UPPSALA
UNIVERSITET

UPTEC STS 20020
Examensarbete 30 hp
Juni 2020

ADDRESSING GRID CAPACITY THROUGH TIME SERIES

Deriving a data driven and scenario-based method for long-term planning of local grids.

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Abstract

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Simultaneously as the societal trends of urbanization, digitalization and electrification of society are moving at a high speed, the Swedish power grid is undergoing a necessary transition to a renewable energy system. Even though there are difficulties on all grid levels, the lack of capacity in some local grids is among the most present problems and originates from the long lead time of grid expansion as well as the challenges within long-term planning of grids. This thesis aims to improve the understanding of future trends' impact on grid capacity needs. More specifically, a scenario-based and data driven method, with an accompanying model, is derived to target local capacity challenges. The trends identified to pose impact on the future grid capacity were electrification of different sectors, energy efficiency actions, decentralized energy generation, energy storage solutions, flexibility, smart grids, urbanization and climate. The thesis concludes that the impact of a trend on national level is not simply equal to the impact on a local level. Similarly, a long-term increase of the national electricity consumption does not necessarily worsen local capacity challenges. Furthermore, the developed model in this project shows potential to provide more detailed and accurate information about consumption than currently used methods based on standardized power estimations, which could favor more transparent decision making when dimensioning local grids.

Handledare: Vincent Gliniewicz
Ämnesgranskare: Uwe Zimmerman
Examinator: Elísabet Andrésdóttir
ISSN: 1650-8319, UPTEC STS 20020
Tryckt av: Uppsala

Populärvetenskaplig Sammanfattning

Sveriges elnät står just nu inför stora utmaningar i övergången från ett traditionellt centraliserat system till ett decentraliserat system som drivs av en mer förnybar elproduktion. Det finns utmaningar på alla nätnivåer men kapacitetsbristen i vissa städer är bland de mest aktuella problemen. Nätkapaciteten påverkas av fortskridande trender såsom urbanisering, digitalisering och energieffektivisering men även av en ökande elektrifiering. Elektrifieringen är i sin tur en direkt konsekvens av strävan efter ett fossilfritt samhälle. Kapacitetsutmaningarna medför en ökad efterfrågan på innovativa lösningar som flexibilitet, energilagring och smarta elnät. Det är viktigt att uppmärksamma nya trender, då dessa förväntas innebära nya risker och utmaningar från både tekniska och socioekonomiska perspektiv. Distributören och nätägaren och Vattenfall Eldistribution är en av aktörerna som påverkar men även påverkas av de kommande utmaningarna. Långa processer och ledtider vid nätdimensionering är en av anledningarna till Vattenfall Eldistributions behov av att kartlägga möjliga framtida scenarion. Genom att förutse effekterna av framtida trender kan planering av lokal nätkapacitet genomföras på ett mer proaktivt sätt. Utifrån denna kontext ämnar det här examensarbetet att skapa förståelse för, samt undersöka kommande trenders påverkan på nätkapaciteten. Mer specifikt syftar projektet till att undersöka hur en datadriven och scenariobaserad metod, med utgångspunkt i tidserier, kan främja långsiktig planering och gynna lösandet av kapacitetsutmaningarna.

Examensuppsatsen inleds med en bakgrundsbeskrivning av den svenska elnätskontexten, Vattenfall Eldistributions arbete med nätkapacitet samt företagets strävan mot att arbeta mer datadrivet. Sedan följer en litteraturgenomgång, där nationella prognoser och scenariorapporter mynnar ut i en mer ingående genomgång av ett flertal identifierade trender som kommer att ha påverkan nätkapaciteten. Trenderna som identifierades kan delas in utifrån flera kriterier: de som utgör decentraliserad och förnybar elproduktion, såsom sol- och vindkraft; de som ökar efterfrågan på el, såsom elektrifiering av transport- och industrisektorn samt befolkningsökning och urbanisering; de som minskar elenergibehovet, till exempel energieffektivisering och energilagringslösningar; och slutligen de trender som fungerar som möjliggörare till ett fossilfritt energisystem såsom digitalisering, flexibilitetslösningar och styrmedel.

Projektet genomfördes i samarbete med Vattenfall R&D under våren 2020. Arbetets tillvägagångssätt var en kombination av en kvalitativ litteraturstudie och kvantitativ översättning av trender. Utifrån det kunde en datadriven modell tas fram som ett alternativ till de nuvarande mer traditionella sätten att planera kapaciteten för lokala elnät. Där de traditionella sätten ofta utgår från effektschabloner använder den utvecklade Python-modellen istället information i tidsserier och visualiserar framtida trender som konsumtions- eller produktionsmönster. Eftersom tidshorisonten för nätplanering, och i förlängningen även modellen, bör vara långsiktig användes även en explorativ och scenariobaserad metod med fokusfrågan *vad kan hända* som utgångspunkt. Genom att utgå från nationella prognoser kunde det antas att en predikterbarhet existerade för vissa av de identifierade trenderna. Det explorativa inslaget bidrog vidare med variationer i trendparametrarna som ingår i prediktionerna. De explorativa scenarioutfallens syfte var således inte att förutspå framtiden, utan att formulera viktiga antaganden och variationer i trenderna samt återspegla osäkerheter om framtiden. Med utgångspunkt i teorier om energimodellering och scenariokonstruktion, lades fokus på en hög grad av ställbara modellparametrar i kombination med 'bottom-up'-strategi, för att gynna både en flexibel och en skalbar modellstruktur.

Resultaten från modellsimuleringarna visar en hög variation i effekterna av de identifierade trenderna. De fåtal trender som förmodas påverka kapaciteten men inte direkt på lokal nivå, exkluderades från modellen. Genom de explorativa scenarierna visualiserades distinkt och varierande påverkan på nätkapaciteten beroende på vilka trender som hade implementerats och i vilken omfattning de var representerade i respektive scenario. Utifrån resultaten kan slutsatsen dras att effekterna av en trend på nationell nivå inte nödvändigtvis reflekteras på samma sätt på lokal nivå. Likaså kan det urskiljas att en förmodad ökning av den nationella elförbrukningen inte vara relaterat till ett förvärrande av lokala kapacitetsproblem.

