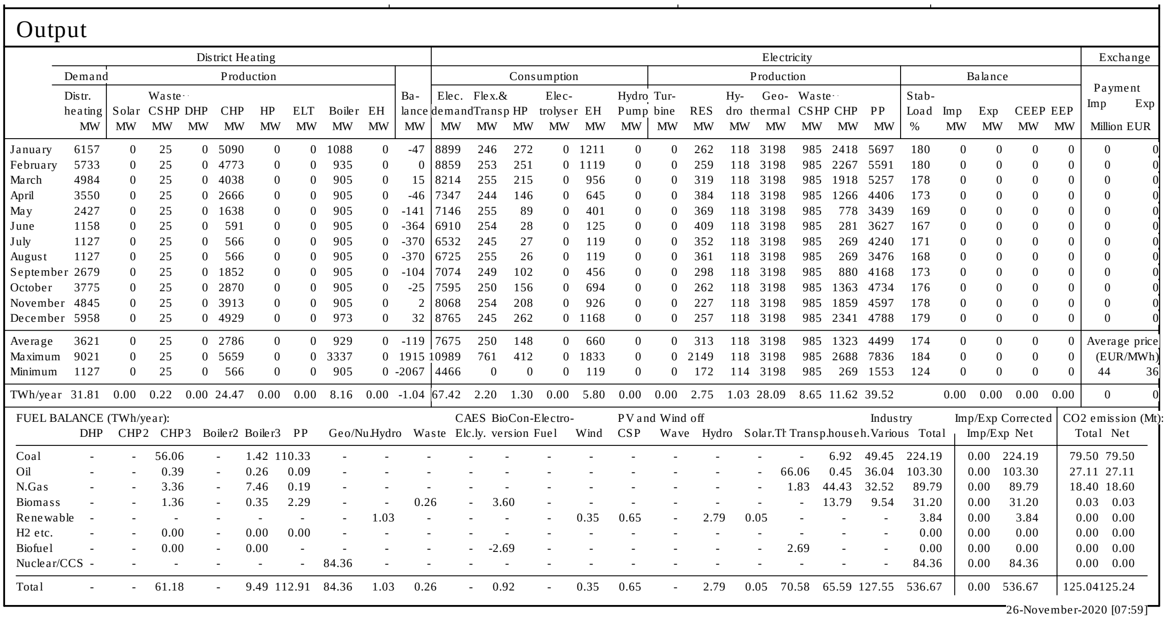
CHP plants are modelled as a combination of CHP back pressure and condensing plants so the Max CHP3 is the PP1 Capacity, which is:

Industrial CHP

	Group 1	Group 2	Group 3	Total	Unit		
CHP Electricity	0	0	8.63	8.63	TWh/year		
CHP Heat Produced	0	0	3.67	3.67	TWh/year		
CHP Heat Demand	0	0	3.67	3.67	TWh/year		
CHP Heat Delivered*	0.00	0.00	0.00	0.00	TWh/year	Distribution	const.txt

