Supporting Municipal Energy Transition through Modelling of Possible Future Energy Scenarios

A Case Study of Kungälv, Sweden

Master's thesis in Sustainable Energy Systems

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Abstract

Municipalities and municipal utility companies have been found to be excellent drivers for the energy transition that is required to meet climate goals [1, 2]. However, municipal energy planning procedures and tools frequently do not account for the interactions between electric distribution grids and district heating networks [2, 3]. Storage solutions for either heat or electrical energy have been similarly disregarded.

In this thesis, a methodology for design and evaluation of transition scenarios for a mid-sized municipality is proposed and applied in a case study of the Swedish municipality of Kungälv. Historical data on load profiles in both electrical and district heating grids is analyzed and used for creation of compound load profiles, which serve as the basis for a robust approach to generating synthetic load curves in alternative development scenarios. A time-discrete numerical calculation model for simulation of cost-optimal system operation on a seasonal scale is introduced. The effects of a range of growth scenarios for local renewable electricity generation and the district heating system on the system behaviour and associated costs are investigated. Heat storage systems are proposed and their effect on the system is analysed.

The results suggest that utility-scale battery storage and seasonal heat storage could be beneficial to the system by lowering energy prices. Synergies between storage and increased local intermittent electricity production are shown. Seasonal heat storage is especially beneficial in scenarios with high usage of district heating, where significant peak generation capacities can be replaced.

Keywords: energy transition, district heating, heat storage, battery storage, intermittent renewables.

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Benedikt Jahn & Nivit Mital, Gothenburg, June 2022

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CHP	Combined Heat and Power
DH	District Heating
ENS	Energistyrelsen (Danish Energy Agency)
HP	Heat Pump
PTES	Pit Thermal Energy Storage
PV	Photovoltaic
RES	Renewable-based Energy Sources

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1 Introduction

Municipal Energy Transition is one of the key concepts for sustainable development. Energy transition can help in reducing the carbon footprint without compromising the energy needs of the mankind. Sweden is taking early and effective actions towards sustainable development and many of the municipalities in Sweden including Kungälv are highly committed to undergo energy transition. The key features of such a transition include increased use of renewable sources of energy, energy efficient production, distribution and consumption, decreased consumption on industrial and residential scale, and less fossil based transportation. This master thesis deals with analysing various aspects, scenarios and possibilities to provide support in decision making in the municipality of Kungälv in achieving its aim of undergoing energy transition in the best possible way.

1.1 Background

Energy transition is a paradigm shift from a system dominated by fossils towards a system based on renewable sources of energy and also supported by strategies that enhances energy efficiency and sufficiency [4]. Most of the European countries including Sweden have set some green targets like getting carbon neutral by 2045, 100% renewable based energy production by 2040 and many sub-targets that help achieve these targets systematically and on time [5].

Scaling of renewables is an important tool for achieving such green targets. According to an analysis by EU-28, renewables have found a comparatively good place in electricity generation but still lags in sectors like transportation and heating. On the European scale, renewable electricity generation almost doubled and reached 22.1% in 2020 when compared to only 9.6% in 2004. While in the case of transportation the share of renewable energy reached to 10.2% in 2020 with almost nothing in 2004 [6, 7]. At the same time, the production of research on renewable energy topics continues to grow accordingly [8].

When it comes to Sweden, renewable energy growth has been relatively more than most of the European countries. In the year 2004, about 40% of the total energy produced came from the renewable sources of energy which further rised to about 60% in 2020. The most visible growth occurred in the transport sector reaching a value of about 30% in 2020 from almost nothing in 2004. In the electricity and heating sectors, the role of renewable energy has always been recorded high since

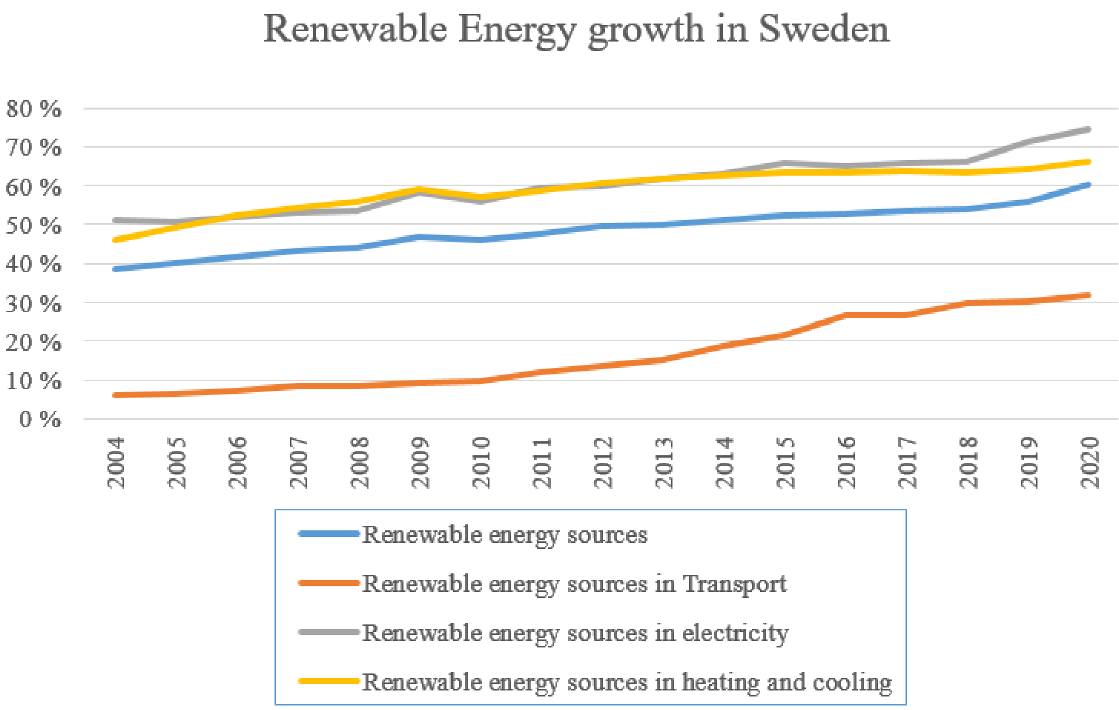

Figure 1.1: Percentage share of renewable energy in types of energy consumption for EU28 [9]

2004, further getting dominant with a value about 70% in 2020 as shown in the figure 1.1. As of now, the remaining electrical demand is covered by the nuclear energy which is not renewable.

In practice, taking action through policies towards the goals of energy transition remains challenging. A multitude of stakeholders is involved in implementing national legislation. As owners of a large number of public buildings and frequently their own local energy companies, municipalities are closely connected with some of the most important stakeholders [1]. This, along with their ability to interact with both local issues and higher levels of government, has made municipalities an excellent driver for envisioning and planning energy transition scenarios [3]. Meanwhile, municipalities also possess some of the most effective policy mechanisms for active implementation of such plans [3, 10].

In Sweden, municipal energy planning has been formalized and required by law since 1977 [11]. While the legislation was initially passed in the aftermath of the 1973 oil crisis in an attempt to reduce the country's reliance on oil for heating, the scopes of municipal energy plans have shifted over time [1, 12], and have now turned into an instrument of national energy transition at a local level. While national goals are set by central governments, municipalities have achieved progress towards carbon neutrality through their individual, decentralized energy transitions.

When it comes to Municipal Energy transition, European dedication and motivation looks quite promising. According to a survey published under the University of

Glasgow, more than 100 municipalities across the Europe laid down initial plans to undergo energy transition out of which around 30 municipalities have shown quite convincing results in this particular direction [6]. Sweden has showed a remarkable progress and honored its commitment towards this green movement without any sort of excuses. Växjö, a municipality in Sweden is a good example for energy transition. It achieved the title of "Europe's greenest city" in 2007 which made it an attractive specimen for policy makers of various other municipalities in various countries planning a similar transition [13]. A major element of its transition was switching heat and power away from oil to biomass through locally produced waste from timber resources. Växjö covers its 65% of power and heat demand from renewables with a fossil free target by 2030. 90% of the district heating and 20% of the electricity demand is covered by a large CHP plant. The municipality also has a biogas plant, solar photovoltaic and solar thermal generation which add to the share of renewables. Further Växjö owns a large proportion of buildings and infrastructural premises and thereby been able to undertake significant energy efficiency measures and retrofit projects for the existing buildings. The town has also set high performance standards for the new buildings to be built to promote energy savings and reduce greenhouse gas emissions. The municipality generated financial resources from numerous sources including public bonds, national government, European commission etc. On the other hand, many municipalities still stand unsuccessful in undergoing this green transition. The common reasons that have been pointed out by municipalities are limited local capacity, financial constraints and political blockages [6].

1.2 Case study

Kungälv is a municipality in the Swedish county of Västra Götaland, located about 15 km to the north of Gothenburg and surrounded to the west, south and east by the Skagerrak coast and Nordre and Göta älv rivers. In 2021, the municipality had almost 48,000 inhabitants, of which 20,000 lived in the eponymous town of Kungälv. Besides that town, which serves as the municipality's seat, the municipality comprises 18 urban settlements, including Kode, Diseröd, Tjukvil, Kärna and Marstrand. Roughly 35% of the municipality's inhabitants live outside these urban settlements in numerous rural communities, spreading over a land area of 362.5 km^2.

The municipality's most recent energy plan was developed in 2009. It is structured in two parts: the information part [14] giving an overview of the current state of the energy system and its transition, and the action part [15] covering the municipal goals and suggestions for tangible action.

Kungälv Energi operates large parts of the local electricity distribution grid, as well as district heating networks in the towns of Kungälv, Kode and Kärna. Customers obtain heat almost exclusively through electric heating or the district heating network. As per the 2009 energy plan oil and natural gas contributed about 5% heating in detached houses and 11% in municipal premises, while contribution in apartment buildings and industries was minimal. In the current state, district heating and electrical heating still play the dominant roles without any reflections of fossil based heating in the official records.

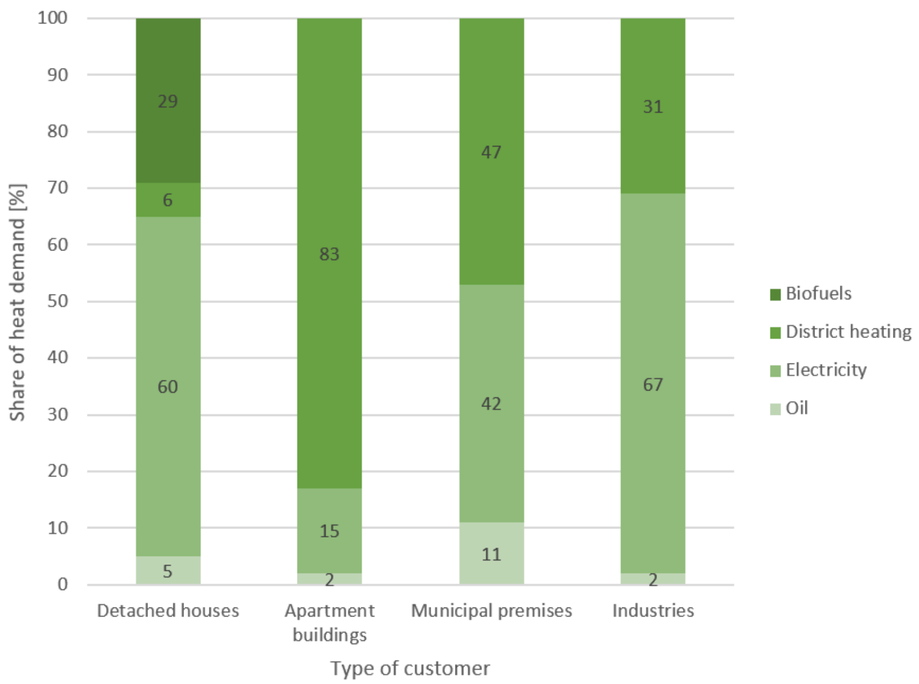

Figure 1.2: Heat in Kungälv by source according to the 2009 report [14]

As can be seen in figure 1.2, the district heating network is the predominant supplier of heat in apartment buildings and municipal premises, with a significant contribution to industrial demand. However by 2009, out of approximately 10,000 single-family homes only 630 were connected to the district heating system in 2009, and out of 6,000 electrically heated households, 2,000 employed electric heat pumps. The remaining load is largely covered with biofuel boilers, but 800 houses still had oil boilers installed in 2009. Nowadays, more than 1,000 premises are connected to the district heating network in Kungälv [16]. The number of economically viable connections in the town is limited by the large number of rural homes far away from the existing network, though there still remains great potential for new connections within or nearby to the network limits.

The district heating networks are centered around three facilities operated by Kungälv Energi. Munkegärdeverket is a co-generation plant in the town of Kungälv fuelled largely by wood chips and residual products from the forestry industry in a 180 km radius, producing roughly 120 GWh of heat annually. The plant has been supplemented by a 10,000 m² solar collector field covering about 1.2% of the grid's heating load since 2002, though the solar heating is being replaced with photovoltaics installations in recent years. An expansion of Munkegärdeverket's capacity by a third production line is planned for 2023/2024 [17]. The district heating network in the town of Kungälv has also been connected to that of nearby Gothenburg since 2009, giving it the potential to purchase up to 19 MW of industrial waste heat mainly in the summer months. Additionally, two smaller pellet plants supply the unconnected district heating systems in Kärna and Kode.

Munkegärdeverket has additionally produced electricity since 2007. At an annual output of 9 GWh, it covered 2% of the municipal electricity load of 372 GWh in 2007. A wind turbine called Vindrosen rated at 2.85 MW was installed in the municipality in 2014 [18]. As of 2022, Munkegärdeverket and Vindrosen remain the only utility-scale electricity generation plants in Kungälv.

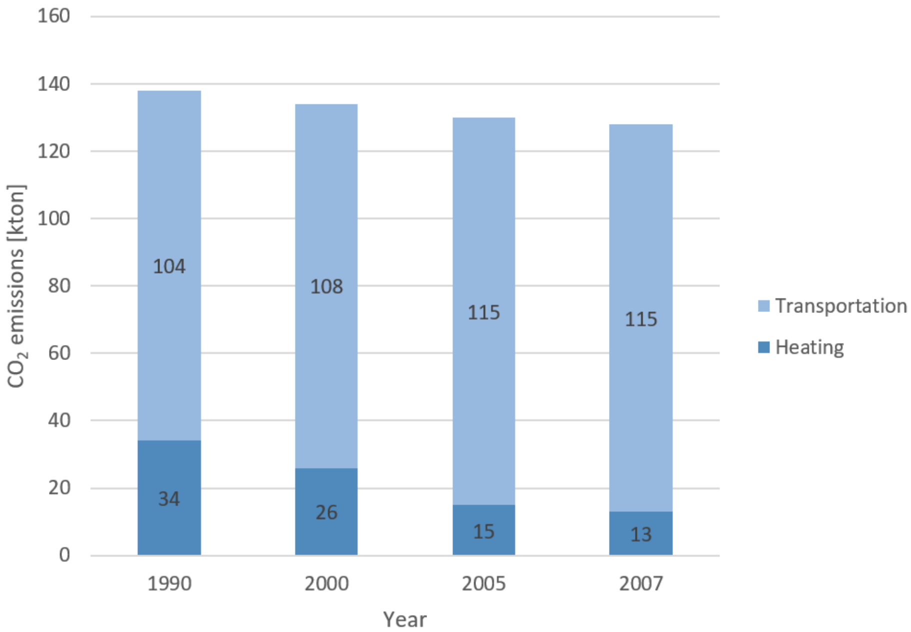

Figure 1.3: Trend in direct carbon dioxide emissions by usage in Kungälv [14].

Electricity and heat are the dominant energy carriers in Kungälv's residential, commercial, industrial and public buildings, but the transportation sector is still largely reliant on fossil fuels. In 2006, transportation was responsible for 43% of the total energy use in Kungälv, with households using 29%. While energy efficiency in buildings increased significantly over the years, so has the amount of traffic in the municipality. This has led to a significant part of emission reductions in the heating sector being offset by the increased traffic between 1990 and 2007, as can be seen in figure 1.3. In the figure, the data on heating was accumulated from reported emissions from economic actors, while the numbers about transportation were calculated using a distribution key and nationally raised statistics [19].

The Kungälv energy action plan is centered around the municipality's climate goals in accordance with national Swedish goals. These goals are not only limited to a reduction of carbon emissions by 100% by 2050, but also encourage an increased usage of renewable energy sources. As such, the plan entailed 100% self-sufficiency in renewable electricity by 2070 and the ambitious goal of eliminating carbon emissions from heating by 2020. The strategies that were deemed suitable for achieving these goals are summarized in table 1.1. According to Johannsen et al. [2], the presence of long-term goals exceeding the length of the municipal election cycle is uncommon among European municipal energy plans, yet is identified as an important planning practice for achieving accountability in energy transition planning.

The energy transition in the municipality is further supported by the NGO Transition Kungälv. Local initiatives, when coupled with concrete goals and viable visions, have proven to be successful in initiating change processes in energy planning [20].

Reduce the total energy consumption	Switch to renewable energy sources and sustainable transport
Outward Efforts 1. Sustainable transport and vehicles 2. Dialogue/advice to companies regarding environmentally friendly and efficient transport and travel 3. Travel habits survey 4. Energy and climate advice 5. Energy efficient companies **Measures for energy efficiency and improvement** 6. Energy efficient street lighting 7. Energy efficiency measures in municipal buildings 8. Energy-smart homes at Kungälvbostader 9. Energy smart homes at Forbo 10. Green IT 11. Energy efficient municipal treatment plants **Environmentally adapted new construction** 12. Control document environmentally adapted construction / Energy requirements for new buildings 13. Energy requirements for new municipal premises	**Measures for environmentally friendly transport system** 14. Environmental adaptation of the Marstrand ferry 15. Bicycle and footpaths 16. Act according to K2020 (40% public transport by 2025) 17. Freight transport by rail 18. Sustainable vehicles and transport in municipal activities **Measures for environmentally friendly energy production.** 19. Renewable local electricity production 20. Expansion of district heating networks in existing buildings 21. Enquiry into local heating at Diserod 22. Finished heat 23. District cooling 24. Energy from biological waste and wood waste 25. Environmentally friendly firing of solid fuels

Table 1.1: Strategies outlined in the 2009 Kungälv energy plan - action part [15]

1.3 Aim

The thesis aims to contribute to the understanding and planning of municipal energy transitions through analysis and evaluation of possible future energy scenarios. The agenda further is to investigate the effect of scaled renewables and availability of storage solutions on the overall energy system by depicting the economics involved as well as the potential benefits in terms of energy prices and goal fulfillment. Since every municipality has its own unique features and limitations, generalized statements are not sufficient to contribute to knowledge building in specific municipalities, thereby a detailed case study will be performed. The subject of this case study is the Swedish municipality of Kungälv, which is in the process of reviewing its energy plan and introduced further in section 1.2.

As a part of this case study, we aim to provide the Kungälv local utility with decision and design support by providing insights in its plan and formulating recommendations based on technical investigation and research to undergo energy transition. Apart from the old energy plan released in 2009, the local utility has further framed some recent ideas with an agenda to achieve the transition in the best possible manner by targeting the key requirements. The first idea is based on heat storage that can provide flexibility with heat energy supply throughout the year with an aim to create the energy security and also reduce dependence on peak generation technologies. This idea requires a deep analysis on methods of energy storage, different types of costs associated, losses in the system, and clear system boundaries. The second idea is based on different scenarios of future energy consumption and the associated power requirements. This idea requires an analysis on the choice of heating method in the future and the way it affects both the electricity and heat networks.