Mer data med större detaljrikedom samt mer genomarbetade trendimplementeringar skulle innebära en förbättrad modell. Trots detta kan vissa fördelar med modellen som metod konstateras. Till skillnad från traditionella metoder, fångas exempelvis tidsaspekten in, något som utgör en viktig faktor vid exempelvis introducering av elbilsladdning i näten. Metoden lyckas även återge en mer detaljerad och exakt bild av den timvisa elförbrukningen – information som är betydelsefull vid nätdimensionering. Till modellen utvecklas ett grafiskt användargränssnitt som möjliggör visualisering och därigenom även mer transparanta och välgrundade beslutsunderlag. Transpararens utgör ett nyckelord genomgående under projektet och reflekteras genom ett kontinuerligt kommunicerande av heltäckande, nödvändig och reproducerbar information. På så sätt understödjs en vidareutveckling av såväl simuleringar, modellen samt metoden att kombinera scenarier och tidserier.

Abbreviations and Important Concepts

AMI	Advanced Measurement Infrastructure
Consumption	Refers to consumption of electric energy in kWh.
Demand	Refers to the demand of electric energy in kWh.
DEG	Decentralized Energy Generation.
DH	District Heating. The supply of heat or hot water from one source to a district or a group of buildings.
DSO	Distribution System Operator, e.g. Vattenfall Eldistribution.
Distribution Grid	Local distribution grid with low voltage level of 40–130 kV.
Electric Energy	Refers to the process of supply of primary energy, conversion to and transfer of electricity, and final use of electric energy in kWh.
Energy	See Electric Energy.
Energy Efficiency	Refers to the process of using less energy to provide the same utility. Only refers to the physical efficiency concept if discussing objects e.g. inverters.
EV	Electrical Vehicle.
GUI	Graphical User Interface.
ICT	Information and Communication Technology.
kWh	Kilo Watt Hour. Unit of electric energy.
kW_p	The peak power of a PV system or panel. kW_p stands for kilowatt 'peak' of a system
Load Curve	Describes electrical energy consumption over a certain period of time.
Load Profile	A typical load curve representing a customer segment.
Local Grid	See Distribution Grid.
Power	Instantaneous power in Watt or Joule per second.
Power Grid	Refers to the Swedish electric power grid.
Power System	Refers to the Swedish electric power grid and the system around it.
PV	Photovoltaics. The conversion of sunlight into electricity. Here referring to solar panels or solar cells producing electric energy.
SvK	Svenska Kraftnät.
Time Series	A series of data points indexed or listed in time order.
Trend	Refers to a general direction in which an artifact, phenomenon or process is developing or changing.
TSO	Transmission System Operator, eg. Svenska Kraftnät

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1. Introduction

The electric power system has a critical role in the Swedish infrastructure and is fundamental for the whole society to function. The power system is currently undergoing a necessary transformation from a conventional centralized system, with a steady electricity consumption, to a renewable and decarbonized energy system with an increasing decentralization of power generation. There are challenges on all grid levels, but the lack of capacity in some local grids is among the most present problems. Trends that may influence the grid capacity at a local level are a continuously ongoing urbanization, digitalization and electrification in combination with progress within energy efficiency and flexibility. It is therefore of high importance to foresee these sorts of future trends and their effects on energy demand in order to respond in time. Future trends have the potential to introduce new risks and challenges for stakeholders from both a technical and socioeconomical perspective. The concerned stakeholders include Transmission- and Distribution System Operators (TSO & DSO) as well as municipalities, local businesses and customers. As the DSO holds a central position among these stakeholders, it is extra vital for them to map out and predict possible impact of future scenarios in order to create a response plan for the grid capacity. Within this context, this project targets DSO level prediction and is carried out at Vattenfall Eldistribution AB, that is responsible for the distribution of electricity in 60 municipalities in Sweden.

The present problem with lack of capacity shows a need to enhance a more proactive way of planning the capacity of the local grid. All the while data driven development shows great potential to assist and optimize strategic planning across the energy sector, it could be leveraged more efficiently. Today, there are large amounts of data generated from many different ICT components of the power system, which could favor distribution and operation of local grid services. In order for the potential of big data to be realized, data management and applications must be integrated into organizational operations [1]. For the DSO this would involve expanding the traditional ways of planning future grid capacities to include further data driven modeling of end-user consumption.

While changes in society happens rapidly, reinforcing the grid takes a long time. Strict regulations and policies regarding grid development and expansion entails slow process and can potentially lead to demand exceeding capacity. Consequently, there is a need to take a longer view and planning must be medium to long-term and take into account both technical and societal factors. This project targets the time horizon of 2040, which naturally implies numerous uncertainties. There is no way to know exactly where Sweden and its energy sector will be in 20 years from now. Thus, the issue is not to predict the most likely scenario, but rather to explore the effects different scenarios could have on the local grid capacity. Against this backdrop, there is research of models aiming at high accuracy short-range prediction on local grids. However, this project seeks to contribute by expanding the time frame and introducing a scenario-based approach, characterized by transparency and scalability.

1.1 Aim and Research Questions

The overarching aim of the project is to improve the understanding of how future trends and outlooks could impact the grid capacity. More specifically, the project will see to the capacity need of the local power grid through using a data driven method with an accompanying model. To do so, the following research questions are chosen:

- Which future societal and technological energy trends can potentially have a large impact on the grid capacity demand on a local level?
- How can a transparent and flexible model be built to quantify and visualize the impact these factors will have on the local distribution grids? Which data should the utility company leverage to build confidence in the model?
- What insights can be gained from using time series as a tool for exploring grid capacity?

1.2 Delimitations

Since this project aims to investigate broad scope of a method to visualize the impact of future energy trends, it is mostly delimited in depth and not by width. In other words, many energy related topics and sectors are touched upon, although not in much detail. Nonetheless, the project has a few delimitations. First, the project focuses on the Swedish context and on the local level of the electric power grid. Second, the area of interest is the electric energy demand related to the grid capacity. Therefore, the centered topic is the electric energy consumption, meanwhile the total energy use is only occasionally touch upon to place the electric energy in a context. Likewise, large-scale power generation and other aspects related to the transmission and regional grid is disregarded but yet sometimes mentioned due to the close relationship between production and consumption. Since area of investigation is the capacity issues on a general level, the grid power flow is not taken into account and the grid is therefore assumed to be stable. Additionally, financial and economic aspects are only briefly discussed due to the project's timeframe. As a last clarification, it is the electric energy consumption and production that is evaluated, not instantaneous power.