FIGURE 22. HEAT AND ELECTRICITY SUPPLY TAB

6.2 CZ-BL-2010 Output Results Sheet



Output

	District Heating										Electricity																			Exchange	
	Demand	Production									Consumption						Production								Balance					Payment	
	Distr. heating MW	Solar MW	Waste-CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Balance MW	Elec. demand MW	Flex.& Transp MW	HP MW	Electrolyser MW	EH MW	Hydro Pump MW	Turbine MW	RES MW	Hydro MW	Geothermal MW	Waste-CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million EUR	Exp Million EUR
January	6157	0	25	0	5090	0	0	1088	0	-47	8899	246	272	0	1211	0	0	262	118	3198	985	2418	5697	180	0	0	0	0	0	0
February	5733	0	25	0	4773	0	0	935	0	0	8859	253	251	0	1119	0	0	259	118	3198	985	2267	5591	180	0	0	0	0	0	0
March	4984	0	25	0	4038	0	0	905	0	15	8214	255	215	0	956	0	0	319	118	3198	985	1918	5257	178	0	0	0	0	0	0
April	3550	0	25	0	2666	0	0	905	0	-46	7347	244	146	0	645	0	0	384	118	3198	985	1266	4406	173	0	0	0	0	0	0
May	2427	0	25	0	1638	0	0	905	0	-141	7146	255	89	0	401	0	0	369	118	3198	985	778	3439	169	0	0	0	0	0	0
June	1158	0	25	0	591	0	0	905	0	-364	6910	254	28	0	125	0	0	409	118	3198	985	281	3627	167	0	0	0	0	0	0
July	1127	0	25	0	566	0	0	905	0	-370	6532	245	27	0	119	0	0	352	118	3198	985	269	4240	171	0	0	0	0	0	0
August	1127	0	25	0	566	0	0	905	0	-370	6725	255	26	0	119	0	0	361	118	3198	985	269	3476	168	0	0	0	0	0	0
September	2679	0	25	0	1852	0	0	905	0	-104	7074	249	102	0	456	0	0	298	118	3198	985	880	4168	173	0	0	0	0	0	0
October	3775	0	25	0	2870	0	0	905	0	-25	7595	250	156	0	694	0	0	262	118	3198	985	1363	4734	176	0	0	0	0	0	0
November	4845	0	25	0	3913	0	0	905	0	2	8068	254	208	0	926	0	0	227	118	3198	985	1859	4597	178	0	0	0	0	0	0
December	5958	0	25	0	4929	0	0	973	0	32	8765	245	262	0	1168	0	0	257	118	3198	985	2341	4788	179	0	0	0	0	0	0
Average	3621	0	25	0	2786	0	0	929	0	-119	7675	250	148	0	660	0	0	313	118	3198	985	1323	4499	174	0	0	0	0	Average price	
Maximum	9021	0	25	0	5659	0	0	3337	0	1915	10989	761	412	0	1833	0	0	2149	118	3198	985	2688	7836	184	0	0	0	0	(EUR/MWh)	
Minimum	1127	0	25	0	566	0	0	905	0	-2067	4466	0	0	0	119	0	0	172	114	3198	985	269	1553	124	0	0	0	0	44	36
TWh/year	31.81	0.00	0.22	0.00	24.47	0.00	0.00	8.16	0.00	-1.04	67.42	2.20	1.30	0.00	5.80	0.00	0.00	2.75	1.03	28.09	8.65	11.62	39.52		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 and CSP	Wind off Wave	Hydro	Solar.Th	Transp.	Industry househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Net	CO2 emission (Mt): Total	CO2 emission (Mt): Net
Coal	-	-	56.06	-	1.42	110.33	-	-	-	-	-	-	-	-	-	-	-	-	6.92	49.45	224.19	0.00	224.19	79.50	79.50
Oil	-	-	0.39	-	0.26	0.09	-	-	-	-	-	-	-	-	-	-	-	66.06	0.45	36.04	103.30	0.00	103.30	27.11	27.11
N.Gas	-	-	3.36	-	7.46	0.19	-	-	-	-	-	-	-	-	-	-	-	1.83	44.43	32.52	89.79	0.00	89.79	18.40	18.60
Biomass	-	-	1.36	-	0.35	2.29	-	-	0.26	-	3.60	-	-	-	-	-	-	-	13.79	9.54	31.20	0.00	31.20	0.03	0.03
Renewable	-	-	-	-	-	-	-	1.03	-	-	-	-	0.35	0.65	-	2.79	0.05	-	-	-	3.84	0.00	3.84	0.00	0.00
H2 etc.	-	-	0.00	-	0.00	0.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00
Biofuel	-	-	0.00	-	0.00	-	-	-	-	-	-2.69	-	-	-	-	-	-	2.69	-	-	0.00	0.00	0.00	0.00	0.00
Nuclear/CCS	-	-	-	-	-	-	84.36	-	-	-	-	-	-	-	-	-	-	-	-	-	84.36	0.00	84.36	0.00	0.00
Total	-	-	61.18	-	9.49	112.91	84.36	1.03	0.26	-	0.92	-	0.35	0.65	-	2.79	0.05	70.58	65.59	127.55	536.67	0.00	536.67	125.04	125.24

26-November-2020 [07:59]

FIGURE 23. ENERGYPLAN RESULTS SHEET FOR CZ-BL-2010

We can see from the results above that according to the data we supplied, the tool simulated that DH covered approximately 35% of the heat demand and the RES share of primary energy is at 6.5%. Below are some graphical results that the tool generates based on the results sheet from figure 23.