Both ideas put forward by the utility Kungälv Energi are linked closely together. The design of storage systems must support future requirements, which can only be predicted with high uncertainty. As energy systems evolve towards a high proportion of intermittent renewable energy supply, energy storage will continue to gain significance in ensuring system stability and also become more economically viable [21]. Therefore, evaluation of scenarios for storage systems in accordance with the first idea put forward by the utility should be preceded by the design of various scenarios for the future growth of the municipality and its energy system. These scenarios may then be used for a techno-economic assessment of different storage options.

1.3.1 Research Questions

The research questions are derived from the ideas listed by the utility in the current state as well as the goals framed in the 2009 plan. The central questions are:

- How are system demand and generation characteristics in the local heat and energy systems affected by different growth scenarios?
- How does energy storage affect the system behaviour?

2

Method

2.1 Approach

Achieving energy transition is an endeavour that requires broad societal consensus to be successful. A working partnership between the private and public sector has been shown to be a strong driver of energy transitions [2, 20]. This consensus may be achieved by aligning stakeholder interests. An effective way to achieve this is by ensuring that growth scenarios associated with the transition progress do not only serve a purpose for increasing sustainability, but are also economically beneficial to society. Since low energy prices contribute to economic growth [22], it can be assumed that the chances of success in achieving a transition is correlated with the degree to which the underlying transition scenario decreases system energy prices.

Therefore, economic data has been considered a key marker of a successful energy transition in this study, in particular the respective average prices of district heating and electrical energy as well as the total investment cost necessary to achieve the transition. The methodology's ultimate goal is therefore to develop, simulate and assess a range of transition scenarios. A scenario is defined by the installed capacities in generation units on the supply side, and in heating units on the demand side. The structure of demand side application of heating technologies is a main driver of electrical and district heating load, while supply side technologies provide insights into operational behaviour and marginal energy prices of the system.

Related system data was provided by interviewees from the local utility Kungälv Energi [16]. This includes time series of the DH and electrical system loads with an hourly resolution. Based on these time series, it has been possible to synthesize load profiles for alternative energy system scenarios. Synthetic load profiles then serve as the basis of further analysis, which is centred around a numerical, time-discrete calculation model.

For comparability's sake, all results of this study have been calculated using the reference year 2021. This year was selected due to its recency and high data availability. The technical parameters were also based off 2021 data and estimations. Therefore, the scenarios presented here are to be interpreted as alternative scenarios for the current system, and should be compared as such. They do not depict a progression, but rather system states that may occur over the course of a transition.

This enables the comparison of individual scenarios, transition paths and measures under equal conditions.

2.1.1 Load profile synthesization

Since the scenarios contain information on the installed capacity of each individual demand-side heating technology as a share of total heat load in the municipality, scaling of that total heat load by the scenario's demand-side heating technology shares results in individual load curves for each installed technology. Depending on the relevant energy carrier, these individual load profiles may be recombined into loads on district heating, the electrical grid and other energy carriers.

Historical load profiles from the Kungälv electricity and district heating systems were available as a basis for determining the total, "raw", heat load profile to be used for the development scenarios. The synthesization rests upon three assumptions:

1. The electrical load consists of a heating component and a non-heating component
2. The electrical heating load variations follow the same patterns as the DH load
3. The non-heating load is not subject to significant seasonal variations

The first assumption is evidently true, since electrical heating plays a significant role in Kungälv. The second assumption is reasonable since electrical heating and district heating ultimately fulfill the same purpose of providing space and water heating. The third assumption is plausible, since comparisons of Kungälv's electrical load profile with those of municipalities with significantly less electrical heating installations yield much higher seasonal variability of electrical load in Kungälv than elsewhere.

The electrical load profile from Kungälv was analyzed in the context of these assumptions. Frequency plots resulting from an FFT of the provided load profiles are shown in figure 2.1. It became apparent that the electrical load has significantly more pronounced peaks at weekly and daily frequencies, including harmonics, than the district heating load, while the only frequency band where the normalized DH frequency exceeds the electrical frequency lies roughly between zero and seven cycles per year. Based on assumption 2., this particularity of the DH load frequency spectrum can be assumed to also be present in the electrical load spectrum. Thus, in order to extract the electrical load that goes into heating, a low-pass filter with a passband frequency of 7 cycles/year was applied to the electrical load signal, with the cut off frequencies representing the raw electrical load. Application of an inverse Fourier transform shifts the signals back into time domain. The constant signal component, after application of the low-pass filter initially entirely part of the heating component, was then redistributed between both electrical load components so that the ratio between peak and base loads in electrical heating matched that of the district heating load. Lastly, a moderate amount of high-frequency noise from the district heating load data was added to the electrical heating profile to match the heat load's short-term variability.

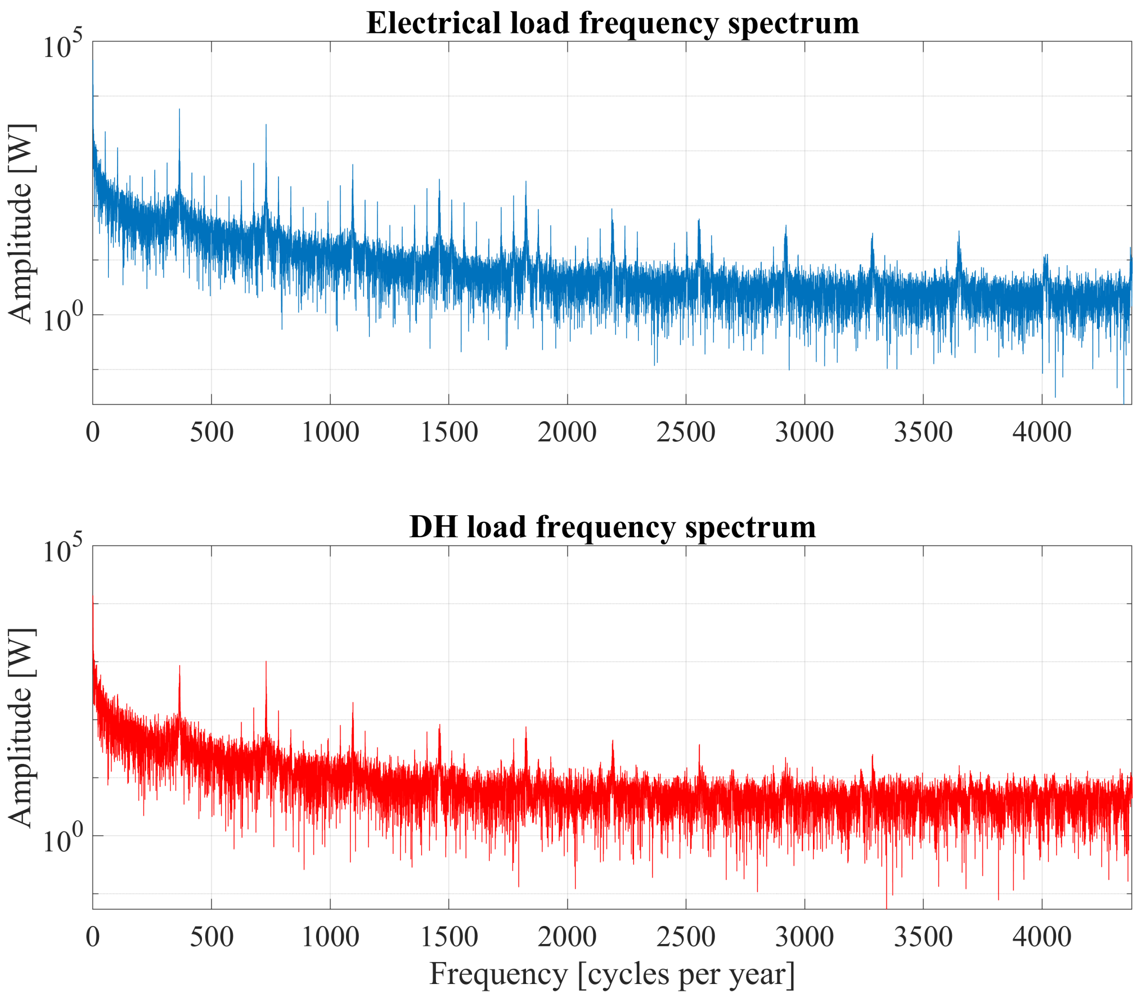

Figure 2.1: The real parts of FFT frequency spectra for the provided load curves in the electrical and district heating grids of Kungälv.

The resulting raw electrical load curve can directly serve as a basis for scenario synthesis, since the electric grid is the only relevant source of electric power in the considered area. The raw heat load, meanwhile, is covered by technologies that are fed by three different major energy carriers: The district heating grid, the electrical grid and biomass. The raw heat load is the sum of each energy carrier's contribution. In order to calculate its raw heat load contribution, the electrical heating load is multiplied with the aggregated efficiency of the installed electrical heating technologies; the biomass contribution is determined by scaling the district heating load curve by the assumed prevalence of biomass heating; and the district heating load profile represents a raw heat demand as-is.

The synthesis of scenario electrical and district heating grid loads from these raw electrical and heat loads is then an inversion of the previous step, where individual heating technologies and energy carriers are allocated a proportion of the raw heat and electrical demands, and either transformed into electrical or district heating loads, or, in the case of biomass, discarded from the model.

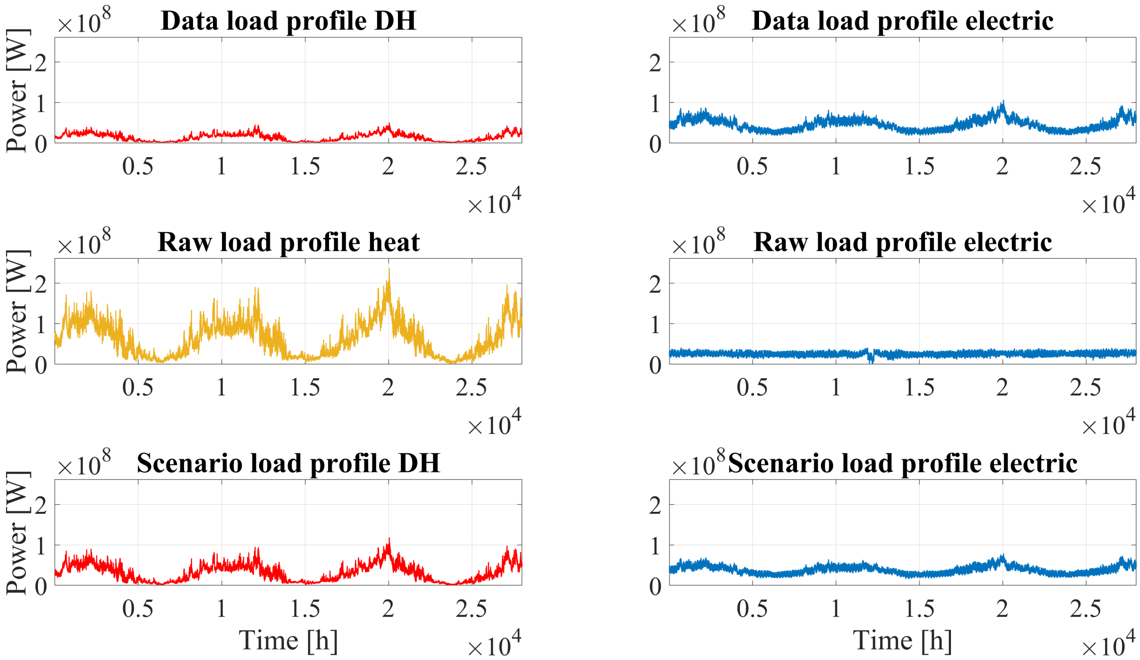

Figure 2.2: Scenario load profile synthesization

In figure 2.2, an example of a progression from the initial data through the raw load profiles to the synthetic scenario load profiles is depicted. In the example scenario, the load on the district heating system is almost doubled, while the amount of electrical heating in the system is decreased. This results in increased DH load and a decrease in electric load, with significantly reduced seasonal variability.

2.2 Modelling principles and implementation

Since the technical and economic circumstances of grid operation cause the emergent behaviour of energy prices and generation units to be complex and hardly analytically predictable, a numeric, time-discrete model/simulation software was implemented in MATLAB for the purpose of this study. Simulations run at a time resolution of one hour, matching the resolution of available data time series.

On a low level, the model takes as inputs the electrical and DH load profiles as well as technical parameters of technologies that play a role in the scenarios. These low level inputs are then supplemented by higher level inputs that serve as the concrete definition of scenarios, i.e. values on installed generation and individual heating technology capacities.

The data load profiles are transformed into relevant scenario load profiles. For each time step within the simulation time - usually one year, so as to capture seasonal variations - the merit order of production technologies is calculated by prioritizing generation units with the lowest or next-to-lowest variable operation and fuel costs. This way, energy market prices are minimized. The calculated merit order determines the dispatch of generation units and thus serves as the model driver.

For the purpose of determining the merit order local to the municipality, imports of electric energy from the electric transmission grid are treated like any other unique supply-side technology. The variable cost of electricity imports is derived from publications by ENTSO-E, the European Network of Transmission System Operators for Electricity, on historic day-ahead pricing in the Sweden-3 pricing zone [23]. Operation of the selected units is then simulated, before the generation characteristics and system marginal cost for DH heat and electricity are recorded. Simulation results may then be used to evaluate system designs, which are adapted iteratively.

A summary of the model structure, components, energy flows and parameters is given in figure 2.3. Energy flows from the supply side through the grids, where some is exchanged with potentially available storage, to the demand side. Notably, consumers require energy in the form of both heat and electrical power. In the model, heat may be acquired either through the district heating network, or through electricity-fed individual heating technologies.

Distribution grids are conventionally designed to be able to distribute loads without congestions or active management of dispatch. Therefore, the grids are not expected to affect generation dispatch. The grids' impact on energy prices is thus limited to an indirect influence through occurring grid losses. As such, the grid models are neither temporally nor spatially explicit, and instead calculate losses on the basis of historical data. The losses in both grids are dependent on the respective system load, whereas the DH grid losses additionally depend on ambient temperature.

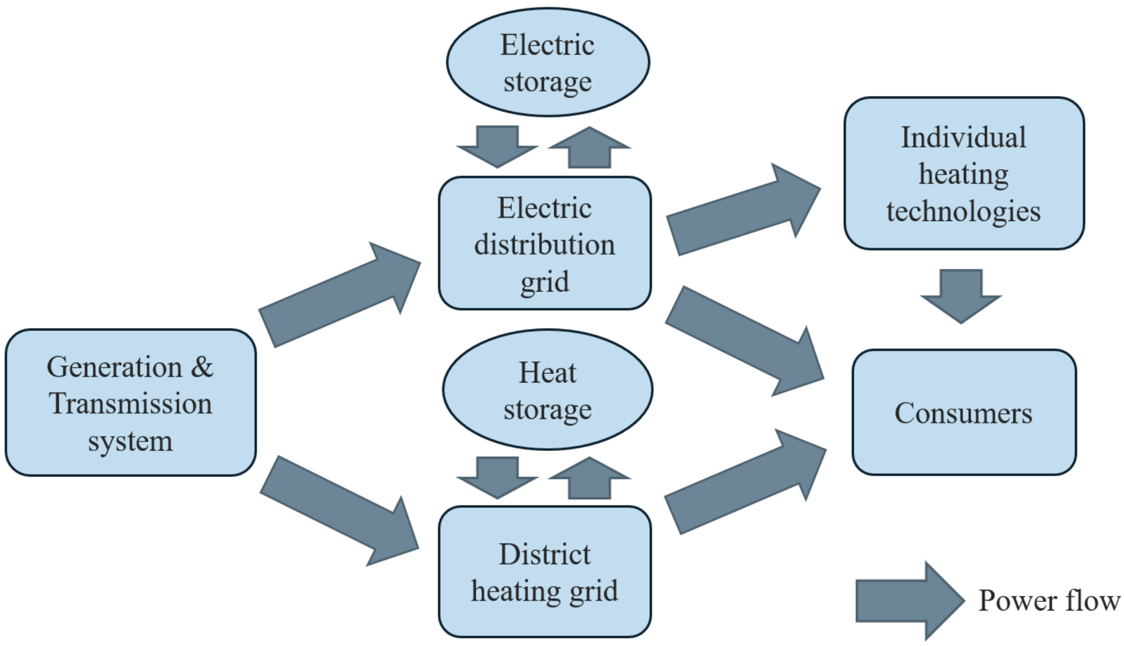

Figure 2.3: Model structure

2.2.1 Storage models

Both storage models are implemented in a similar fashion. The storage models are described using heat storage as an example.

The presented storage models take into account efficiency of charging and discharging as well as stationary losses on the basis of heat transfer from the heat storage to its surroundings and the natural decay of electrical storage over time. An accurate calculation of losses is important for the purpose of limiting charging and discharging capabilities of storage systems.

Since both types of losses are proportional to the storage state, they can be described using first-order differential equations. The following equation describes the change in stored heat within the heat storage over time:

$$\Delta Q(t) = Q(t) - Q_0 = \int_0^t \dot{Q}_{\text{exchange}}(\tau) - \dot{Q}_{\text{loss}}(\tau)\mathrm{d}\tau \qquad (2.1)$$

Where $\dot{Q}_{\text{exchange}}$ is the sum of power flows between the storage and the district heating grid, and $\dot{Q}_{\text{loss}}$ refers to the losses to the environment caused by imperfect insulation.

The exchange heat flow $\dot{Q}_{\text{exchange}}$ is highly variable when observed over longer periods of time and its integral is therefore calculated numerically. For that purpose, $\dot{Q}_{\text{exchange}}$ is assumed to be constant throughout each model time step:

$$\int_0^t \dot{Q}_{\text{exchange}}(\tau)\mathrm{d}\tau = \dot{Q}_{\text{exchange}} \cdot t \qquad (2.2)$$

The losses in the form of heat transfer to the environment meanwhile can be described continuously as follows:

$$\dot{Q}_{\text{loss}}(t) = h \cdot \Delta T(t) = h \cdot (T_{\text{storage}}(t) - T_{\text{ambient}}) \tag{2.3}$$

In this equation, T_{storage} is itself a function of time, due to the heat flowing into and out of the storage.

$$T_{storage}(t) = \frac{\Delta Q(t)}{c_{\text{p, medium}} \cdot m_{\text{medium}}} + T_0 \tag{2.4}$$

The relations described in (2.2), (2.3) and (2.4) can be used to expand equation (2.1):

$$\Delta Q(t) = \dot{Q}_{\text{exchange}} \cdot t - \int_0^t h \cdot \left(\frac{\Delta Q(\tau)}{c_{\text{p, medium}} \cdot m_{\text{medium}}} + T_0 - T_{\text{ambient}} \right) \mathrm{d}\tau \tag{2.5}$$

The differential equation in (2.5) can then be solved analytically as follows:

$$\Delta Q(t) = c_1 \cdot e^{-\frac{h}{c_{\text{p}} \cdot m} \cdot t} + c_{\text{p}} \cdot m \cdot \left(\frac{\dot{Q}_{\text{exchange}}}{h} - (T_0 - T_{\text{ambient}}) \right) \tag{2.6}$$

With the factor c_1 being determined using the boundary value $\Delta Q(t = 0) = 0$:

$$c_1 = -c_{\text{p}} \cdot m \cdot \left(\frac{\dot{Q}_{\text{exchange}}}{h} - (T_0 - T_{\text{ambient}}) \right) \tag{2.7}$$

Based on the solution presented in (2.6), the precise development of heat in the storage over the course of a discrete time step is calculated. Heat flows that serve to charge or discharge the storage are then fed into the model as time series of a resolution matching these time steps.