1.3 Thesis Outline

The thesis is organized in the following way. Chapter 2 provides background information and essential context. Since the quantitative parts of the project is largely based on the qualitative parts, description of the methods is split into two chapters. First in chapter 3 the overall research design is presented. The quantitative parts of the project are described in more detail in chapter 6, after the results of the literature review and the relevant theoretical concepts have been portrayed in chapter 4 and 5. Chapter 7 contains results of the model and the simulations while chapter 8 carries out a wider discussion of the combination of the qualitative and quantitative parts combined. Lastly, the conclusions are summarized in chapter 9 while with thoughts on future work can be found in Appendix after the references.

2. Background

This chapter intends to depict background and context in which the project was carried out. The chapter declares the motivational factors of the project in more detail as well as describes the current situation and practices of a DSO, in terms of working with capacity in local grids.

2.1 Motivators of the Study

The power grid is not built upon speculation [2], meaning that the grid is not over expanded in case of future usage, neither by the Swedish TSO nor the DSOs. A power grid with overcapacity which is not optimally and fully utilized cannot be justified from a socioeconomic perspective. The expansion of the grid therefore needs to go hand in hand with the capacity need of households and companies as well as the increase of power production. Historically, the grid expansion was able to keep up and new grid connections was established with ease. However, this fact does not still hold true. During the latest years there has been a rapid and accelerating growth rate of the larger cities in Sweden. Construction of historic extent and pace in combination with electrification of industries constitutes a major challenge within the constraints of today's power grid. The growth rate of the larger cities has led to new prerequisites and requirements of the energy infrastructure within these regions. Moreover, extra pressure has been put on the regional as well as local grids and upholding capacity has become a challenge. Within the electricity context, lack of capacity means that even though there are enough energy within the system as a whole, there is trouble transferring it to customers within a limited geographical area, especially large consuming areas [3].

The capacity challenge is most present in the local and the regional grid, but the solutions need to go through national procedures. Current regulations and policies regarding grid development and expansion entails slow processes that can take up to 10 years' time [4],[5]. The actual building and physical expansion of the grid takes a lot of time but the most time-consuming part is the long lead times. Planning ahead and long-term becomes vital when the grid expansion and permission processes are slow. Hence, the DSOs have a lot to benefit from good estimations of future trends.

To do prognoses for the future electricity use is not a trivial task, and even more complex on local levels because of the heavy variations in local grids, where more detailed information is required. Presently, there are several scenario reports about the future Swedish energy- and electricity market constructed using conventional energy models (which will be discussed in detail in chapter 3). These scenarios are generally focused on the national level, sometimes on grid area level such as mid Sweden (SE3), but mainly concern electricity use in total, per sector or per capita. It appears that there is a gap between the nationwide scenario reports and scenarios at the regional and local level. Similarly, the widely used energy models for scenario planning, such as Sweco's Apollo model [6] or the TSO Svenska kraftnät's (SvK) BID3 model by ÅF [7], tend to focus on grid area level or higher. It seems reasonable to bridge the gap between the national scenario reports and models, and the distribution level since the DSOs should be equally prepared for the future electricity market.

To summarize, there are three main background motivators of the project and why new approaches to local grid planning are needed. First, the lack of capacity in the local grids is becoming a highly present problem which is not expected to become less challenging in the future. Second, planning models need to look further ahead to be able to tackle the time-consuming procedures of grid expansion. Lastly, much previous research as well as developed tools focus on the national outlooks, leaving a gap to be filled from the local perspectives.

2.2 Overview of the Swedish Electricity System

Electricity is the largest energy carrier in Sweden with a total electricity use of 126 TWh (excluding losses) in 2018 [8]. The Swedish electricity generation is largely based on hydropower and nuclear power which together accounted for 80 % of the electricity generation in 2018, compared with 96% during 1990. The expansion of renewable electricity has increased since the 2000s, mainly due to an increased amount of wind power. The electricity use has declined slightly since 1990 despite a population increase and Sweden has been a net-exporter of electricity for 10 years. The Swedish electricity system can be divided into two flows; the physical transfer of electricity and the financial trade of electricity, both visualized in Figure 1 below [9].

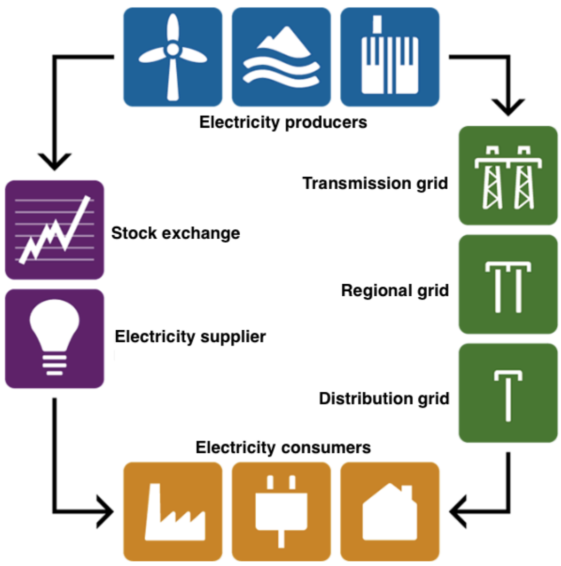

Figure 1 *The electricity route described by SvK [9].*

The financial trade takes place on organized marketplaces, where electricity is traded on different time horizons, or via bilateral agreements between producers, suppliers and end-users [10]. Most of the trade takes place on Nordpool on which a spot market for trading electricity per hour for delivery the next day (the day-ahead market) while a smaller portion is made directly between electricity generators and electricity suppliers (the intraday market) [10]. A weak year for the Nordic hydropower combined with increased emission rights prices in 2018 resulted in the highest spot prices for electricity since 2011 [8]. On the contrary, the average spot price for this March 2020 is the lowest for that month ever [11]. Additionally, since electricity cannot be stored on a large scale, it needs to be used when it is produced, and balance must be obtained between production and demand at all times in the grid. SvK have system responsibility for upholding the national balance in the grid and does so through power reserves and bilateral agreements with so-called balance operators [12].