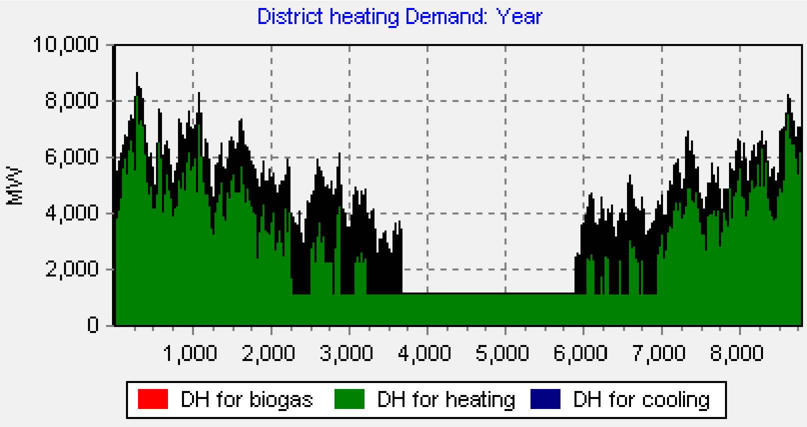


FIGURE 24. YEARLY DISTRICT HEATING DEMAND CZ BL 2010

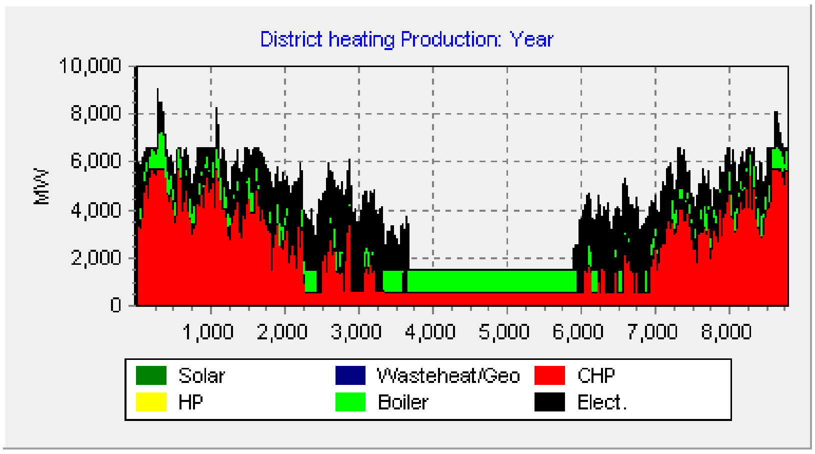


FIGURE 25. YEARLY DISTRICT HEATING PRODUCTION BY FUEL

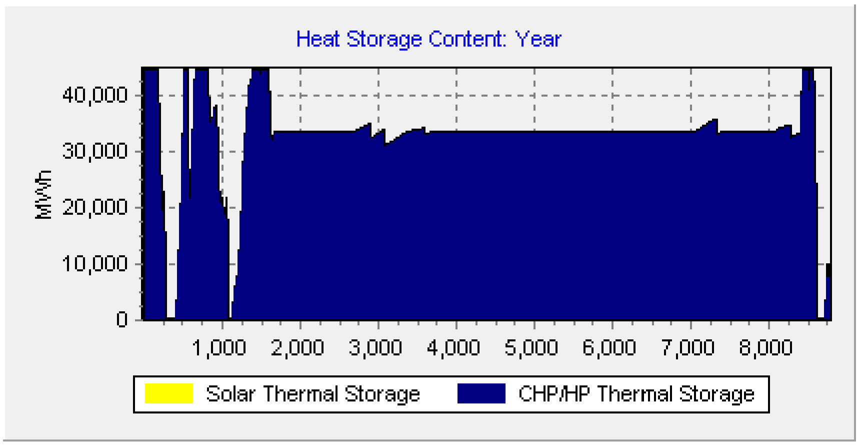


FIGURE 26. YEARLY SOLAR & CHP/HP THERMAL STORAGE CONTENT

7. Conclusion

The aim of this thesis was to identify suitable modeling and simulation methods for the revitalization of district heating networks. Throughout the district heating generations reviewed, a clear trend was observed. Low-temperature networks and refined links between the electricity and heating sectors are vital for the flexibility needed to integrate variable renewable energy sources. Some of the most prominent sources of heat expected in the future of DHN are CHPs, heat pumps and industrial excess. Putting this in context of the Czech Republic, the level of technology currently in use within its network is considered to be outdated. The network relies intensively on fossil fuels such as brown coal which covers over 50% of the fuel consumed in CHP as a heat source for DH. While an abundance of excess heat sources from industry and cogeneration is being wasted. This limits the overall efficiency of the system and highlights the significance of linking the electricity and heat sectors.

Energy planning and design tools are expected to be able to seamlessly integrate the aforementioned trends of the energy sector. Most considerably, they are expected to be able to properly incorporate the diverse new supply technologies and support their integration into current networks. They are also expected to utilise the synergies of different sectors of the energy system to improve the overall efficiency and reduce cost of energy. Throughout the comprehensive comparison done on each of the stated tools, it has been noticed that the prior statements are indeed reflected in the capabilities and objectives of the tools.

The regional and national scale energy planning tools have proven their reliability throughout numerous research papers of supporting accurate simulations of future DHN. EnergyPLAN has already been used by HRE to formulate country level case studies that covered 90% of the European energy market for 2050. Including the full transition to a 100% renewable smart energy sector. THERMOS the map-based energy planning tool could be demonstrated as a valuable solution in measuring the accurate size of a building instead of estimates. This would significantly improve the accuracy of energy demand profile predictions. Finally, SAM could be used to extract information on the availability of renewables and concentrated solar to support the transitioning of smart energy systems.