2.2.2 Economic indicators

Average annual energy prices and investment cost were identified as key indicators for assessing the success chances and viability of a transition scenario.

Investment cost is calculated based on data from technology catalogues published by the Danish Energy Agency [24, 25]. To include the fixed operation and management cost over the lifetime of newly added installations, a net-present-value-approach was chosen. In this approach, a discount rate for future cash flows is chosen and applied consecutively. Since fixed operation and management costs are independent of time, the net present value of all investments in the model can be calculated as the sum of a geometric progression:

$$NPV = C_{\text{capital}} + C_{\text{fixed O\&M}} \cdot \frac{1 - (\frac{1}{(1+r)^n})}{r} \tag{2.8}$$

Where C_{capital} denotes the initial capital cost, $C_{\text{fixed O\&M}}$ the fixed annual operation and management cost, n the system's technical lifetime and r the discount rate.

The choice and usage of social discount rates is considered a controversial issue among economists [26]. Because the capital cost calculations are mostly for the purpose of comparison among simulation results, a standard annual discount rate of 2% was chosen.

For the average energy prices, the mean of the annual time series of system marginal costs in electricity and heat production, weighted with the total system load at the same time, is calculated. It should be noted that this market model is most suitable to describe the behaviour of large, well-functioning markets such as the Swedish electricity market, and is of limited applicability in the district heating system and whenever local renewables are at the margin in the electric distribution system. The merit order effect is commonly used to predict short-term price developments and neglects long-term operator decisions that necessarily take investment and fixed operating costs into account. These long-term effects are analyzed as a separate indicator in this study, while the determined energy prices must be understood as a lower limit for energy prices that can be expected.

Excess generation from intermittent renewables is ignored due to this study's scope. The assessed scenarios for municipal energy development preclude any predictions or scenarios for the development of the wider, e.g. national, energy system. To what extent curtailment would be necessary in case of overproduction is therefore highly uncertain. Additionally, in case net-exports of low-price electricity from the local energy system are possible, these exports result in a benefit to the generation operators in favour of a societal benefit, and can therefore not act as an indicator for the success of the municipal energy transition.

Because private customers acquire energy through energy provider companies, this measure of average energy prices does not necessarily accurately reflect the price paid by the customers. However, decreased marginal costs in energy production can encourage energy providers to pass some of the savings on to their customers, thus benefiting both citizens and local businesses.

2.3 Technologies

The technologies are broadly classified on the basis of demand side and supply side, and then further divided on the basis of heat and electricity output.These technologies include the current state technologies installed in Kungälv as well as some other prospective technologies that might become part of the municipality in near future.

The technical and financial data for different types of generation technologies used in the model is derived from the Danish Energy Agency database (ENS database) [27]. Out of the supplied parameters, Technical lifetime [years], Fixed Operation and Maintenance (O&M) cost [€/W_{en}·yr], Variable O&M cost [€/MWh], Investment cost [€/W_{en}] and Electricity consumption [$W_{\text{el, in}}/W_{\text{en, out}}$] are used in the model. Technical lifetime, Fixed O&M cost, and Investment cost are required to calculate the net present value of the different technologies involved. Variable O&M cost is required to determine the running cost of the technologies and electricity consumption is included to represent the efficiency of the electrically fed heating technologies.

All the generation technologies with different parameters used in the model are mentioned in the tables A.1 and A.2 present in the Appendix.

The financial parameter "Variable O&M cost" as per the ENS database doesn't include the fuel cost and thereby, current state fuel costs along with different import costs are seperately provided to the model wherever required, as shown in 2.1. The price data is derived from estimates made by interviewees from Kungälv Energi [16]. To maintain compatibility with ENS data, the estimates were converted from Swedish Kronor to Euros using the 2021 average exchange rate (see 2.4.8).

	Price [€/MWh]
Wood chips	19.7
GOT DH import-summer	14.7
GOT DH import-winter	59.1

Table 2.1: Additional fuel and imports costs in the year 2021

2.3.1 Demand side Technologies (Individual)

Demand side technologies are those technologies which are directly available at the customer's side. Here, it includes all the individual heating technologies run by electricity, biomass, solar heating, and also the district heating substations. The share output of these technologies mainly depend on various parameters like electricity price, district heating price, district heating availability, and incentives on individual technologies that come under distributed generation. In this case study different future energy scenarios are framed and analysed based on techno-economic aspects which in turn could support decision making about supply side technologies based on the results interpreted about demand side technologies through different possible scenarios made.

The pie chart below displays the current situation (year 2021) of demand side technologies in Kungälv:

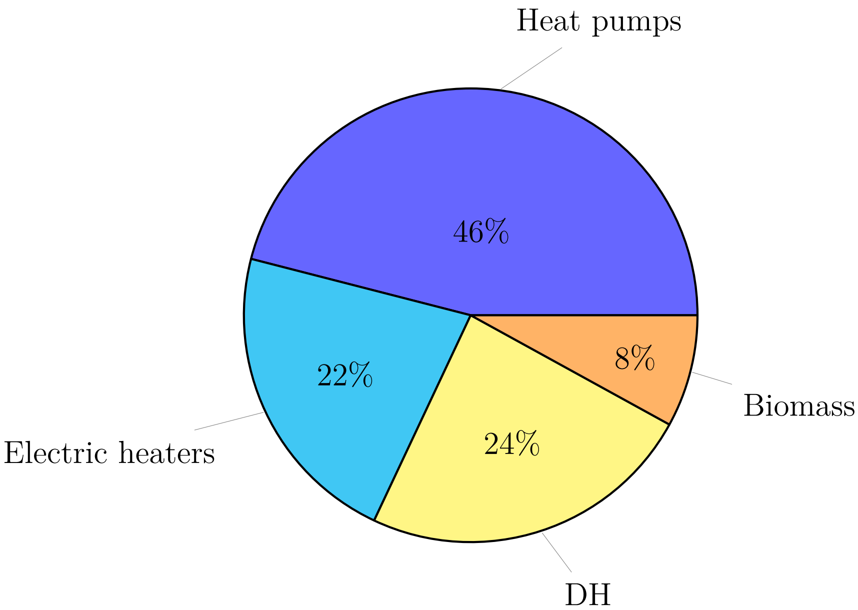

Figure 2.4: Current shares at the demand side in terms of heat energy output

2.3.1.1 District heating substations

District heating substations act as a demand side technology since it serves as a reservoir of heat supply to satisfy both the hot water and space heating demands. The input node is connected to various supply side technologies like imports, CHP plant, and solar district heating. Since the output node is directly available through substations at the demand side, this technology on a broad level is considered as a demand side technology in our model [27].

2.3.1.2 Electrically Fed Heating

Electrical heating technologies mainly comprises of different types of heat pumps and electric heaters. The different heat share outputs from different types of heat pumps and the electric heaters per unit heat produced through electrical heating in the current state are as displayed below:

2.3.1.2.1 Heat Pumps A heat pump is a device that transfers heat energy between different spaces, mostly to indoor spaces from the outer environment. There are mainly two types of heat pump technologies- compression heat pumps driven by electricity and absorption heat pumps driven by the thermal energy. In this master thesis we will only count for compression heat pumps since they are most commonly installed in Nordic regions especially in the residential sectors [27, 28].

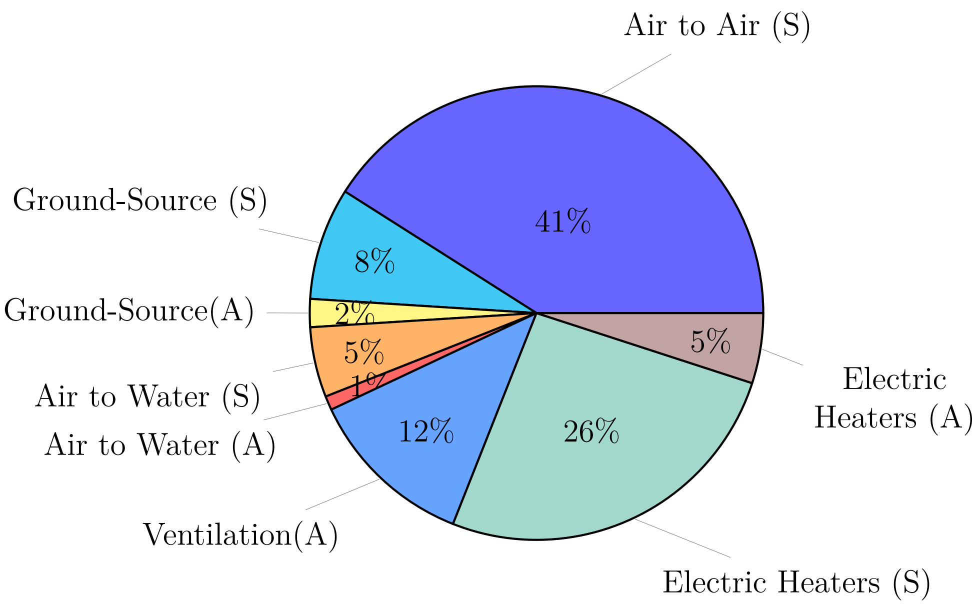

Figure 2.5: Heat energy output share of different electrical heating technologies; (S:single family house; A:Apartment)

- **Air to Air heat pumps**

  Air to Air heat pumps extract heat from the ambient air and transfer it to inner space via the help of a heat exchanger. This type of heat pump is only capable for space heating and cannot support domestic hot water supply. The working mechanism can also be reversed in this particular type of technology and thus these heat pumps can also work as air conditioners. The reasons behind its high deployment in the society are low investment costs, easy installation and high efficiency. A further reduction in costs is anticipated in the near future making this technology more competitive in the market [28].

- **Air to Water heat pumps**

  Air to water heat pumps transfer heat from the outside ambient air to system of water which provides space heating through the radiators or underfloor heating systems.It can also fulfill domestic hot water demand by providing heat to hot water cylinder. These heat pumps can be easily installed along with lower space requirement. The heat supply temperature can go upto 65°C in as of now but expected to rise to 75°C in the near future [27].

- **Ground-source heat pumps**

  Ground-source heat pumps can also supply the entire heat demand of a house/ building like the air to water heat pumps. These heat pumps have a more stable heat source which here means a temperature that is maintained above freezing. This leads to a more stable efficiency and thereby these heat pumps have comparatively higher seasonal COP and a longer life time as compared to air to water heat pumps. The heat supply temperature can go as high as 75°C.

These heat pumps are a bit more expensive then air to water heat pumps, but enhanced and non-noisy operation makes them an attractive option over other available options. The only disadvantage is increased space requirements [27].

- **Ventilation heat pumps**

  Ventilation heat pumps extract heat from the air in the ventilation outlet and then transfer it to the air intake in the ventilation system. It can behave both as air to air and air to water heat pumps but mostly preferred as the latter one to provide heat for domestic hot water supply [29]. Because their heat source, exhaust air, is already at the desired temperature, ventilation heat pumps achieve high efficiencies. However they require the heated building to be equipped with a controlled ventilation system.

2.3.1.2.2 Electric Heaters It is a technology that converts the electrical energy directly into heat energy and thereby can't exceed an efficiency of 100%. Electric heating can meet the heat demands for both the hot water requirements and the space heating. Electric heating is a very mature technology with a low investment cost and thereby widely used on both domestic and commercial scales.

2.3.1.3 Solar Heating Systems

The solar heating system consists of solar collectors, storage tank with heat exchangers, pump and a control unit. The solar collectors captures the heat energy present in the incoming solar radiations and then transfers it to a system of water flow and storage with the help of heat exchangers. This technology can cover a significant amount of hot water demand during summers but covers the space heating demand to a very minor degree. It is advisable to install other technologies like heat pumps along with the solar heating systems to cover the entire heat demand. The temperature attained lies between a range of 20-80°C depending on parameters like operating condition, collector type etc. The energy consumption and its distribution on time highly governs the performance of a solar heating system. A high consumption per square-metre of collector plate is favourable in keeping the efficiency high.

2.3.1.4 Biomass Boilers

Biomass boilers are also preferred as an effective individual heating technology in most of the Swedish municipalities. The most popular bio-fuel is wood pellets and chips. Biomass boilers are mostly available in two variants- Manual stoking and Automatic stoking of fuel. Low finances and a some degree of decarbonization makes this technology competitive in the individual heating market [27].

2.3.2 Supply side Technologies (Centralized)

These are the generation technologies present at the utility scale including the energy imports. These technologies are further divided into heat and electricity generation technologies. These technologies serve as the main generation units in the energy system.

2.3.2.1 Electricity Generation Technologies

2.3.2.1.1 Solar Photovoltaic It is an electric power system which gives electrical energy as output by converting the input usable solar energy through photovoltaics. It consists of several components including panels that intakes solar power and convert them into electrical energy, an inverter that converts primary DC output into grid compatible AC output, and various other accessories for mounting and clamping. On municipality level solar photovoltaics can be used on different scales to produce electrical energy. They can be installed on the rooftops of individual houses, building and other premises and thereby act as a potential source of distributed generation. They can also act as a source of centralized generation and provide utility scale electrical supply by placing multiple grid connected PV panels adjacent to one another on a piece of land prone to a satisfactory level of incoming solar radiations. Utility scale PV has a lower cost per megawatt (MW) capacity installed as compared to rooftop setting which is potentially due to economics of scale [30].

Currently in Kungälv, the solar PV capacity is about 4300 kW (2021) which is further expected to rise in the years to come. The utility plans to convert most of the solar heat collectors into solar PV with the passage of time [16]. In the model solar PV technologies has been classified as PV rooftop and PV utility scale.

2.3.2.1.2 Wind power This technology makes use of wind turbines to convert the kinetic energy of incoming wind into electrical output. The wind turbines can be placed individually or as a setting of multiple grid connected wind turbines called as wind farms [31].

Currently in Kungälv, the wind power capacity is 2.85 MW which provides about 7400 MWh of electrical energy per year [32]. Utility in Kungälv has decided not to expand wind power due to regulatory reasons like noise pollution that might occour from the wind turbines as well as due to potential threat to some rare open air living creatures. Seven wind turbines were planned to be installed in Kungälv but the project was has been stopped for the same reasons as stated above [16]. But at the same time potential of wind power to sustainable development can also not be ignored. Thereby in our model we include generation technologies based on wind power which includes onshore wind turbines, near shore wind turbines and domestic wind turbines. Near shore wind turbines serve as a possibility in future due to the fact that Kungälv is surrounded by Skagerrak coast as well as connected to Nordre and Göta älv rivers.

2.3.2.1.3 Electrical Imports Currently, most of the electrical energy requirements in Kungälv is fulfilled by imports from Vattenfall energy company [16]. The maximum capacity of import connection is not known but is assumed to be considered sufficient and reliable throughout the year.

2.3.2.2 Heat Generation technologies

These technologies supply heat to the district heating grid. It includes the utility scale generation technologies in the municipality as well as the import lines connected.

2.3.2.2.1 Solar District Heating This technology consists of wide fields equipped with solar thermal collectors that captures the solar heat and transfers this heat into a heat storage or fed directly into the district heating network of the settlement. These type of solar collectors are installed on empty large fields or on rooftops of houses and buildings [33].

In Kungälv, about 600 kW of solar district heating capacity is installed currently. At the moment, Utility is planning and started to slowly decommission the existing solar district heating park due to cost issues, which they plan to entirely convert into utility scale solar PV generation.

2.3.2.2.2 Combined Heat and Power(CHP) A CHP produces both heat and electrical energy at the same time. The output of these two forms of energy can be altered as per the requirements and conditions by making changes in the energy extraction mechanism. Currently, there are different types of CHP plants available in the global energy system that operates on different fuels, boilers, turbines and few other main parameters [34].

Currently, Kungälv has a 48 MW CHP plant known as "Munkegärdeverket" that uses wood chips as the major fuel and runs constantly except the core summer months to cover the heat demand of the municipality. During the summer months this CHP plant is mostly closed for maintenance purposes and the heat demand is entirely covered by Gothenburg connection imports and solar district heating in the Munkegärdeverket premises. The utility plans to expand the size of this CHP plant which serves as a good move towards self-sufficiency and meeting increased energy demands in future.

2.3.2.2.3 Gothenburg connection - Heat import In addition to the CHP plant, Kungälv also receives a significant part of its heat demand through imports from Gothenburg. The maximum size of the import connection is 19 MW [16]. This import connection works around its maximum capacity during the summer months and as a peak technology during winters. In the time to come, the prices for imports might increase due to changes in Gothenburg demand. Since this would decrease the connection's competitiveness, the utility aims to become self sufficient in the future.

2.3.2.3 Storage Technologies

2.3.2.3.1 Pit Thermal Energy Storage (PTES) It is a man-made water reservoir meant for storing thermal energy. Firstly, a large pit is created, then an embankment is constructed with the excavated material and then finally connected to district heating system. An insulating and floating lid is used to cover the pit storage. The key benefits of PTES over other types of other thermal energy storage solutions are high storage size, ability to charge and discharge rapidly, low costs, high specific heat capacity, and good heat transfer characteristics. The storage volume ranges between 50000 to 500000 m^3 which corresponds to about 5000 to 40000 MWh energy in a single charging process [24].

In Kungälv, the utility plans to introduce a thermal energy storage to manage the variations in heat demand especially during winters when the demand is high resulting in increased imports and the associated high energy prices.

2.3.2.3.2 Grid-scale electric battery storage Batteries are an electrochemical storage technology where electrical charge from the grid is stored through reduction and oxidation of a cathode and an anode. Grid-scale batteries are used in a wide range of applications. This includes energy-intensive applications like peak load shaving and congestion relief, as well as power-intensive applications like frequency and voltage regulation. Losses occur both during standby and during charging and discharging. Since batteries are charged and discharged using direct current, a power converter is usually required to connect a battery system to the grid, which causes additional losses of 1-2%. The most common type of battery used for such grid level purpose is lithium-ion batteries [24].

Due to high investment costs, large capacities are as of yet rare in realized installations. The world's largest battery system has a capacity of 100 MW/129 MWh and is used for peak shaving. The largest battery that is used exclusively for auxiliary purposes is sized at 32 MW/8 MWh [24].