The transmission over distances takes place at different voltage levels from production plants to end-users. The three different grid types, visualized in Table 1, in the overall national grid levels consist of the high-voltage transmission grid owned by SvK, the medium-voltage regional grids and the local low-voltage distribution grids where the voltage is transformed down to the end-user voltage level.

Table 1 *Different voltage levels and their traditional function in the overall national grid*

Grid Level	Standard Voltage level	Power [MW]	Function
National	220-400 kV	1000	*Long distance transfer* *Load balance between power plants*
Regional	(40-130 kV)	100	*Regional distribution, some large industries are connected*
Distribution/ local	(40-130 kV)	10	*Local distribution, directly to industries*
Consumption	(400/230 V).	0-1	*Distribution to end-users*

The different voltage levels enable transfer of electricity depending on locations and utility. High voltage levels are suitable for transferring electricity over long distances and low voltage levels are suitable for distribution over short distances to the end customers in a substation. In the Swedish grid, there are an estimated 175,000 substations in large cities as well as rural areas. These substations serve customer groups of various size, depending on their location, from a few customers to several hundred. In the substation, the incoming connection from the medium-voltage network is transformed down to low-voltage and can then supply the end user [13] . Traditionally, the production has been primarily connected to the high voltage transmission grid. However, with an increased share of renewable power production, more decentralized power generation (DEG) are connected to all grid levels posing challenges for the grid stability. The electricity grid operators control and maintain the grids to ensure that the end customers receive the electricity they need. Since the grids function as natural monopolies, the revenues are regulated by Energimarknadsinspektionen, who ensures that the grid operators do not charge excessive costs to the end customers and that grid investments are socio-economically sound [9].

2.3 Vattenfall Eldistribution and Capacity Planning

Vattenfall Eldistribution is one of Sweden's biggest DSOs. The Distribution Business Area comprises the electricity distribution operations in Sweden, including managing and planning future grid expansion. With a mission to provide a high security of supply while simultaneously contributing to a sustainable society, Vattenfall Eldistribution strives towards facilitating more small-scale renewable electricity generation as well as allowing new connections in fast developing areas. The capacity challenge is such areas is targeted by the company through both short- and long-term solutions. [14]

In the short term, Vattenfall Eldistribution is working on developing of smart digital system solutions [14]. Digital marketplaces are being developed where there is opportunity to release capacity and to ensure more efficient use of the grid. This involves both more flexible production and consumption and has resulted in that the DSO offers opportunity to sign load and production management agreements as well as conditional grid agreements with larger customers in areas where a lack of capacity is a fact. Vattenfall Eldistribution has procured local electricity production in areas with grid capacity shortages and has agreed with major electricity users to reduce their electricity use during critical periods. Releasing capacity in the grid also enables the connection of new customers. Local markets for flexibility services are tested where, for example, through the CoordiNet project [14], Vattenfall Eldistribution is moreover exploring the possibilities of more efficient use of the electricity grid together with electricity grid companies in both Sweden and the rest of Europe [14].

The development of smart digital systems is a way to target the urgency of the capacity shortage. However, in the longer-term physical expansion and reinforcements of the grid are required to resolve the lack of capacity. SvK needs to expand and strengthen the transmission grid in the regions where there is a lack of capacity in order for Vattenfall Eldistribution and other DSOs to be able to expand and connect customers to their regional and local grids, all the while upholding grid stability [14]. To cope with and balance these two contradictory requirements prioritized work areas are [15]:

1) Development of more accurate and reliable forecasting and power simulation tools in order to reduce uncertainty factors.
2) Standardized collection of forecast data and how to quantify growth forecasts and projections.
3) Proceed from standardized methods to more data driven methods in order to incorporate local influence.
4) Enable connection of loads that risk to deteriorating the grid stability.
5) Power regulation and control of connections with intensive power demand.
6) Power regulation and control of “all” customers through new digital market solutions.

As mentioned, building grids are time consuming and must be planned long-term. Vattenfall Eldistribution's department Customer & Market Analysis are targeting the questions of capacity and new connections through working with long-term prognoses. Through continuous dialogues with municipalities and regions, plans on grid expansion can be included earlier in the municipal planning and more accurate estimations about demand for future connections can be achieved [16].

In order to estimate the magnitude of the added connections, standardized power estimations which indicate the applied power contribution are used [16]. The standard power estimations can for example be an average small house with electricity heating or an apartment with district heating (DH). The standardized values is originally obtained from energy measurement in kWh and electricity measurement in substations, also from using energy per square meter [17]. To calculate a comparative value of the peak load, the Velander formula is used. Traditionally, the loads and the grid functions have been relatively predictable, and the consumption patterns has followed few input variables such as cold or warm weather [15]. The values and calculations has gradually been developed from being developed analogously to being compared with real digitalized measured data [17],[15]. New trends have initiated more complexity in analyzing measurement values due to for example more renewable power production or capacity trading on flexibility markets. Interpreting measured values and deciding on what parameters to use when designing the grid have thus become a more multifaceted question and new tools for quantifying risks needs to be established [15]. Concludingly, today's way of planning has room for progress in terms of utilizing new tools, techniques and data.

2.4 Towards Data Driven DSOs

Data analytics are now playing a more central role within the energy system, much like in most industrialized systems. Advances within ICT has enabled an information layer to be added to transmission and distribution grids. The wide installation of smart meters and sensors has enabled the collection, storage and analysis data. Through using huge amount of data from electricity networks in combination with other information system, many benefits can be brought to the existing as well as future energy system [18]. However, for the opportunities to be realized there has to be data to enable the developments of data analytics.