Likewise, local scale energy system design and optimization tools have proven that they are capable of integrating RES and low carbon technologies into their models. TRNSYS, OpenModelica and Dymola have been used in applications that aim at revitalizing local energy systems. These are tools that can uncover solutions for systems that cannot be connected to the network due to feasibility issues. HOMER oriented on the electricity sector has also been used for techno-economic analysis of off-grid systems to meet their load using hybrid RES configurations.

From the tool practice, we can clearly note that the process of simulating a country level scale model is very data intensive. Especially, due to the energy demand data required being in an hourly time-step. Nevertheless, the tool has the potential to produce highly accurate demand forecasts that is essential for the revitalization of the district heating network in the Czech Republic.

Appendix A: Simulation Tool Summary

Abbreviations used in the table: **Application:** EP - Energy Planning, ED - Energy Design. **Purpose:** S - Scenario, IDS - Investment Decision Support, ODS - Operation Decision Support, PSAT - Power System Analysis Tool. **Assessment Method:** S - Simulation, O - Optimization, LP - Linear Programming, NLP - Non Linear Programming, ABS - Agent Based Simulation. **Approach**: BU - Bottom-Up. **Supply Technology Capabilities:** PV - Photovoltaics, GSHP - Ground Source Heat Pump, TES - Thermal Energy Storage, CHP - Combined Heat and Power. **Scale:** SP - Single Project, B - Building, L - Local, D - District, N - National**,** C - Continental. **Stakeholder:** M&UP - Municipal & Utility Provider, T&R- Technicians and Researchers, C - Consumers.

Software Tool	Developer	Application	Purpose	Assessment Method	Approach	Tool Focus	Supply Technology Capabilities	Step	Scale	Stakeholder	Availability	Application in Practice and Research
EnergyPLAN	Aalborg University (DN)	EP	S, IDS, ODS	S, O	BU	Deterministic Input/Output model for long-range policy planning of heating, cooling, transportation energy demands and supply	Solar thermal, GSHP, TES, Boilers, CHP	Hourly	D, N, C	M&UP, T&R	Free, Open-source	IDA's Energy Vision 2050 [23] Zero Carbon Energy System in South East Europe in 2050 [68]
TRNSYS	Wisconsin University (US)	ED	PSAT	S, L/NLP	BU	Break down of single/small project energy systems into individual components	PV, Solar thermal, GSHP, TES, Boilers, Chillers, CHP	Sub-hourly	SP, B, D	M&UP, T&R	Commercial, Open-source	Optimum Design and Operation of an HVAC Cooling Tower for Energy and Water Conservation [47] Software-in-the-Loop-simulation of a District Heating System [48]
HOMER	NREL & DOE (US)	EP & ED	IDS, ODS	S, O	BU	Promoting the use of RES especially PV and wind for ON/OFF grid solutions	PV, Solar thermal, Concentrated solae, TES, Boilers, Chillers, CHP	Sub-hourly	B, L	C, T&R	Commercial, Closed-source	Optimal Sizing of a Hybrid System of Renewable Energy for Lighting Street [51] Techno-economic feasibility analysis of a solar-biomass off grid system [52]
THERMOS	Centre for sustainable energy (UK)	EP	IDS, ODS	ABS, O	BU	Map-based web tool that provides the methods, data and tools to accelerate development of low-carbon energy systems	GSHP, TES, Boilers, CHP	Hourly	SP, B, D	T&R, C	Free, Open-source	A combined spatial and technological model for the planning of district energy systems [72] Accelerating the development of low-carbon heating & cooling networks [55]

OpenModelica	Linköping University (SW) & OSMC	ED	PSAT	S, O, NLP	BU	Integration of HRES in small scale energy systems using individual components	PV, GSHP, Boilers, Chillers	Sub-hourly	SP, B, D	T&R	Free, Open-source	An Automated Approach to Building and Simulating Dynamic District Heating Networks [70] Building and Simulating Dynamic Models of District Heating Networks with Modelica [59]
DYMOLA	Dassault Systemes SE (FR)	ED	ODS	ABS, O	BU	A multi-engineering domain platform that uses mathematical equations to describe dynamic behaviour of system components	PV, GSHP, Boilers, Chillers	Sub-hourly	SP, B, D	T&R	Commercial, Open-source	Dynamic Simulation of District Heating Networks [76] Achieving lower district heating network temperatures using feed-forward MPC [77]
SAM	NREL & DO (US)	EP	IDS	S, O	BU	Performance and financial model for the generation and trading of electricity using RES	PV, Solar thermal, Concentrated solar, TES	Sub-hourly	SP, B, N	M&UP, T&R, C	Free, Open-source	Technical and Economic Analysis of a Grid Tied PV Plant [69] Simulation modelling of a concentrating solar thermal power plant [66]

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