2.4 Assumptions

For modelling work to be efficient it is necessary to have the complete set of data. The data needs to be consistent and reliable to produce trustworthy results as the output from the designed model. In this thesis, the backbone of the database is mostly the data provided the utility in Kungälv and the database available through Danish Energy Agency (ENS database). To fill some of the data gaps and estimate the numbers not available directly, some assumptions were made throughout the modelling work. These assumptions are as follows:

2.4.1 Splitting of electrical load between heat pumps and electric heaters

To split the electrical load of heating between the heat pumps and the electric heaters we referred to Kungälv's energy plan of 2009 [14]. The energy plan states the number of heat pumps installed in different types of infrastructures like single family houses, apartments, industries and government premises. Since no detailed list of electricity driven technologies is mentioned in the plan, it is assumed that the other potential technology is electric heaters. Assuming a mean COP of 3 for the heat pumps and an

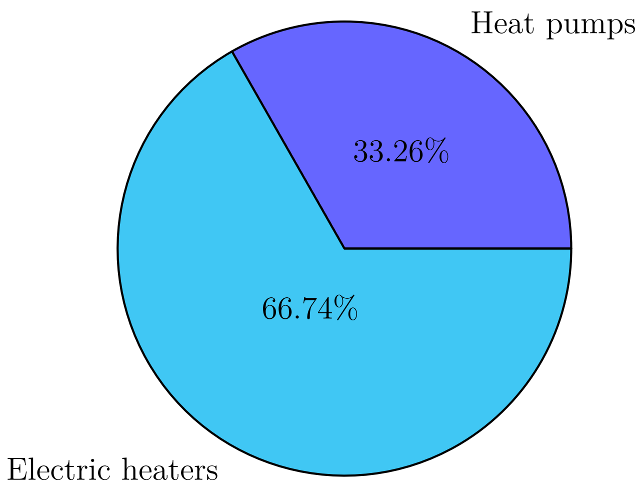

Figure 2.6: Electrical heating load shares

efficiency of 1 for the electric heaters, the shares per unit electricity fed for electrical heating was then calculated for these two potential technologies as of 2009.

To scale the electrical share values to 2021 level, a scaling approach was adopted which is explained below:

$$\alpha_{\mathrm{HP},\ 2021} = \alpha_{\mathrm{HP},\ 2009} \cdot \frac{N_{\mathrm{HP},\ 2021}}{N_{\mathrm{HP},\ 2009}} \cdot \frac{L_{2009}}{L_{2021}} \tag{2.9}$$

Where:

α_{HP}: Share fed to heat pumps per unit electricity for heating purposes.

N_{HP}: Number of heat pumps.

L: Electrical heating load in Kungälv as per the data furnished by the utility.

The different shares estimated are displayed below:

2.4.2 Shares of electrical input per unit electricity fed into heat pumps for each type of heat pump

The shares were estimated as per the annual sales of different types of heat pumps in Sweden [35, 36]. The contribution from each type of heat pump to electrical heating was determined by multiplying individual heat pump technologies shares with the overall contribution of heat pumps as determined in (2.9).

$$\alpha_{\mathrm{HP\ type}} = \frac{S_{\mathrm{HP\ type}}}{\Sigma(S_{\mathrm{HP\ type}})} \cdot \alpha_{\mathrm{HP},\ 2021} \tag{2.10}$$

Where:

$S_{\text{HP type}}$: Sales of a particular type of heat pump. $\alpha_{\text{HP, 2021}}$:Share fed to heat pumps per unit electricity for heating purposes in year 2021.

The shares of different types of heat pumps estimated are displayed in Figure 2.7.

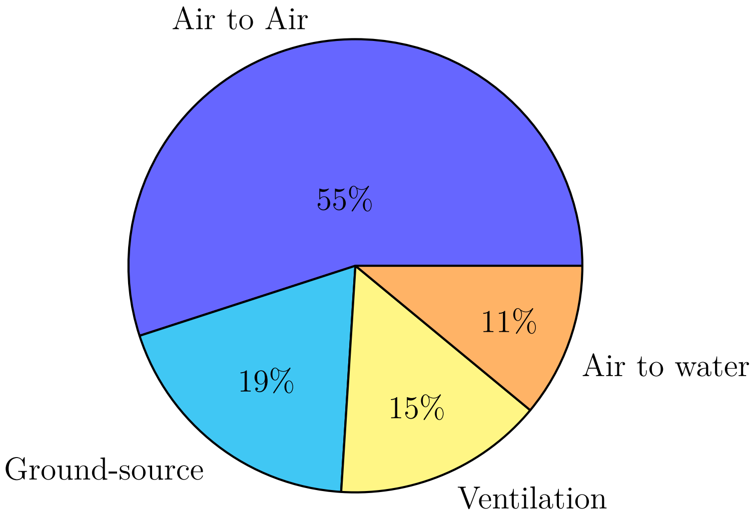

Figure 2.7: Heat pumps existence shares

2.4.3 Splitting the electrical consumption for heating between single family houses and buildings

The splitting was done as per the information furnished by the Kungälv Energy plan 2009 [14]. According to this energy plan, about (5/6) of the total electric consumption for heating goes to single family houses and the rest (1/6) goes to the apartment buildings. The splitted values here further aided in dividing electricity consumption shares of different electrical heating technologies as per their existence in single family houses and apartment buildings.

Due to the special technical properties of air-to-air- and ventilation heat pumps, this assumption was not made for these heating technologies. Ventilation heat pumps can only be installed in combination with controlled ventilation systems, which are rare in small residential houses. Therefore, it has been assumed that ventilation heat pumps are exclusively installed in commercial and apartment buildings. This might be an underestimation, since newly built single family houses may include forced ventilation and ventilation heat pumps. Air to air heat pumps meanwhile are assumed to be present only in single family homes, since they can merely cover a building's space heating demand, which is generally served by central heating in larger buildings.

2.4.4 Share of heat output from Heat Pumps through aggregated COP approach

To estimate an appropriate share of heat demand covered by the heat pumps under electrical heating, an aggregated COP approach was adopted due to the fact that there are different types of heat pumps in the system with different COP values [27]. An aggregated weighted mean of COP values for different kinds of heat pumps is calculated on the basis of the share of their individual electricity consumption. The value so obtained is referred to as "aggregated COP" here which is then used to estimate an approximate value of total heat output by all the heat pumps in the system per unit total electricity fed into heat pumps for heating purposes. The approach is mathematically expressed below:

$$COP_{\text{aggregated}} = \frac{\Sigma(COP_{\text{individual}} \cdot E_{\text{individual}})}{\Sigma(E_{\text{individual}})} \tag{2.11}$$

Where:

$COP_{\text{individual}}$: Individual COP of the specific heat pump type taken into account.

$E_{\text{individual}}$: It denotes share of electricity fed into a specific type of heat pump per unit electricity fed for heating into heat pumps as a whole.

This overall heat output from heat pumps per unit electricity consumption (as calculated above) along with the heat output from electric heaters per unit electricity consumption aided in calculating the total heat load covered by electricity in 2021 as per the grid data furnished by the utility.

The model has seven types of different heat pumps.

2.4.5 Scaling down of national statistics to Kungälv

For the biomass contribution of heat demand, the data specific to Kungälv seems to be unavailable directly. Thereby, to fill such data unavailability issues we adopted an approach that takes into account the national statistics [37] and then scaled it down to the Kungälv municipality level by the population split approach, as displayed below:

$$D_{\text{Kungälv}} = D_{\text{National}} \cdot \frac{p_{\text{Kungälv}}}{p_{\text{National}}} \tag{2.12}$$

Where p refers to population in the year 2021, and D refers to an arbitrary set of data.

2.4.6 Estimation of capacities of some generation technologies in the current state

Currently in Kungälv, the generation technologies include a CHP plant, solar thermal collectors for heating, solar PV's, and a wind turbine. The capacities for the CHP plant and the wind turbine is available specifically but not for the solar technologies. To estimate these unknown capacities for the model, the following approaches were adopted:

2.4.6.1 Solar PV capacity

The capacity was assumed to be the maximum energy output in the year 2021 as per the data sheets furnished by the utility for past few years based on hourly time resolution.

2.4.6.2 Solar thermal collectors for district heating

As per the official website of Kungälv energy [32], currently there are 331 panels installed for solar district heating. Taking a mean size of about 2 kW per panel, the capacity is estimated to be about 600 kW.

2.4.7 Availability profiles for wind and solar

Solar and wind are intermittent sources of energy. Intermittency here refers to the variability in energy yield throughout the year. Availability profiles are used to describe the environmental conditions that cause this intermittency, e.g. the varying solar irradiation throughout each day and year, cloud cover and wind speeds. It is a detailed list of values that reflect the prospective available capacity per unit maximum capacity installed. This range of values ($0 \leq$ availability ≤ 1) serves as the availability profile for a year. It helps the energy model in planning the participation of these intermittent sources of energy in the overall energy system, with a principal aim of cost optimisation of energy at all the time steps.

2.4.7.1 Solar availability profile

Here the availability profile for a year is based on a two step approach. First step being finding capacity by estimating the maximum load output during the year based on the assumption made earlier. The second step being taking the ratio of load output at each time step of the year to the maximum capacity.

$$A_{\text{solar}} = \frac{L}{P_{\text{peak}}} \tag{2.13}$$

Where:

L: PV generation at each time step

P_{peak}: Installed capacity of PV

2.4.7.2 Wind availability profile

It is similar to the mechanism adopted for solar availability profile except the fact that the capacity for wind power in Kungälv is known (2850 kW).

$$A_{\text{wind}} = \frac{L\ [\text{kW}]}{2850\ \text{kW}} \tag{2.14}$$

Where:

L: Wind turbine generation at each time step

2.4.8 Currency conversion

The model contains different types of technologies that further have different cost parameters associated with each of them. The ENS database, which serves as a key data basis for the aforementioned technology parameters, contains techno-economic data sets in Euros (€). Therefore, all prices are given in Euros in the model and this report. Other data, i.e. fuel prices and heat import costs, was supplied in Swedish Kronor (SEK). The 2021 average conversion rate of 10.1465 SEK/€ [38] is used for currency conversion.

2.5 Scenario selection

In order to assess different development perspectives for Kungälv, several scenarios depicting alternative energy systems were designed. These scenarios represent the general trends that the municipality and utility aim for - an increase in connections to the district heating system, and increased renewable electricity production. To answer the research question, some scenarios with storage solutions supplementing the energy system were added.

Due to the large number of model parameters, it was necessary to limit the scenario domain for simulations. This domain was selected under several criteria:

- Sustainability, i.e. no net CO_2-emitting generation units should be used in the transition scenarios.
- Kungälv's latest energy plan inspired the approach to scenario selection - particularly the 2009 goals of increasing the connections to the district heating system and achieving self-sufficiency in local renewable electricity production by 2070. Other goals, however, were not included in scenario making due to them being unrealistic or expired, including the goal of replacing electric heating in the municipality with biomass boilers and a share of 100% sustainable mobility by 2015.
- The possibility for the local utility to take direct action towards achieving the scenario, because municipalities and local utility companies are major contributors and drivers of successful energy transitions.

- Other constraints, like the improbability of onshore wind power expansion due to regulatory concerns.

Thus, ten base scenarios were selected, grouped into two series of scenarios. The A-series contains scenarios A1 to A5, in which the share of local intermittent renewable electricity progressively increases from 10% to 50%. This is achieved by building a small offshore wind farm of up to twelve individual turbines, as well as up to 57 MW_{peak} of utility-scale photovoltaic generation. This capacity exceeds the summer-time peak system load of approximately 40 MW, but is necessary to achieve a high rate of self-sufficiency due to the poor yield in winter.

In scenarios B1 to B5, the same amount of offshore wind converters and a significantly reduced amount of utility-scale photovoltaics results in the same share of intermittent renewable electricity generation. Each scenario in the B-series, for the sake of comparability, achieves the same renewable rate as its counterpart in the A-series. In B, a significant change in demand-side heating technologies is taken into account. In these scenarios, usage of biomass boilers for heating decreases to 4% of the raw heat demand, while district heating covers 50% of the heating load. According to assumptions made by Kungälv Energi interviewees, approximately 50% of the municipalities inhabitants, i.e. the population of the Kungälv-Ytterby urban area, could be connected to the district heating grid at a cost that makes for a viable financial investment. The electrical load, specifically in winter, is reduced significantly by this measure, meaning that less renewable capacity is required to achieve a high rate of intermittent renewable generation. Especially solar power benefits from increased district heating connections, since that process shifts loads away from low-yield winters. However, the increased load on the district heating system necessitates further expansions of the CHP, up to 120 MW or 96 MW with seasonal heat storage.

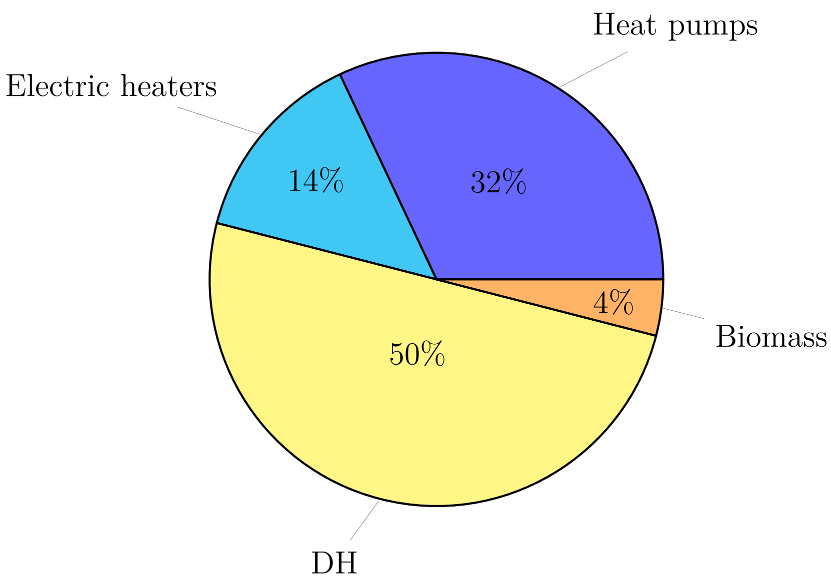

Figure 2.8: Heat energy output share at the demand side in Scenario B

Seven special scenarios were investigated based on the insights gained in the base growth scenarios A1 through B5. These scenarios are extensions of scenarios status-quo, A5, and B5 and thereby have the same capacities of intermittent renewables installed as their base scenario.

A5H, B5H and status_quo_H closely resemble Scenarios A5, B5 and status_quo, but additionally the district heating grid includes 4.5 GWh of pit thermal energy storage (PTES) at a charging capacity of 30 MW. Because heat production in Kungälv's energy system is dominated by the local CHP's output and heat transferred from the Gothenburg district heating system, the merit order for heat production is determined largely by both of these technologies' variable costs. While the CHP's operating and fuel costs remain stable throughout the year, the excess heat from the Gothenburg system is considerably more expensive during the winter months, when capacities are needed locally in Gothenburg. This behaviour is characteristic of district heating systems, where seasonal variations are much larger than short-term variations. This results in seasonal storage being more viable in the district heating system than in the electrical system. Additionally, heat storage capacity is far cheaper than electrical storage capacity - by a factor of 200 to 300, according to estimates published by the Danish Energy Agency [24]. For this study, first assumptions for storage capacities were made based on the size of already existing installations. In particular, the electrical storage was inspired by a 20 MW/80 MWh Lithium-Ion battery system in California, while initial values for the PTES were based on a 30 MW/12,125 MWh system in Gram, Denmark [24]. The final design values are the result of an iterative process seeking to maximize the impact on energy prices while minimizing the required installed capacities.

Similarly, A5E, B5E and status_quo_E are equipped with additional electric storage, specifically utility-scale Lithium-Ion batteries [24] with charging and storage capacities of 50 MW and 50 MWh, respectively. Smaller charging capacities can make sense from a business perspective, but generally do not decrease electricity prices.

Table 2.2 displays the installation capacities for different technologies required to achieve the different scenarios proposed here. The installed capacity of utility-scale PV was the free variable to achieve the desired share of intermittent renewable electricity generation.

Scenario	Intermittent renewable [%]	CHP heat [MW]	PV utility scale [MW]	Near shore wind [MW]	Storage [MW]/[MWh]
status_quo	2.4	48.000	0.000	0.000	-
status_quo_E	2.4	48.000	0.000	0.000	E 50/50
status_quo_H	2.4	48.000	0.000	0.000	H 30/4500
A1	10	48.000	18.114	8.400	-
A2	20	48.000	27.090	25.200	-
A3	30	48.000	40.464	42.000	-
A4	40	48.000	45.714	67.200	-
A5	50	48.000	57.454	100.800	-
A5E	50	48.000	57.454	100.800	E 50/50
A5H	50	48.000	57.454	100.800	H 30/4500
B1	10	120.000	10.794	8.400	-
B2	20	120.000	12.124	25.200	-
B3	30	120.000	16.384	42.000	-
B4	40	120.000	14.074	67.200	-
B5	50	120.000	16.764	100.800	-
B5E	50	120.000	57.454	100.800	E 50/50
B5EH	50	96.000	57.454	100.800	E 50/50 H 30/4500
B5H	50	96.000	57.454	100.800	H 30/4500

Table 2.2: Installed capacities of generation technologies for different scenarios

3

Results

In this chapter, the various conducted model simulations are introduced and notable results are described. As per the scenario selection taken into account (see 2.5), generation curve of different generation technologies are displayed and the important change depicted with each of them is pointed out. For scenarios with storage solutions, the behavioural characteristics of the storage solutions are plotted and their effects on the energy systems is analysed. An overview of the economic indicators in each of these scenario is given in table 3.1.

3.1 Scenario A

In this scenario, the load curves remain same as in the status-quo. The new feature introduced is the integration of local renewable generation.

3.1.1 Scenario A1

In this scenario, the local renewable intermittent generation covers about 10% of the total electrical load. As depicted from the figure 3.1, these renewables contribute more to the system during summers as compared to winter time due to less generation and elevated demand.

The weighted average of the yearly electricity price, as described in 2.2.2, remains the same. The benefit to the system is decreased amount of imports especially during the summer time and thereby a very initial step towards self-sufficiency. The total investment cost required for attaining this scenario from the status-quo level came up to be about 507 M€.

3.1.2 Scenario A2

In this scenario, the intermittent renewable contribution is increased to 20%. At this point, this local renewable generation covers a significant amount of demand during summers along with being at the margin at some time steps, as shown in fig 3.2. PV utility scale display an almost similar generation pattern throughout the summer time while near shore wind turbines further scale up the overall renewable output taking care of the peaks whenever significantly available.

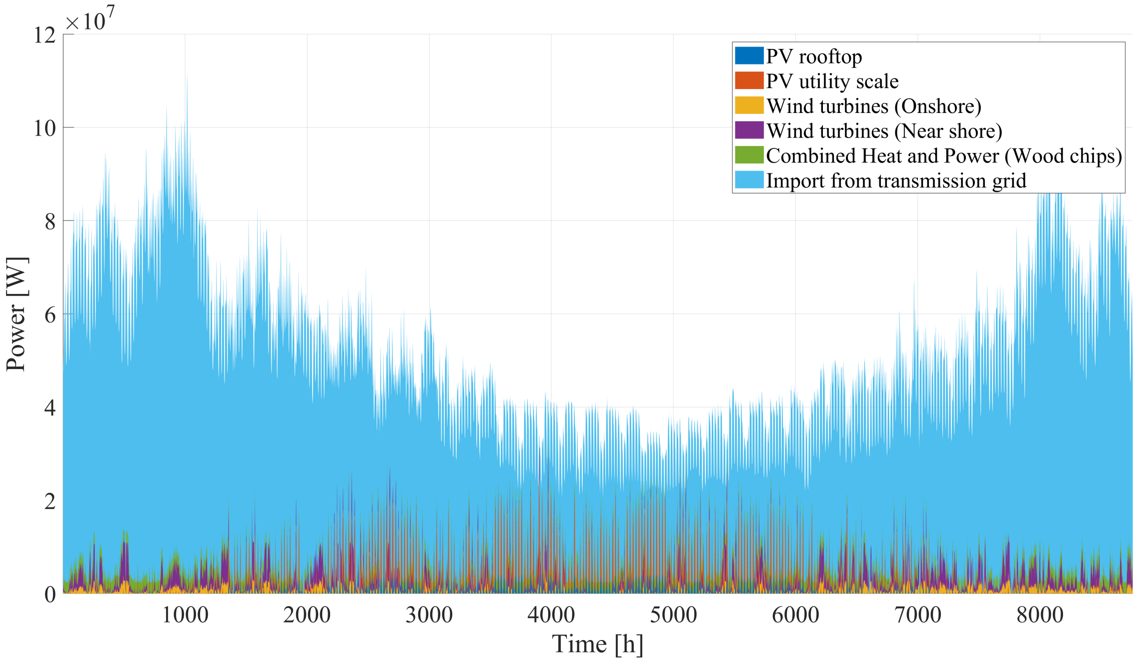

Figure 3.1: Generation curve - Scenario A1

Since these technologies start to act as marginal technologies for some hours in the summers, the average yearly electricity price decreases by 0.31%. An additional investment of 53.5 M€ is required to scale the scenario A1 to A2.