On the one hand, there is The General Data Protection Regulation (GDPR) which was implemented during 2018 by the European Union (EU). GDPR is a law that requires organizations to uphold the privacy rights and safeguard personal data of anyone within the EU. The regulation includes eight privacy rights that must be facilitated and seven principles of data protection that must be implemented. It also empowers state-level data protection authorities to enforce the GDPR with fines or sanctions [19]. The new law has had visual impact on energy data and its availability. The transition to stricter data laws has led to data becoming increasingly securitized and less open. Previously open databases have been taken down and sharing of data is kept to the minimum, even within companies and organizations. Nonetheless, the intention behind GDPR is not to hinder data from being used but rather to make sure data is used for the right reasons with consent from the owner. Moreover, aggregated, anonymized data is not covered by GDPR restrictions.

On the other hand, all DSOs are obligated to log data hourly wise consumption data since 2009 [20]. Even though this consumption data, currently, is mostly used for economic purposes (billing), it is yet to reach its full potential. The collecting of data is thus already in place. As Vattenfall has the ambition to become fossil free within one generation, utilizing time series can be one way of making it happen. For the DSOs to be part of the transition to a fossil free and modern Swedish energy market, much can be done when it comes to data driven modelling of future trends to understand their impact on the grid. Data driven refers to that progress in an activity is compelled by data. To work data driven means to unify statistics, data analysis and their related methods to analyze and understand a phenomena in order to extract knowledge or insights from data [21]. The DSOs have great potential to utilize existing data and transition to smart, automatized actors who are prepared for future outlooks. In extension to being prepared, DSOs could be the enablers of upcoming technology. For example, for an increased share of small-scale solar power production, use of Electric Vehicles (EVs) and flexibility at household level to be realized, the DSOs should not only be ready for this kind of change in customer behavior, but also act as the encouraging and supportive business for the customers.

To sum up, there are many benefits to be derived from using data. Even if the physical meters and data collection already exists, much of the potential is yet to be utilized.

3. Research Design

In this chapter the overall research design and general information about the project are described whereas the quantitative method is presented in chapter 6.

The study behind this thesis was conducted on behalf of Vattenfall R&D in Solna, in cooperation with Vattenfall Eldistribution. The original plan was to carry out the project on site during a 20-week period between February and June 2020. Due to the Covid-19 outbreak only the first 7 weeks could be carried out on site while the remaining weeks was completed remotely. The research included a combination of qualitative and quantitative methods.

3.1 Literature Review

The project was initialized by studying relevant previous research. The literature review consists of a main top-down structure, meaning that extensive national scenario reports were first examined and when certain trends and factors was mentioned in several readings, those trends were selected for further investigation. The reason behind reviewing scenario reports is due to the fact that previous prognoses and forecasts about future events show good accuracy within a time span of 10–15 years but tend to have lower accuracy looking at 30–35 years [22]. Also, scenarios have become an adequate method to deal with deep uncertainties through stressing the importance of multiple views of the future in the exchange of information about uncertainties [23],[24]. Since the scope of the project is wide and spans across many areas, the literature review could have been close to infinite. Consequently, reviewing relevant research and reports was a continuous process throughout almost the entire project.

3.2 Modeling

The model was developed alongside the literature review and all parts of the model are implemented upon conclusions drawn from the qualitative work of the project. The development of the model started with an investigation of previous model approaches and model frameworks. Departing from a study of energy model classification (see section 5.2), a type and structure was then chosen. The model was developed using Python. The reason behind this choice was the open-source nature and large developer community of the language in combination with Python being the most popular choice among data scientists [25],[26]. Additionally, personal taste played a part in the decision. To gain transparency and scalability as well as support further development, the code was documented and commented following the official style guide for Python code (see [27]). To favor scalability, the model was built using an object-oriented programming style where each class represented a tangible part of the local grid. An in-depth description of the model and the accompanying data can be found in chapter 6.

3.3 Individual Contributions and Responsibilities

The project was carried out through a continuous collaboration between two students and the work was evenly divided. Karin, with an IT systems profile, carried out the main parts of quantitative work; including programming the model and preprocessing the data. Frida, with an energy systems profile, is behind most of the main qualitative parts; finding appropriate data, conducting the literature review and mapping out energy trends. How the different trends were modeled as well as how scenarios were composed was developed cooperatively. Moreover, evaluation as well as interpretation of the results was conducted in common and the thesis was jointly written and processed. All parts of the thesis are fully backed by both authors.

3.4 Limitations

The project revolves around a critical part of the Swedish infrastructure. Therefore, most of the data as well as previous developed grid models are security classified or under GDPR regulation. Since the project aims to derive a data driven method, access to data is vital. Hence, lack of data becomes a limitation. While Vattenfall Eldistribution is a large company, it is not yet fully data driven. That entails that mechanisms such as data catalogs and APIs are not in place to make data well documented and easily accessible for authorized users. Even though Vattenfall Eldistribution already gathers much relevant data that could have been leveraged within the scope of this thesis, data was oftentimes not available. The great number of employees at Vattenfall Eldistribution requires a lot of security measures but while the level of data maturity is still not high, the access to data was restricted. Additionally, as data is often viewed as resource or a competitive edge, obtaining data from third-party sources was challenging even when data was non-confidential.

The project was carried out during the spring term 2020 when there was an outbreak of the pandemic virus Covid-19. The pandemic implicitly had a negative effect on the project by mainly the governmental guidelines of social distancing. The business, as well as the academic, climate were stressful, as employees made rough priorities among skype-meetings and limited work tasks to the necessary. Lastly, the project was limited by what could be achieved within the given timeframe.

4. Literature Review

This chapter reviews a selection of reports and scenario studies that concern the future Swedish energy system. In the first part of the chapter focus lies on how the national Swedish energy consumption could develop until 2050 and underlying causes. The second part of the chapter examines four national scenarios of 2050 by Energimyndigheten. The scenarios are explorative with distinctive social and political directions, resulting in extensively different energy systems. The third section of the chapter highlights the translation into local level and impact on the DSO through an end user scenario. The chapter lastly covers a more in-depth section, about significant trends derived from the initial three sections of the chapter.