3.1.3 Scenario A3

The renewable integration reaches a value of 30%. At this point, these intermittent renewables take care of most of the summer load along with being at the margin for a relatively higher number of hours, as shown in fig A.3. This local output is also relatively higher in the winter time and thereby helps in reducing the total imports throughout the year.

A more visible reduction of 2.72% in average yearly electricity price is observed. An additional investment of 57.2 M€ is required to scale the scenario A2 to A3.

3.1.4 Scenario A4

Here the local intermittent renewable generation is further scaled up to 40%. Now these local technologies act as the dominant generation technologies for most of the time in summers as well as also start to act as marginal technologies during few winter hours, as shown in the fig 3.3. Though PV continues to add significant value to generation, near shore wind turbines support the system vastly whenever solar availability is less.

Due to such a high penetration throughout the year, the average yearly electricity price experiences a downfall of about 6.88% when compared to status-quo. At this

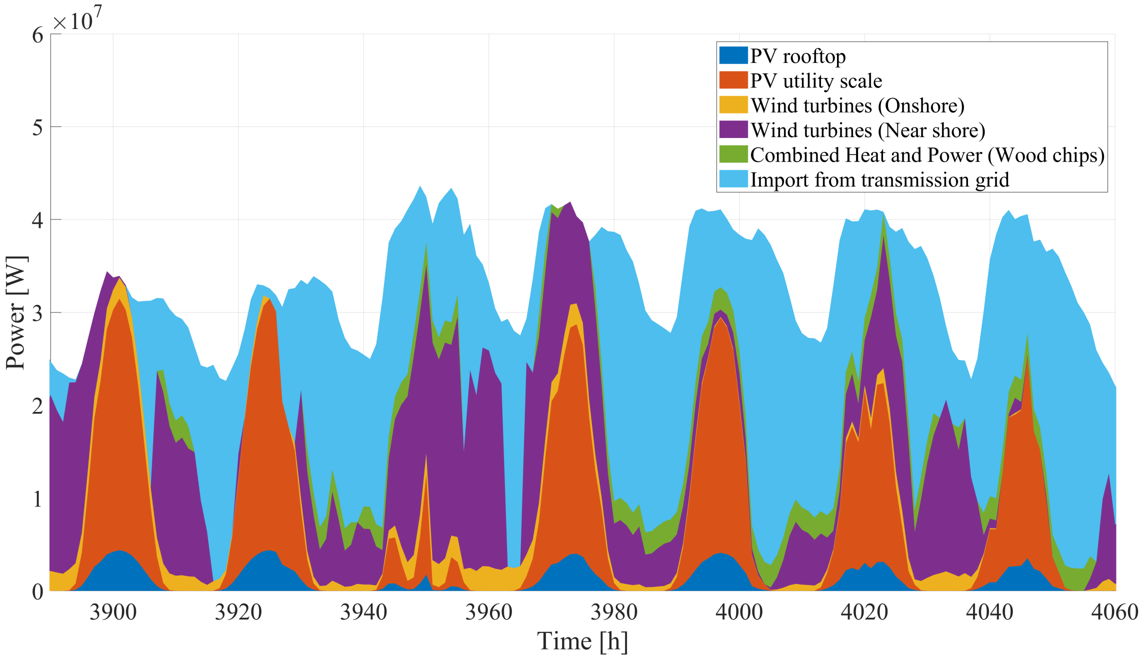

Figure 3.2: Generation curve A2 - summer week

point, the local renewable generation starts to complement the massive imports to a relatively higher degree as observed in the previous scenarios. An additional investment of 73.4 M€ is required to scale the scenario A3 to A4.

3.1.5 Scenario A5

This is the extreme case of the Scenario A series with an integration of local intermittent renewables by 50% in the overall system. The imports lose the dominance almost entirely during the summer time while the contribution of renewables in winter becomes much more significant, as shown in the fig 3.4.

Now the average yearly electricity price reduces by 14.3% from the status-quo level. This is mostly because of intermittent renewables being at the margin for quite large number of hours throughout the year including the winter period. An additional investment of 102 M€ is required to scale the scenario A4 to A5.

3.2 Scenario B

In this scenario, the electrical load curve becomes flatter when compared to the status-quo scenario. This is because district heating becomes more dominant than electrical heating which further lead to peak shaving in the electrical grid as well as the curve becomes flatter in nature. On the other hand, the district heating curve has more elevated peaks due to increase in load throughout the time frame.

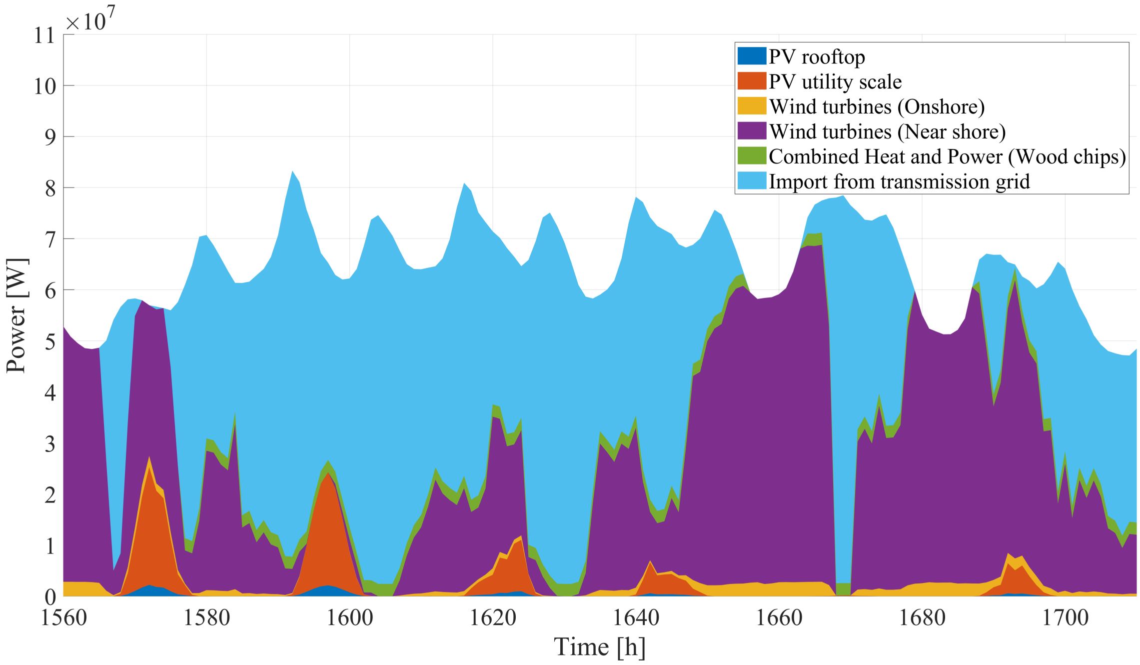

Figure 3.3: Generation curve A4 - winter week

3.2.1 Scenario B1

Due to the increase in intermittent local electrical generation to 10%, the import magnitudes have decreased as compared to the status-quo. The renewable generation technologies have a better a combined output during summers but also supports the system during winters as per their availability, as shown in fig 3.5.

The average yearly electricity price decreases by 1.08% due to reduction in electrical heating which further results in overall lower electrical load without any elevated major peaks, thereby avoiding high electricity prices as compared to status-quo. On the other hand there is an increase of about 1.74% in yearly average heat price mostly due to the increase in district heating load. Although the marginal cost of electricity doesn't decrease much with increase in local renewable generation, thereby not a significant aid to customers in terms of energy prices. The total investment cost required for attaining this scenario from the status-quo level came up to be about 507 M€.

3.2.2 Scenario B2

The main feature of this scenario is further increase in intermittent renewable local electrical generation to 20%. The increased local renewable generation starts producing a significant output as compared to scenario B1, shown in the fig A.7. The most important characteristic of these output levels is that the local renewable technologies now begin acting as marginal technologies though for few hours in the year.

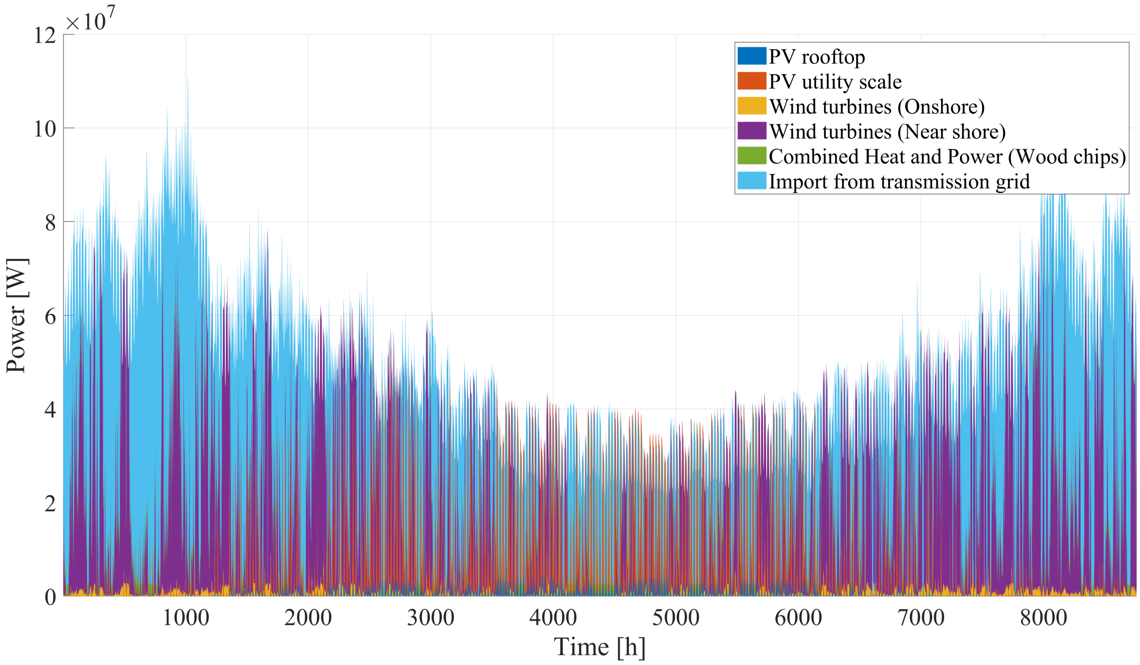

Figure 3.4: Generation curve - Scenario A5

The average annual electricity prices decreases by 1.33% from the status-quo level due to the fact that increased renewable generation acts at the margin at few instances over the year as well as the electrical heating still remains less. Since the load on district heating remains the same as depicted in the scenario B1, the reduction in average annual heat price remains the same. An additional investment of 47.1 M€ is required to scale the scenario B1 to B2.

3.2.3 Scenario B3

This scenario is further modification of scenario B3, shown in fig A.8. The local renewable electrical generation is scaled to 30%. At this point, as depicted from the generation curve, the intermittent renewables act as technologies on the margin for more hours in the year.

The average annual electricity price further decreases by 3.11% from the status-quo level. Here the marginal cost of electricity display a visible reduction and thereby serves as a benefit to the economy of the overall system. An additional investment of 49.6 M€ is required to scale the scenario B2 to B3.

3.2.4 Scenario B4

Now, the local intermittent renewables are further expanded to 40% in the system. At this point, local renewables act as marginal technology during most of the summer period as well as produce a significant output during the winter time, as shown in fig A.9. Apart from a significant output, these intermittent technologies start to act as marginal technologies at few hours in the entire winter period.

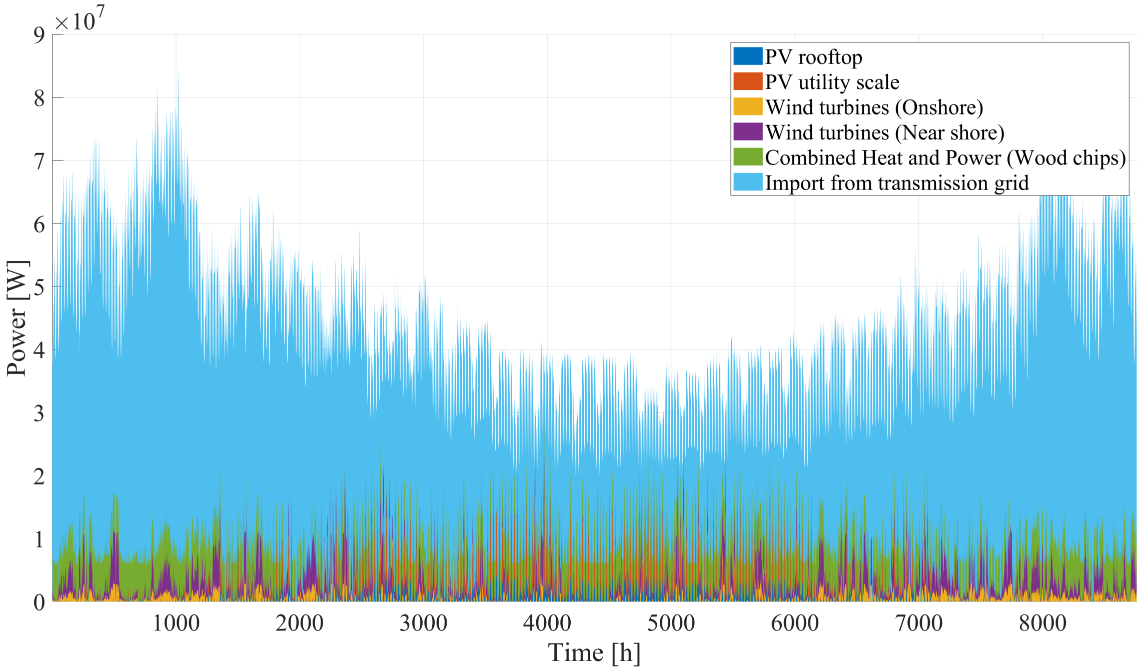

Figure 3.5: Generation curve - Scenario B1

The average annual electricity price drops by 8.28% from the status-quo level. Such a significant cost reduction is due to these renewable technologies acting on the margin for a significant number of time steps (hours) over the year. The benefit to the energy customers as well as to the entire economy is further scaled up. An additional investment of 67 M€ is required to scale the scenario B3 to B4.

3.2.5 Scenario B5

This is the extreme case of the Scenario B series with an integration of intermittent generation technologies by 50% in the overall system. At this point, these particular technologies act on the margin for quite a lot of time steps in the year, thereby complementing the previously dominant imports for a notable period of time over the year, as shown in the fig 3.6.

The average annual electricity price undergo a downfall by 18.10% from the status-quo level. Such a high cost reduction is due to these renewable technologies complementing the imports for a significant period of time in the year. An additional investment of 94.2 M€ is required to scale the scenario B4 to B5.

3.3 Heat storage scenarios

For scenarios status_quo_H, A5H and B5H, seasonal heat storage with a charging capacity of 30 MW and an energy capacity of 4500 MWh was added to the model of Kungälv's district heating system. Since the large storage capacity proved to be sufficient for covering peak loads throughout the winter months, the local CHP's

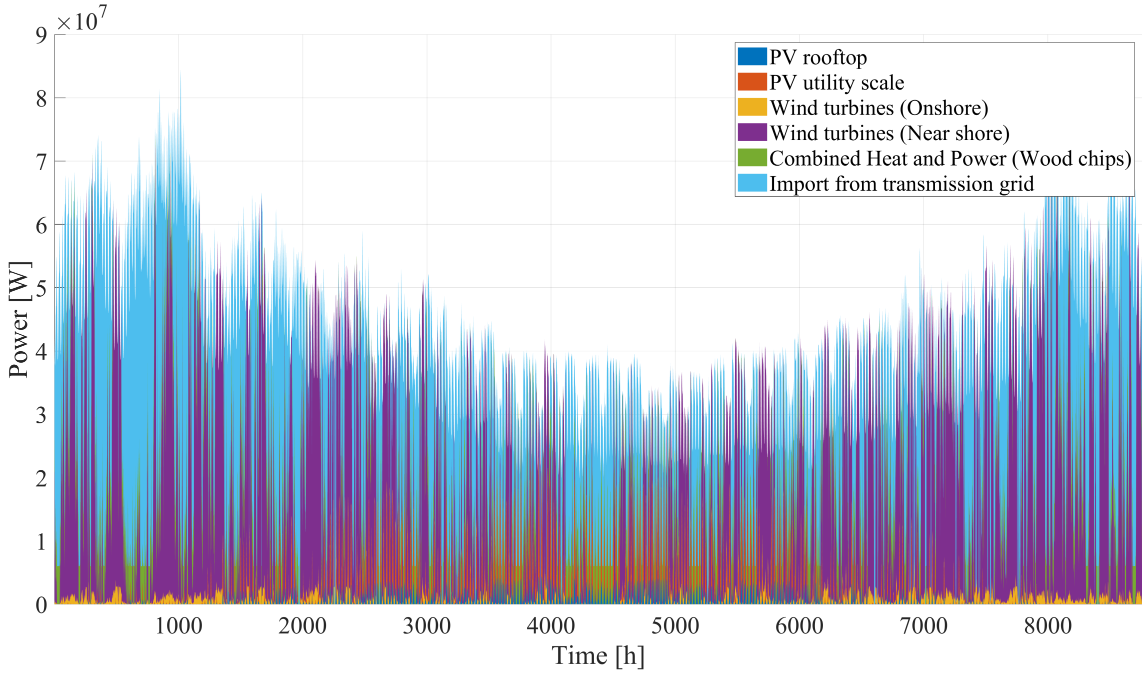

Figure 3.6: Generation curve - Scenario B5

expansion to a capacity of 120 MW that had previously been necessary in the B-series of scenarios was reduced to 96 MW in Scenario B5H, significantly reducing total investment costs by 20% compared with scenario B5. Additionally, in both A5H and B5H the average marginal district heating cost decreased by 5.4% and 3.8%, respectively, reducing the price difference between the A- and B-series of scenarios that is caused by the higher demand in B-type scenarios from 0.50€/MWh to 0.10€/MWh. This price reduction occurred in spite of the additional costs associated with storage losses during charging, discharging and due to stationary heat transfer to the environment. Even in the current system state, the addition of 4.5 GWh of seasonal heat storage was found to decrease average marginal electricity prices by 0.90€/MWh, for an estimated capital investment cost of 1.8 M€.

While decreasing average marginal heat prices, the usage of heat storage also comes with a slight increase in average marginal electricity prices. This is due to the heat storage decreasing usage of the CHP, which lessens the amount of low-cost electricity that can be produced in the plant's co-generation turbine.

In figure 3.7, the storage state for both A5H and B5H is shown throughout one year. Notably, The storage in B5H is discharged further than in the corresponding scenario with less district heating usage, which is especially visible during the period of extreme cold during the early part of the year. However, both storages are replenished comfortably during summer, when low-price excess heat from Gothenburg is available.

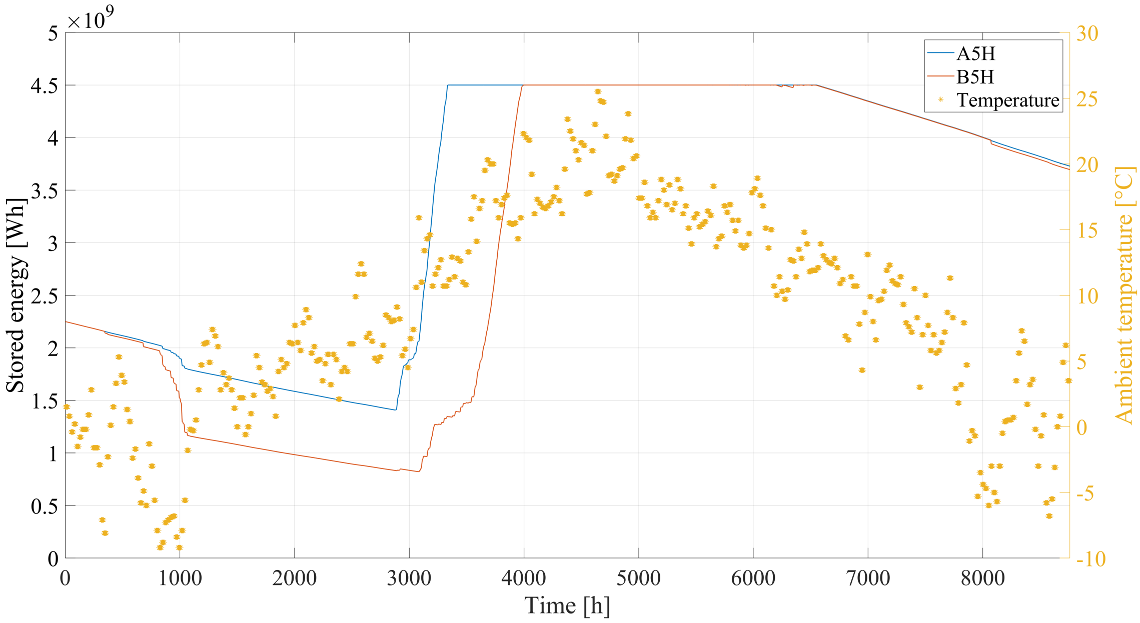

Figure 3.7: Time series of stored energy for scenarios A5H and B5H.

3.4 Electrical storage scenarios

50 MW/50 MWh of Lithium-Ion battery storage complements the electrical grid in special scenarios status_quo_E, A5E and B5E. Battery storage with lower capacities may also be financially viable from an operator point of view, but cannot on its own contribute to decreasing marginal electricity costs, since lower capacities can rarely cover the entire residual load in cases of low wind and solar output. Because batteries, while charging, act as large loads on the system, they may simultaneously also increase the marginal electricity price during low-load hours. This can lead to an overall negative impact of storage on average electricity prices, if the storage is not sized to cover a significant part of the residual load during times of low intermittent production.

An example of electric storage operation characteristic results in late summer is given in table A.11.

Finally, in scenario B5EH, an expanded district heating system is combined with both short-term electrical and seasonal heat storage. The electric storage makes up for the negative impact of seasonal heat storage on electricity prices, thus achieving lower average heat and electricity prices than in the base scenario B5.

3.5 Economic Results

For the different scenarios discussed, an economic evaluation is performed. The key parameters in this evaluation are weighted average yearly price of electricity and heat, and total investment required from status quo level. These results are tabulated in 3.1. Additionally, the table contains data on relative price decreases of both heat and electricity, for which the weighted average energy price decrease as compared to the status quo has been normalized with the respective scenario's investment cost.

From the data obtained, it is quite evident that installing the heat storage solution in the current state is beneficial since it results in a significant decrease of heat price. Installation of battery storage also leads to reduction in electricity price but investment cost is high as compared to heat storage. Increased usage of local renewable generation, as lined out by the progression through A1 to A5, offers significant reductions in electricity prices at moderate investment costs. This evolution could, due to the modular and decentralized nature of renewables, be driven partially by private investors and a multitude of small stakeholders.

The same holds true for the progression from B1 to B5. However, the B-series of scenarios comes at a steep investment cost for achieving the associated high coverage of heat loads with district heating. This is mainly caused by the CHP expansion and can be reduced through additional usage of seasonal heat storage, as is apparent in scenarios B5H and B5EH. Altogether, scenario B5EH displays a considerable reduction in both heat and electricity prices with a reasonable investment cost when compared to other scenarios in the B-series.

Scenario	Avg. yearly price of Electricity (€/Wh)	Avg. yearly price of Heat (€/Wh)	Investment cost (€)	Relative price decrease Elec	Relative price decrease Heat
status_quo	7.40E-05	2.35E-05	0	-	-
status_quo_E	7.38E-05	2.35E-05	1.02E+07	2.01E-14	0.00E+00
status_quo_H	7.40E-05	2.26E-05	1.82E+06	0.00E+00	4.99E-13
A1	7.40E-05	2.35E-05	3.83E+07	0.00E+00	0.00E+00
A2	7.37E-05	2.35E-05	9.18E+07	2.50E-15	0.00E+00
A3	7.20E-05	2.35E-05	1.49E+08	1.35E-14	0.00E+00
A4	6.89E-05	2.35E-05	2.22E+08	2.29E-14	0.00E+00
A5	6.34E-05	2.35E-05	3.24E+08	3.27E-14	0.00E+00
A5E	6.29E-05	2.35E-05	3.34E+08	3.30E-14	0.00E+00
A5H	6.34E-05	2.26E-05	3.26E+08	3.26E-14	2.79E-15
B1	7.32E-05	2.40E-05	5.07E+08	1.57E-15	-8.08E-16
B2	7.30E-05	2.40E-05	5.54E+08	1.82E-15	-7.40E-16
B3	7.17E-05	2.40E-05	6.04E+08	3.81E-15	-6.79E-16
B4	6.79E-05	2.40E-05	6.71E+08	9.14E-15	-6.11E-16
B5	6.06E-05	2.40E-05	7.65E+08	1.75E-14	-5.36E-16
B5E	5.97E-05	2.34E-05	7.90E+08	1.81E-14	1.30E-16
B5EH	6.02E-05	2.33E-05	6.37E+08	2.16E-14	4.02E-16
B5H	6.10E-05	2.27E-05	6.12E+08	2.12E-14	1.36E-15

Table 3.1: Economic Results

4 Discussion

It is quite evident from the load curves in scenario B that the demand variations in the electrical grid are subject to varying electrical heating load in the system and with decreased electrical heating, the electric curve tends to become flat in nature as compared to the load curves obtained in scenario A. This supports the thesis that the electrical non-heating load tends to remain almost constant throughout the year.

A range of scenarios were established based on the share of district heating load, with and without heat and electrical storage. The only variable parameter being scaling of renewable intermittent local generation integration (10% to 50%) in the system. The intermittent generation was expanded through increase in capacities for utility scale photovoltaic and near shore wind turbines, keeping the current state rooftop photovoltaic and onshore wind capacity constant. The most interesting fact observed while scaling up the intermittent renewables was that these technologies have the potential to act at the margin not only in summer time but also to a good extent in winter time when the load is comparatively quite high, especially in scenarios with high usage of district heating. This is a good sign towards self-sufficiency and lowering the energy costs during high net load hours almost throughout the year.

When coming to the economics of the overall system with scaled intermittent renewable local generation, the investment costs in both scenario A and B series without storage, tend to follow a smooth rise when scaling the local intermittent generation up to 40%, but when scaled further, the cost curves start rising quickly, ultimately asymptotically approaching 100%. This serves as a potential indicator that with other essential parameters remaining same, scaling till 40% is more economically viable. The investment curves along with the average annual electricity price curves for both the scenario series A and B without storage is shown in Figure 4.1.

Adding utility-scale energy storage to the distribution systems has the potential to lower costs of both electricity and heat. Heat storage in particular can be dimensioned to serve as seasonal storage. 4.5 GWh of pit thermal energy storage can make Kungälv's district heating system independent from expensive heat imports during winter, and reduce significantly the needed capacity in the Munkegärdeverket CHP when the current target of complete coverage of the Kungälv-Ytterby urban area with district heating is met.

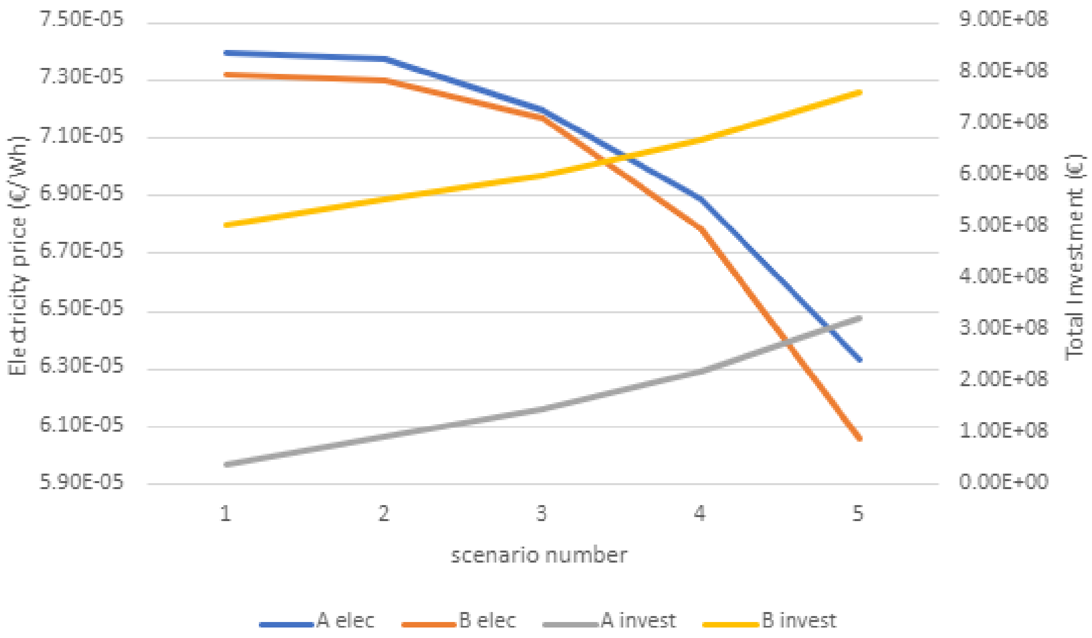

Figure 4.1: Economics of intermittent generation scaling

This way, by adding seasonal heat storage to the system, capital costs for achieving a high degree of DH coverage can be reduced significantly, since the CHP expansion accounts for a large part of capital investment costs in such scenarios. This amounts to a lifetime investment cost reduction of more than 150 M€ in Scenario B5H compared to B5. Simultaneously, the price-optimizing operation of the heat storage leads to 2.1 M€ in savings on energy prices over its lifetime. Addition of heat storage of the same size to the current system is expected to result in total savings of 1.4 M€, for an investment cost of 1.8 M€.

After comparing the current state with the 2009 energy plan's 2020 goals, it can be stated that the goal for renewable local production has not been completely achieved as per status quo, but can be made possible in the future with some investment costs. The DH expansion goal is still in process, while the other remaining goals need an integral survey and assessment.

The proposed method for generation of synthetic load curves has been shown to be robust and realistic. The generated system load profiles for status quo simulations result in a system behaviour that closely resembles historic data, capturing both extreme events and short- and long-term variability. Application of the methodology to differing demand side structures has also yielded credible results.

There are several limitations to this study. An analysis of a mobility transition towards electric vehicles might be relevant. Such a mobility transition will have a considerable impact on the electric load structure. Meanwhile, flexible charging behaviours and even usage of BEV storage capacities in a vehicle-to-grid context are expected to have a positive impact on the grid, potentially reducing the amount of necessary stationary storage capacity [39]. However, charging behaviours vary strongly depending on technical and regulatory parameters, and their effect is therefore highly uncertain.

Different charging behaviours for the introduced stationary storage systems are also a possibility. Especially electrical storage can also be used primarily for auxiliary services and supporting power quality instead of lowering energy market prices. Even when operating storage under the same objective as in this study, the optimization can be improved. For example, the search for local minima and maxima in energy prices could be supported by a predictive algorithm.

Additionally, there might be a scope of some uncertainties in the assumptions framed for estimating the heat output shares of different heating technologies in the system. The data evaluated in most of these assumptions have been derived from the legitimate sources of information including the municipality's energy plan 2009, thereby significant uncertainties through data procurement and processing are not anticipated.

Ultimately, each simulated scenario has its own technical and financial specifications. The scenario that gets directly or indirectly adopted by the utility depends on many other important stakeholders. Willingness to invest in the energy transition is hardly predictable. A strong political will, easy and early access to finance, along with active participation of everyone involved directly and indirectly can help the Kungälv municipality to achieve the required sustainable municipal energy transition.

5
Conclusion

A methodology for designing load scenarios based on technical assumptions and evaluate those scenarios using generation characteristics and economic key values has been proposed and demonstrated using the example of the Swedish municipality of Kungälv. Likely development scenarios for Kungälv's energy system have been created and evaluated using a MATLAB model.

After assessing the results, it can be concluded that the overall heating load is one of the most governing parameters for both the heat and electricity system. If the district heating is expanded, the electrical heating load is reduced which further makes the electrical load profile smoother and flatter in nature while making the heat load curve more subject to higher peaks and variations. These peaks in the heat system can be managed by increase in capacities of the Combined Heat and Power plant, and by a heat storage solution.

Seasonal heat storage is a merit to the energy system since it can facilitate a comparatively lower expansion of DH to cover the same demand and thereby reducing the energy prices. It has been shown that a seasonal storage capacity of about 4.5 GWh can replace 24 MW of installed CHP capacity in the case of Kungälv. Non-seasonal heat storage is less beneficial, since short-term price fluctuations are rare in the constrained district heating market. On the other hand, electrical storage should be designed with a lower energy capacity due to the high investment cost, in favour of relatively high discharge capacities. Battery storage only influences the energy prices if the installed power size is sufficiently large to outperform marginal technologies.

To make the municipality achieve its aim of self-sufficiency, expansion in the local renewable generation is required. Increased share of such local generation not only decrease the amount of imports required, but also reduces the energy prices in the overall system. Intermittent generation becomes much more effective with high district heating in the system. This fact is best achieved with renewable integration level of at least 30% or more in the electricity generation system. Low electricity prices further benefits the heat production through electrical heating wherever district heating remains unavailable at the very moment.

Further research should be done on the effects of electromobility on energy transition. Since energy storage solutions act as a catalyst in achieving the energy transition, a detailed study of storage operation control schemes is of interest, as they have a high influence on the storage behaviour in the energy system.

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A

Appendix

	Technical lifetime [yrs]	Main Electricity consumption [W_e/W_h]	Fixed O&M cost [€/W_{en} ·yr]	Investment cost [€/W_{en}]
Air to Air HP (existing single)	12	0.2060	0.0230	0.2615
Air to Air HP (new single)	12	0.2174	0.0600	0.4440
Air to water HP (existing single)	16	0.3174	0.0440	1.5640
Air to water HP (existing apartment)	20	0.3440	0.0108	0.6879
Air to water HP (new single)	16	0.3390	0.0554	1.2140
Air to water HP (new apartment)	20	0.3630	0.0140	0.7718
Air to water HP general LPP	12	0.3300	0.0510	1.2280
Ground-source HP (existing single)	20	0.2900	0.0410	2.0720
Ground-source HP (existing apartment)	20	0.3125	0.0067	0.6410
Ground-source HP (new single)	20	0.3077	0.0550	1.9320
Ground-source HP (new apartment)	20	0.3440	0.0096	0.7300
Ventillation HP (apartment)	15	0.1851	0.0064	0.4770
Solar heating (existing single)	25	0.0000	0.0124	0.9857
Solar heating (existing apartment)	20	0.0000	0.0030	0.5780
Solar heating (new single)	25	0.0000	0.0157	0.5714
Solar heating (apartment)	20	0.0000	0.0030	0.5780
Electric heating (single)	30	1.0000	0.0080	0.8967
Solar heating (new apartment)	30	1.0000	0.0003	0.6856
Biomass boiler automatic (existing single)	20	0.0000	0.0374	0.4860

Table A.1 continued from previous page

	Technical lifetime [yrs]	Main Electricity consumption [W_e/W_h]	Fixed O&M cost [€/W_{en} ·yr]	Investment cost [€/W_{en}]
Biomass boiler automatic (existing apartment)	20	0.0000	0.0038	0.2200
Biomass boiler automatic (new single)	20	0.0000	0.0375	0.4700
Biomass boiler automatic (new apartment)	20	0.0000	0.0063	0.3313

Table A.1: Heating technologies data - Demand side

	Technical lifetime [yrs]	Fixed O&M cost [€/W_{en} ·yr]	Variable O&M cost [€/MWh]	Investment cost [€/W_{en}]	Electricity consumption [$W_{el, in}/W_{en, out}$]
PV rooftoop	35	0.0134	0.0000	1.1800	0.0000
PV utiilty scale	35	0.0113	0.0000	0.5625	0.0000
Solar thermal collectors	30	0.0000	0.2100	1.5571	0.0000
Wind turbines (Onshore)	27	0.0140	1.5000	1.1188	0.0000
Wind turbines (Near shore)	27	0.0500	5.0000	1.6999	0.0000
Wind turbines (small domestic)	20	0.0950	0.0000	3.8000	0.0000
Combined Heat and Power (Wood chips)	25	0.1490	4.4871	3.5432	0.0000
Compression-Air source heat pump	25	0.0020	1.7000	0.8600	0.2658
Compression-sea water heat pump	25	0.0040	1.2000	0.4800	0.2730