4.1 Future Electricity Consumption 2040-2050

Kungliga ingenjörsvetenskapsakademin's (IVA) report *Future pathways - electricity* consumption [22] investigates how the power system could evolve looking at 2050 and what alternatives there are for future outcomes. IVAs' point of departure is how the need for electrical energy will develop as well as how customers can play a more active part on the future electricity market [22]. The report starts by highlighting how the electricity consumption has been relatively constant (120-140 TWh excluding losses) for the past 25 years [22]. IVA estimate the total future electricity consumption 2050 excluding losses to range between 128-165 TWh in relation to the current use of 126 TWh [8],[22]. In collaboration with Energiföretagen, the research project *North European Energy Perspectives Project* (NEPP), similarly to IVA, has developed an in-depth scenario analysis on how to maintain a secure electricity supply [28]. The results from NEPP's demand scenario show a similar increase in electricity consumption <u>including losses</u> at 2045 by more than 50 TWh (from today's 140 TWh to 190 TWh). Also SvKs long term market analysis estimate an increase from 140 TWh to 179 TWh [7].

IVA describes how the decarbonization of society as a whole affects the energy system and requires a transition of both energy production and consumption. Simultaneously, as society is becoming more digitalized, the use of smart IT-solutions will increase rapidly and consequently demand more electricity [22]. The IVA report systematically addresses how the consumption of electricity can change based on possible occurrences and events in Sweden and internationally. The factors deemed to be of greatest importance for the future electricity use in Sweden and are divided as follows:

- Economic development – including business development and structural transformation.
- Population development – with uncertainty in the assessment of the number of residents in Sweden by 2050.
- Technological development – continuous improvements and technological inventions and innovations.
- Political decisions and policy instruments – having a direct and indirect influence on the future electricity consumption.

Both IVA and NEPP estimate that the decarbonization will increase and that the current already low use of fossil fuels will be completely phased out by 2040, resulting in new fossil-free activities being facilitated through an increased electrification [22],[28]. The NEPP report presents three different scenarios with diverse conditions and production alternatives. The scenarios are based on important trend factors that are likely to have an impact on the development of electricity use. The scenarios are; 1) 100% fossil-free renewable electricity, preferably central, production; 2) 100% fossil-free and renewable electricity generation with a greater proportion of decentralized production; 3) 100% fossil-free electricity production with both renewable and nuclear power production. NEPP argue that the energy sector can cope with an increasing demand for electricity in different ways, depending on the production alternatives available. Both NEPP and IVA agree on some specific future trends that are underlying factors which causes the increased electricity use. The trends which contribute to an increasing consumption are electrification of the industry and transport sector, more data centers, an increase of electrified heating solutions, and population growth [22],[28]. However, IVA explicitly states, in addition to population growth, a continuous urbanization. On the contrary, there are also trends which decrease consumption such as energy efficiency actions. In addition, an increased amount of DEGs, demand side flexibility and energy storage solutions are mentioned as important trends [22], [28]. While the NEPP report is mostly focused on fossil-free electricity generation meeting demand, it also presents a quantification of needs for new and reinforced transmission and distribution systems [28]. Significant reinvestments in the electricity grid are required, regardless scenario. Another aspect that is taken into account is Sweden's electricity system as an integrated part of the Nordic and European electricity systems implying the issue of securing a robust power system [28].

To summarize, the two nationally focused scenario reports bring up some key aspects that concern the future power consumption. The essence here is the relationship between large scale national trends and local impact. Some of the trends are derived from the local grid i.e. EVs, demand side flexibility, energy storage, energy efficiency or DEGs. Other trends have impact *on* the local level but departure from changes in larger sectors i.e. electrification of the industry, an increased amount of data centers or the process of urbanization.

4.2 Explorative Scenarios – Four Swedish Energy Systems at 2050

The Swedish government has a long-term goal of a sustainable and resource-efficient energy supply with no net emissions of greenhouse gases by 2050 [29]. Related to that goal, Energimyndigheten initiated an inquiry about challenges, possible choices for the future national energy system titled *Four futures – The energy system after 2020* [29]. Based on different strategic choices and priorities, four explorative scenarios were constructed and thought to show some conceivable development paths for the Swedish energy system [29]. The report takes off from a national perspective where priorities for the future energy system is based on societal development and political decisions [30].

The scenarios are fundamentally influenced by global conventional trends. Among the global trends are increasing global warming and natural resources scarcity as well as more global focus on environmental-, nature- and health related questions. Also, an increase and development of globalization, digitalization and technology and lastly, the global shift from people living in poverty to more highly educated populations, are mentioned.

In the first explorative scenario named *Forte,* energy is a catalyst for economic growth and prosperity. The energy policy is focused on a reliable and stable supply of energy and electricity at low prices to ensure a continuous growth for the industry. The scenario is not far from the present Swedish energy system with large centralized electricity production units that serves the passive customer. In Forte, the environmental impact of the industry can only decline on the premises that it does not affect the competitiveness of the industry. While the total energy consumption is unchanged, the total electricity generation is slightly higher than today, and the share of renewable energy production is 50 %. The expanded industry sector in Forte contributes with more waste products which favors the sector of DH. New investments in nuclear instead of renewable power production are made in order to cope with the global climate goals but electrification of the vehicle fleet as well as decarbonization of other sectors are unprioritized questions. [29]

In scenario two, *Legato,* energy is seen as a scarce resource globally that should be shared equally. The focus in Legato lies on global justice and ecological sustainability. The wealthier countries like Sweden are transitioning to a simpler lifestyle in solidarity and out of environmental reasons. The economy is based on a circular system and the consumption of energy has declined vastly in the industry as well as in the individual households where travels has also declined. Large investments are made in energy efficiency and R&D to enhance the transition to a more sustainable, biomaterial-consuming society. Politics has a strong climate focus centralizing the CO2-tax. Fossil fuels as well as nuclear power have been deprecated since 2030 and policy instruments like green certificates are in place to promote the development of renewable energy, especially wind power. The power system is moreover characterized by long-term sustainability. [29]

The third scenario, *Espressivo,* describes a Sweden where energy is a mean of expression and individualism and energy policies is characterized by new services and trade, facilitating self-production and decentralization. The total energy use is similar to today, but the distribution between different types of energy and how the energy market is functioning has undergone major changes. The energy system is characterized by a high degree of flexibility and individual solutions. The freedom of the individual is central in the political discussion and focus lies on diversity and individualism centering small collaborative societies. Single households wish to manage their own production and consumption of electricity since it is seen as more efficient and progressive. Many people live in low-energy houses and drive EVs, but governmental environmental and climate issues are prioritized secondary to individual choices. Technological development is speeding up and digitalization enhances new services. The energy system consists of numerous microgrids and many people choose to disconnect themselves from the central grid. Small and local spot markets are becoming more common and local residents have great influence on investment decisions regarding local energy systems. The energy market and Nordpool is connected to Europe but is mostly used by the industries and service sector. Those sectors go together and invest in combined heat and power systems and small modular nuclear. [29]

In the fourth scenario, *Vivace*, energy is a catalyst for socioeconomical growth. Sweden is a global pioneer within green tech and the political focus lies on innovation, demonstration and commercialization of modern environmental innovations. Politicians have moreover a strong mandate to initiate change and technological innovations are sold on the international market. The electrification of the entire society is central, and the state finances high-speed trains connected to the rest of Europe. Forestry and bio-refineries make up a large part of the industry and larger national interests are given higher priority than municipal and local interests. A big part of both the energy system and society as a whole is centralized governed and digitalized. The industry is formed by clusters where reuse of other nearby industries residual products is common and major investments in energy efficiency and optimization is done. Hydropower in Sweden is increasing, and an increased extraction of forest is being solved through high production zones with less biodiversity requirements. The battery is a key component in the new high-tech energy system and the Swedish battery industry is a player at the forefront. [29]

To sum up, the explorative scenarios are not supposed to give a clear and definite picture about the future, but rather function as a way to broaden the range of possible outcomes. The explorative scenarios touch upon the whole energy system from large scale production to end-user’s consumption. Through interpreting these scenarios on a local level, one can visualize impact of future trends on the distribution grid and hence compare different distinctive futures. A summary of Energimyndigheten’s four scenarios is found in Table 2.

Table 2 *Summary of Energimyndighetens explorative scenarios. [29]*

	Main priority	Key words	Governmental focus	Energy system	% of renew.	Demand side flexibility	Managing power peaks
Forte	*Energy is a catalyst for economic growth and prosperity*	*Industry Nuclear Economic growth*	*Industry & service sector*	*Centralized*	*50%*	*Limited*	*Strategic power reserve*
Legato	*Energy is a scarce resource that should be shared equally*	*Sustainability Circular systems Decreased consumption*	*Fast environmental transition*	*Renewable*	*~ 100%*	*Moderate to high*	*Centralized regulated*
Espressivo	*Energy is a mean of expression & individualism*	*Self-sufficiency, local solutions, New markets*	*Individual solutions*	*Decentralized*	*75%*	*High within individual systems*	*Local or individual responsibility*
Vivace	*Green tech is catalyst for socioeconomical growth.*	*Innovation, Technology Digitalization Batteries*	*R&D*	*High tech*	*~ 100%*	*High 100 % automatic*	*Market solved*

4.3 Future Local Scenarios and Their Impact on the DSO

In the report *End-user scenarios and their impact on the DSO*, Widén and Sandels describe scenarios on a local level [31]. Widén and Sandels analyze how various national changes at the local customer premises related to new behaviors and technologies could impact the DSO. The purpose of the investigation was to firstly, present a simulation model framework, secondly, define possible future customer pathways and key performance indicators to measure the impact on DSO and lastly, to present simulation results from both rural and urban distribution grid cases in Sweden. The customer-related scenarios that were used in the simulation and analysis were based on possible future pathways for the Swedish DSOs which per say were derived from global trends and the aforementioned scenarios composed by Energimyndigheten. Widén and Sandels uses the following trends for their scenario developments; 1) Energy efficiency, 2) Electrification, 3) Small scale production, and 4) Digitalization and flexibility [31].

For the simulations, the studied case was a Swedish municipality where data included: topics of geography, demography/socioeconomics, heating, electric demand, distribution grid, energy production, and ICT infrastructure. The model framework consisted of a clustering algorithm to categorize the customers based on their load data. The clusters with belonging information functioned as input to a bottom-up simulation (see section 5.2 for further explanation) load model that coordinated load profiles based on end-user behavior and weather situations. The load model included electricity use from; appliances, domestic hot water, space heating, electric vehicles, and production from local PV-installations. The model was also used to simulate flexibility from EV charge and space heating with respect to varying spot prices [32].

4.4 A Closer Look at Upcoming Trends

4.4.1 Electrification – Industry and Transport Sector

Numerous future scenarios declare that the demand of electricity will increase due to the ongoing decarbonization. Developing energy efficient technologies for heating such as efficient heat pumps in combination with carbon capture storage, warmer climate and more flexible consumption are thought to dampen this increasing electrification [22]. These diminishing actions can however not be taken for granted and electrification appears to be inevitable for a fossil free society. Three key trends are thought to have extra influence on the total electricity demand; 1) data centers, 2) electrified industries, and 3) electric vehicles [22].

During the last couple of years, an increasing number of electricity intense data centers have been established in Sweden. Globally, data centers and server halls stand for 2% of the CO2-emissions and 3% of the total energy consumption [33].Tech giants such as Facebook, Amazon and Google are currently establishing data centers in Swedish cities and are examples of new businesses that can be difficult to plan for in a timely manner, since the size can vary from 100 kW to larger data centers that require connection effects of 100-500 MW [34]. In comparison a medium-sized Swedish city have an approximate power demand of around 250 MW. The data centers offer a new income generating industry sector for Sweden and the advantages for the external tech companies are many; access to natural cooling, relatively low spot prices, heat recycling connections and fossil free power generation [35].

The industry stands for 40% of the total national energy consumption and 20-25% of the CO_2 emissions [36]. As part of the climate policy framework the emissions are to be reduced to net zero at 2045. Material and energy efficiency in industry sectors for petrochemistry, steel and wood pulp are proposed to reduce emissions. However, for major reductions electrification is required, as well as fuel exchange and possible carbon capture storage. For example, an electrification caused by production hydrogen instead of coal in the steel and iron industry would greatly increase electricity consumption. The model was also used to simulate flexibility from EV charge and space heating with respect to varying spot prices.