Table A.2: Generation technologies data - Supply side

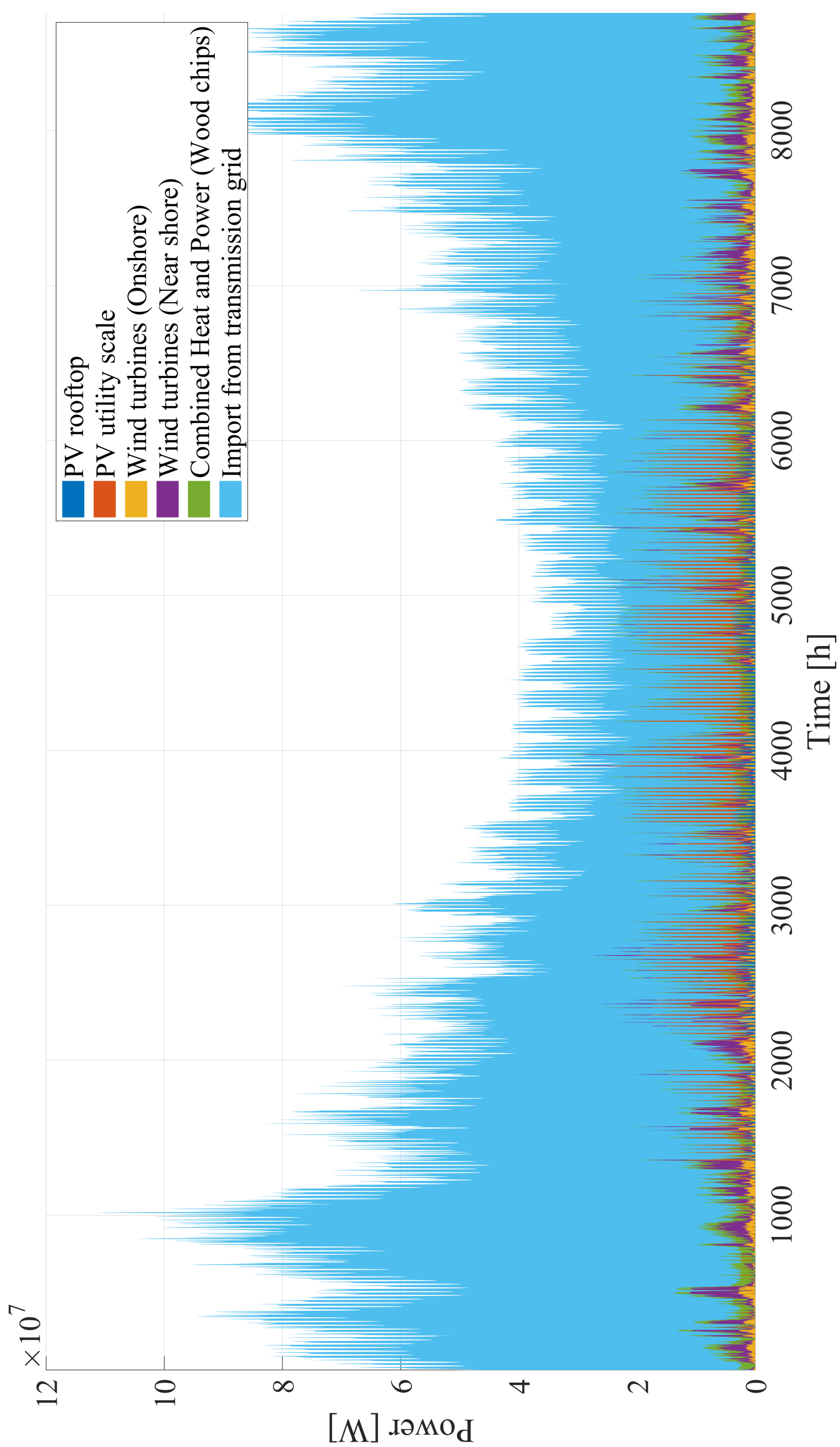

Figure A.1: Generation curve scenario A1

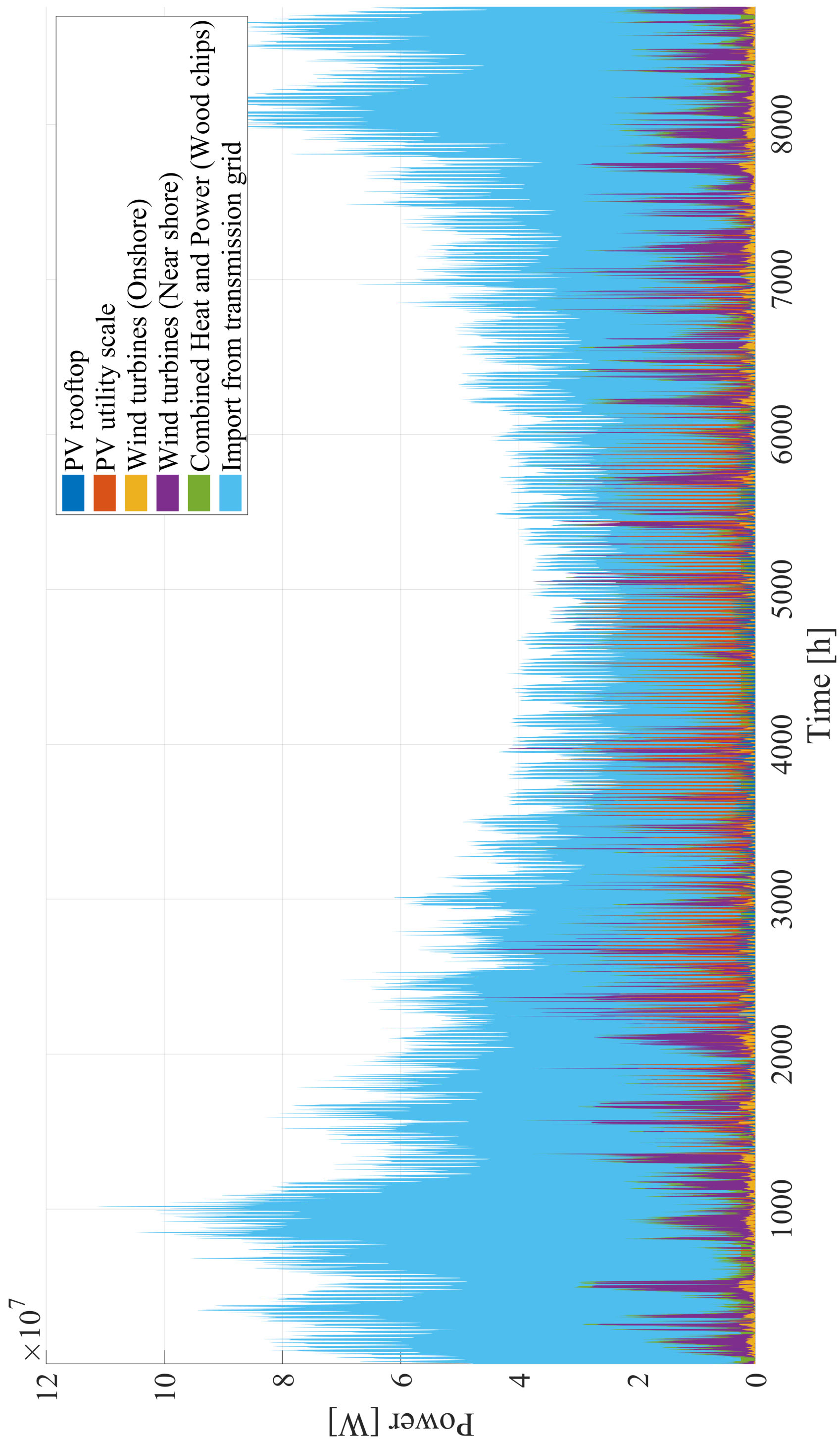

Figure A.2: Generation curve scenario A2

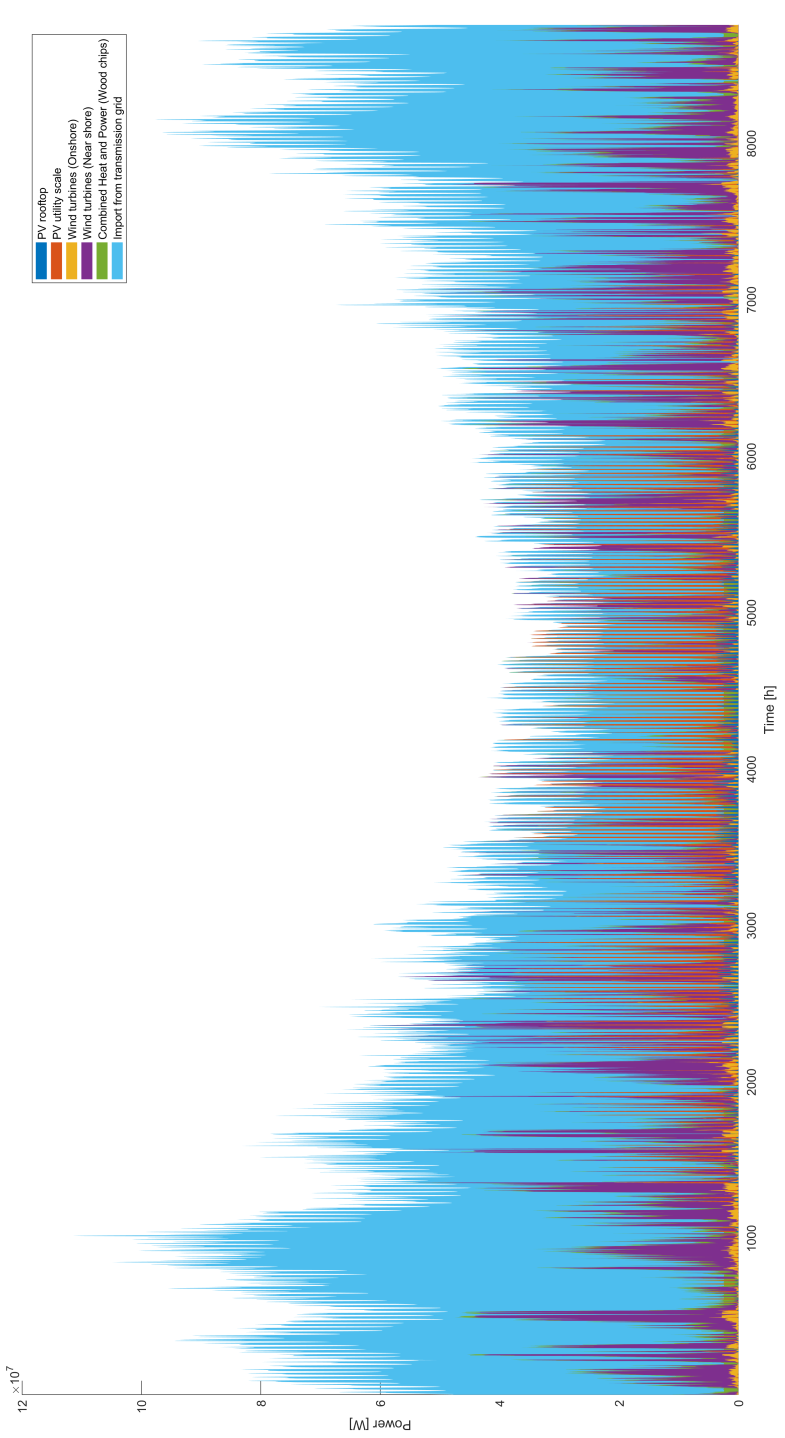

Figure A.3: Generation curve scenario A3

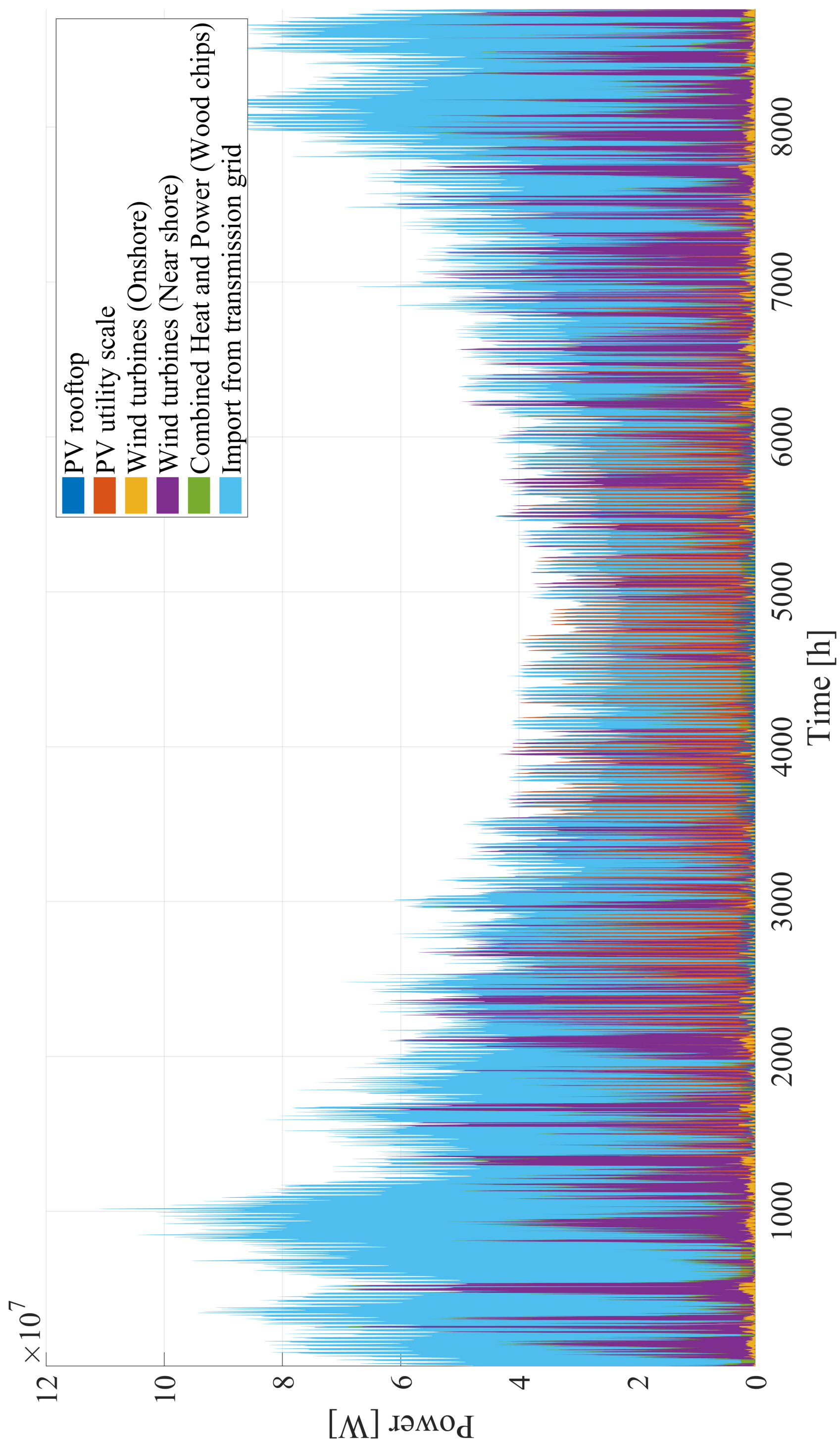

Figure A.4: Generation curve scenario A4

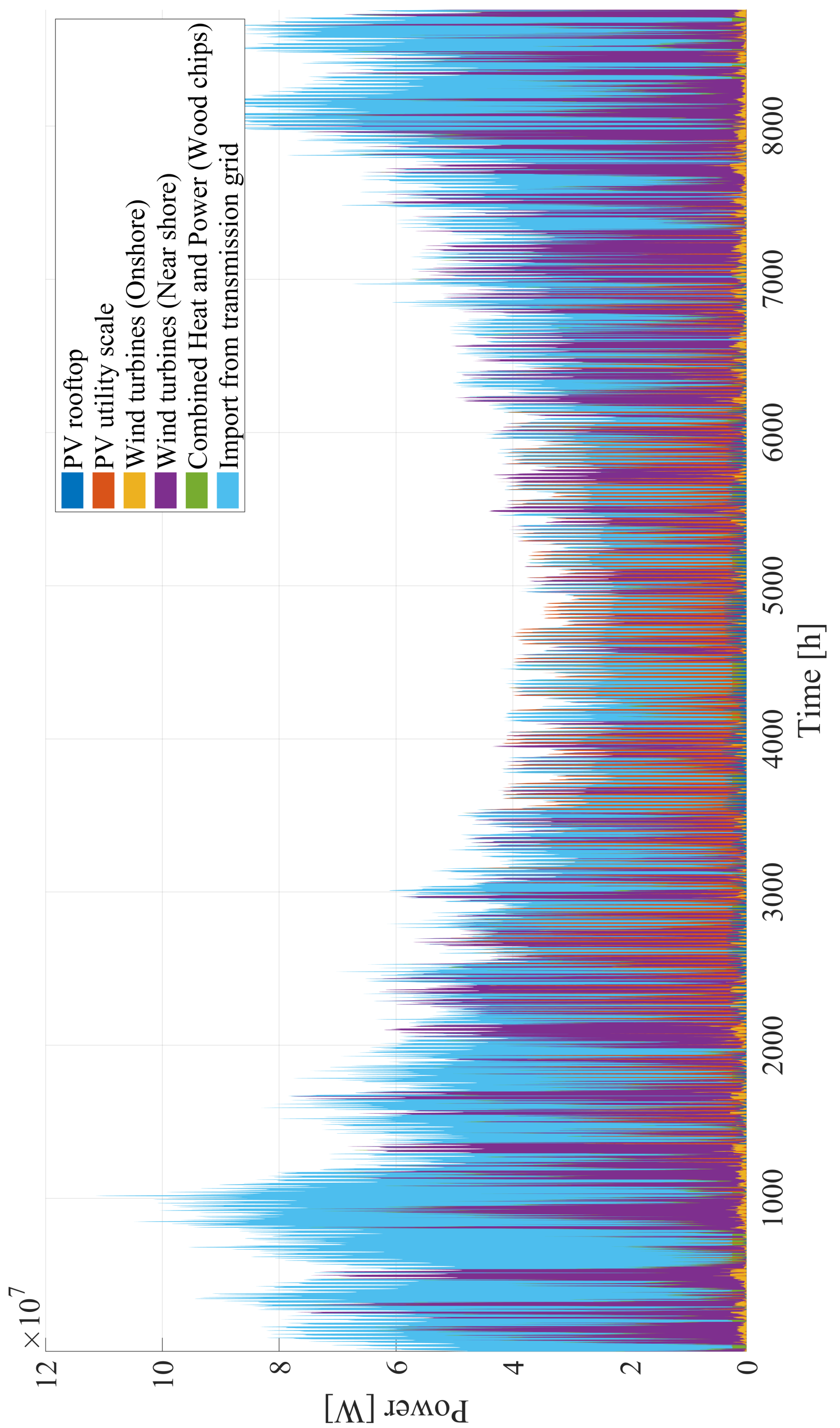

Figure A.5: Generation curve scenario A5

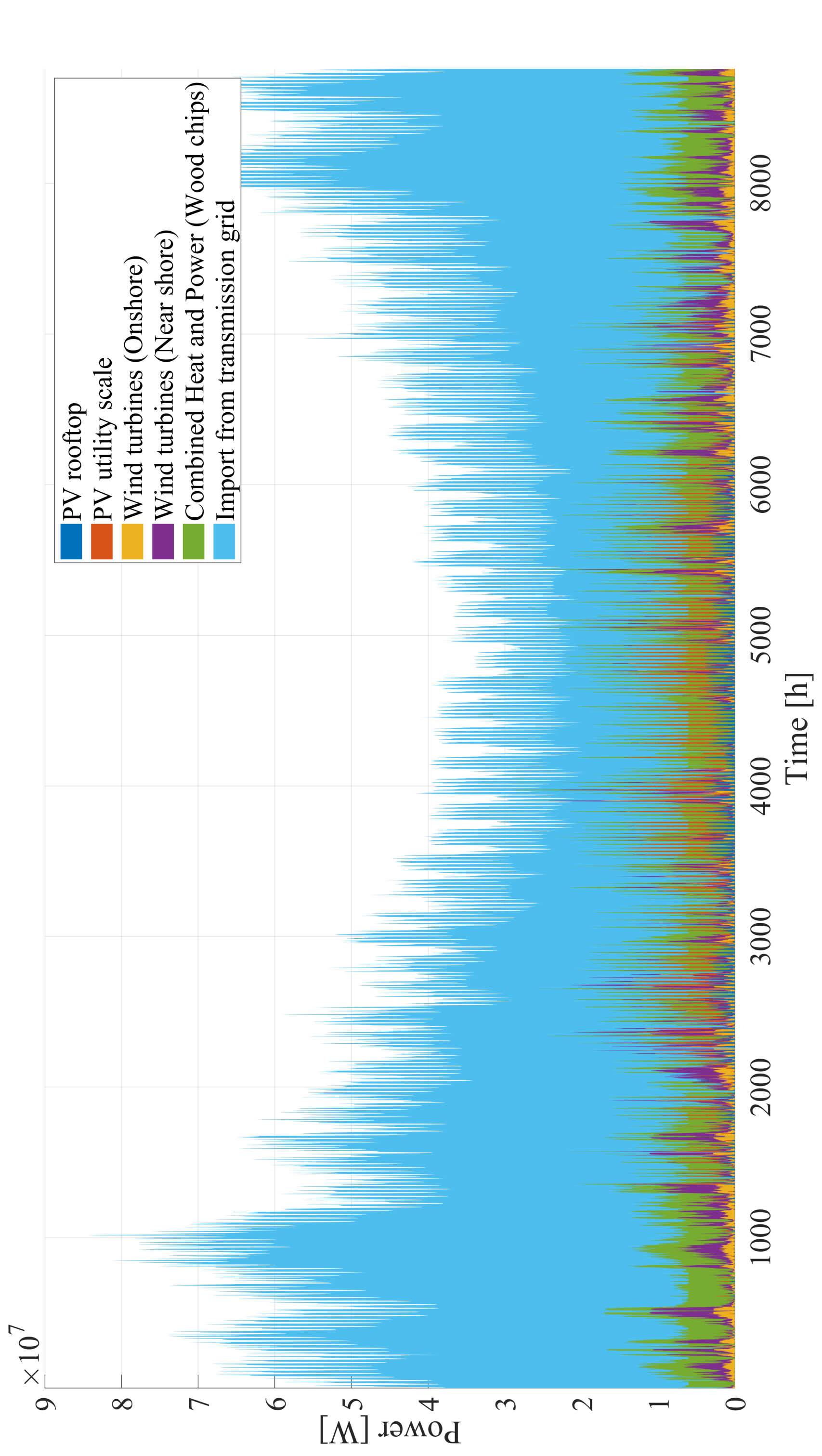

Figure A.6: Generation curve scenario B1

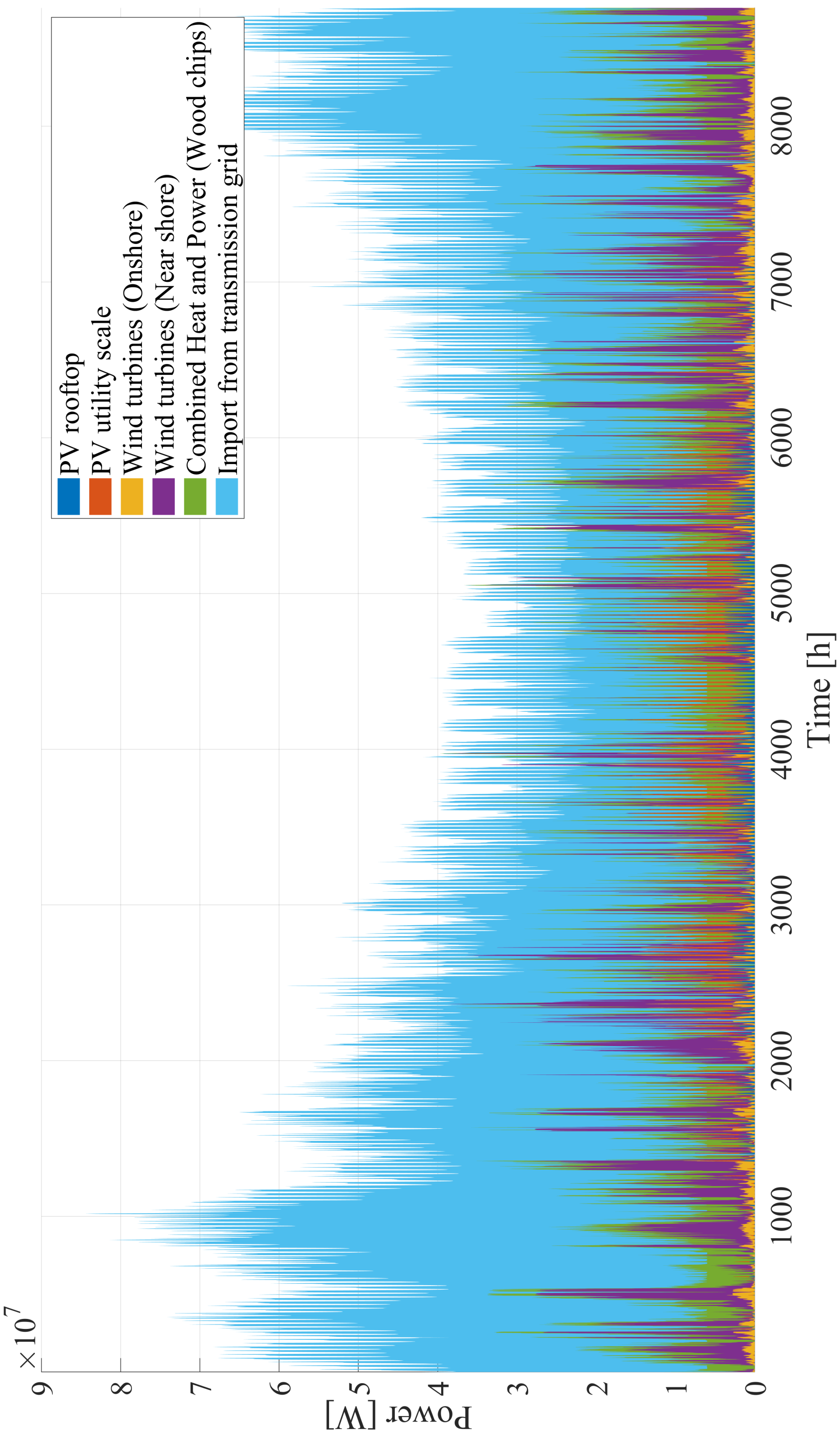

Figure A.7: Generation curve scenario B2

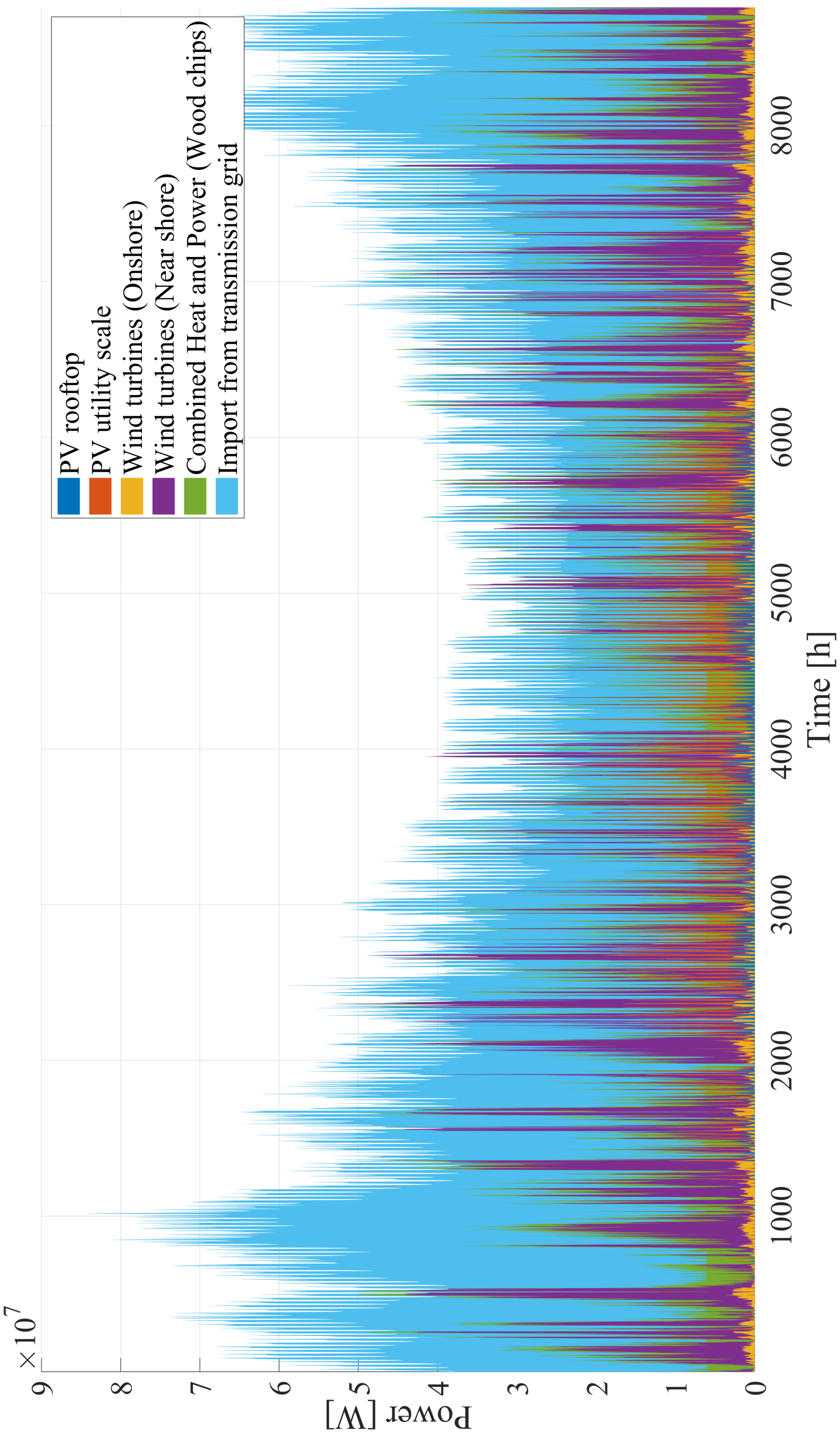

Figure A.8: Generation curve scenario B3

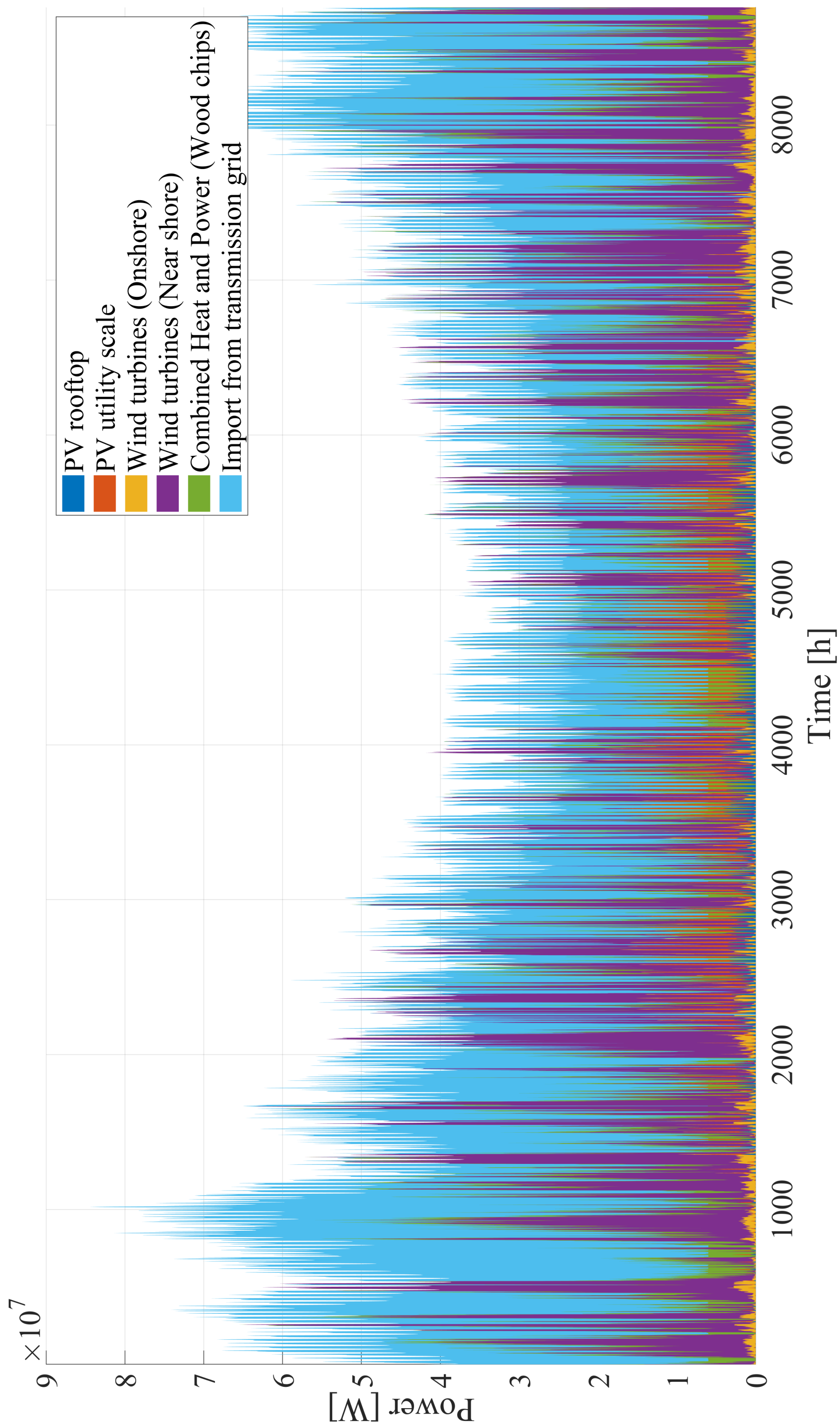

Figure A.9: Generation curve scenario B4

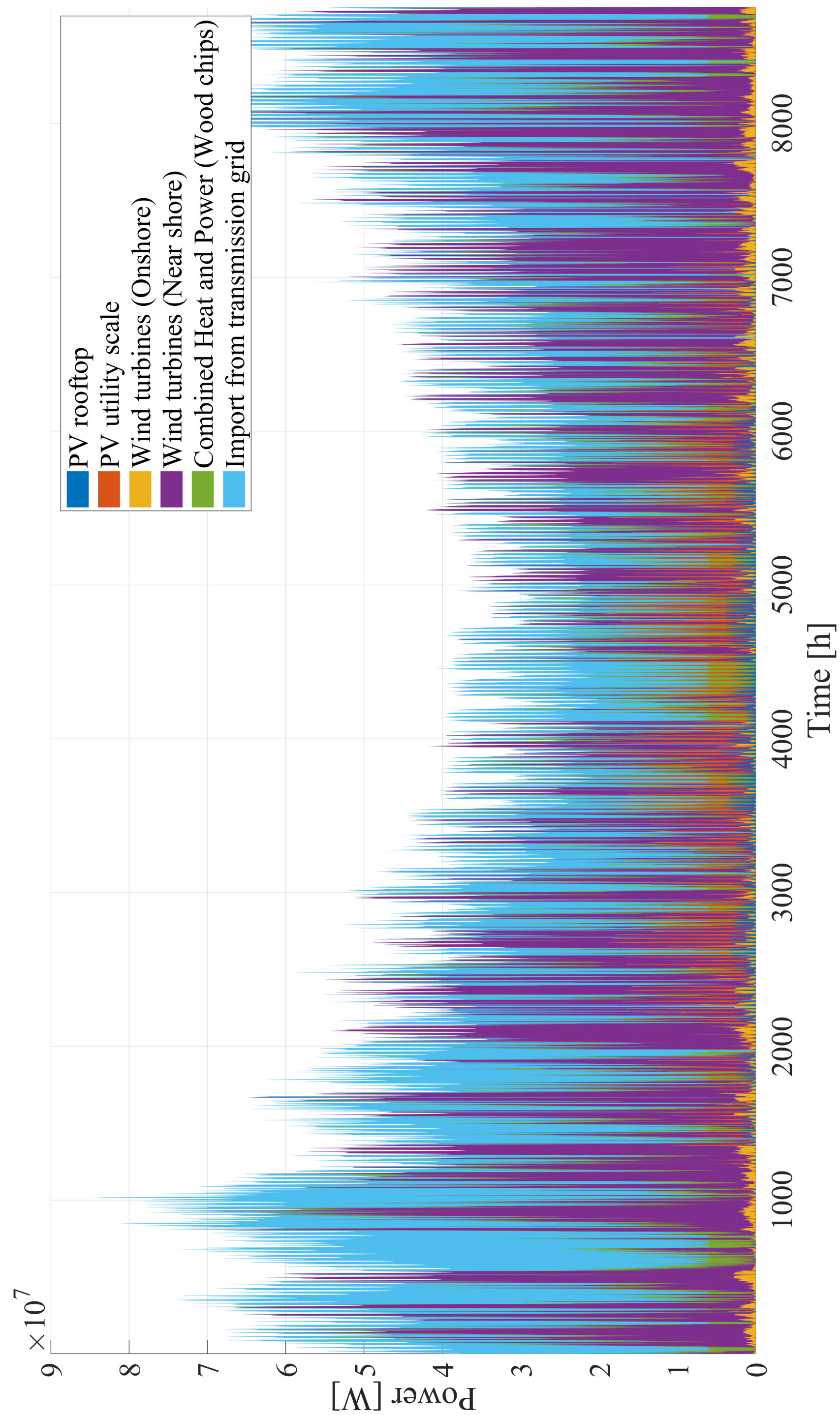

Figure A.10: Generation curve scenario B5

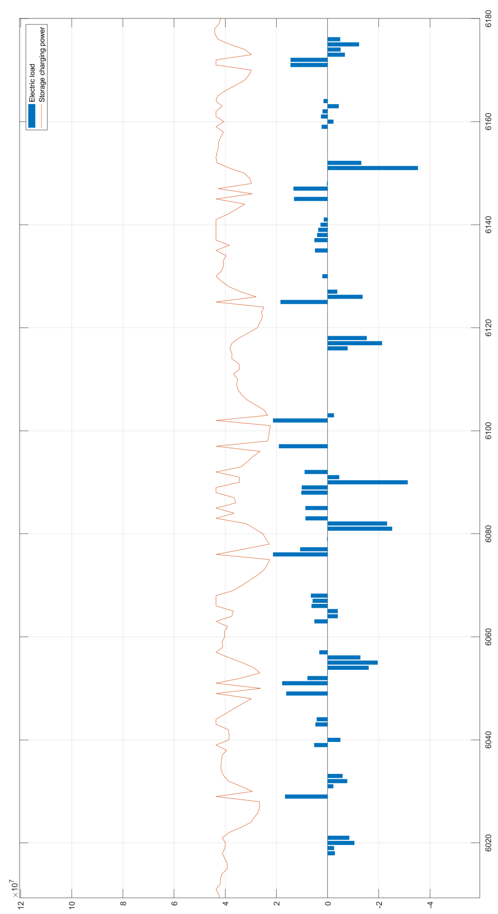

Figure A.11: Time series of charging and discharging electrical storage in a week in September.