Currently, the transport sector is dominated by fossil fuel driven vehicles and the sectors' use of electricity is only 3 TWh [37]. Sweden's Climate Act and Climate Policy Framework have set the target that the emissions from domestic transport, with the exception of domestic flights, are to be reduced by at least 70% by 2030 compared to 2010 and net zero by 2045 [38]. To reach this goal, several approaches are on topic as potential solutions such as a more efficient IT-driven infrastructure and community planning in combination with the use of biofuels and electricity instead of fossil fuels. According to the IVA report about future pathways for electricity demand, a long-term sustainable transport system will probably be supported by both renewable electricity and biofuels, where the two function as complementary rather than competing [39]. Table 3 illustrates some of the opportunities and obstacles with an electrified transport sector.

Table 3 *Opportunities and obstacles with an electrified transport sector.*

Condition	Opportunity	Obstacle	Influences
Light weight vehicles		X	*Efficiency, battery lifetime,*
Heavy-duty transportation		X	*Efficiency, battery weight,*
Energy demand	X	X	*Current high energy supply. Weather dependency after nuclear decommissioning.*
Infrastructure		X	*Access to charging stations*
Interest	X		*Energy- and environmental targets, local environmental impact (noise/ emissions, travel distance limit*
Economy	X	X	*Unsecure and heterogenous policy instruments, uncertain sport price, continued cost reduction.*
Regulations	X	X	*Policy- and decision makers*
Electricity grid	X	X	*Potential local grid problems. Increase of variations in consumption e.g. grid congestion/ lack of capacity due to simultaneous charging.*

Table 3 visualizes the complexity of electrifying the transport sector. Many factors need to be taken into account and the subject concern both the government, large parts of the national infrastructure, businesses and end-users. Of the new produced vehicles, the 11559 registered EVs currently stands for 2,16 % of the total market share [40]. The prognosis for EVs points in a different direction and according to Powercircle, EVs are predicated to dominate the new car sales market by 2026 and cover 90 % by 2030 [38]. There are different types of EVs, the main typed are chargeable electric vehicles and plug in hybrid electric vehicles. The later currently stands for 65 % of the market share and former for the remaining 35 % , although Powercircle estimates that chargeable EVs will dominate the market by 2025 [40].The capacity of EVs moreover range between 0,2 and 0,153 kWh/km [41] . Lastly, an electrification of the vehicle fleet will have influence on the grid. However, the charging and use of EVs can either be compatible with the existing load profiles and even out the power demand. Contrariwise EVs could also worsen critical load peaks. When the EV is used as an active component in the electricity grid, it is called Vehicle to Grid [42]. Vehicle to grid is a broad concept and means that the battery in the electric car can supply power to the grid, making the charge is adapted to local conditions. In this situation, the car communicates with the charger - which in turn communicates with the grid operator, an aggregator that aggregation the total loads from the EVs and the network owner. Together these actors control the energy flows in a way that optimizes the customer's benefit based on far more parameters than just time, main fuse and electricity price [42].

4.4.2 Energy Efficiency

Energy efficiency is often expressed as an increased utility with existent energy consumption, or existent utility through decreased energy consumption. Up until now, energy efficiency has been a combination of the two. Continuous efficiency actions and development in technology have resulted in a stagnation in consumption despite electrification and population growth. In Figure 2 the CO2-emissions in metric tons per capita in Sweden is presented, indicating energy efficiency leading to a reduction in consumption [43].

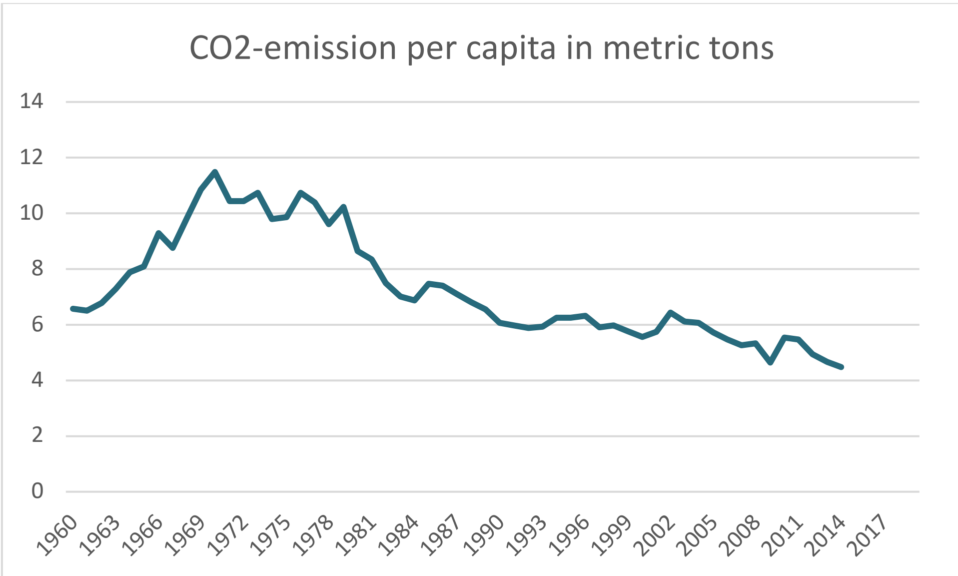

Figure 2 *CO2-emissions per capita in Sweden 1960–2014 [43].*

The factors driving energy efficiency in society can be divided into political, economic, technical and structural factors. Structural energy efficiency means that companies, unprofitable factories and production lines are closed down and replaced with more efficient ones. This also means that newly built houses are more energy efficient than old ones. So-called autonomous efficiency means that companies are constantly removing bottlenecks and increasing the utilization rate of their facilities, and that local owners and private individuals are replacing old products with more energy efficient ones. The EU 2030 climate and energy framework includes EU-wide targets and policy objectives for the period from 2021 to 2030. The key targets for 2030 include 30% improvement in energy efficiency [44]. Sweden has a goal of 50% more efficient energy use at 2030 compared to 2008 through a decrease in energy intensity [45]. Yet, energy efficiency can be difficult to measure and quantify.

Still, there are several ways to comprehend and quantify energy efficient actions. One example area which concerns the household customers is the energy use for heating. According to the directives of Boverket's building rules (BBR) buildings and premises and are obligated to not exceed limits set by BBR [46]. These limits concern for example existing residential buildings consumption through using the primary energy number which consist of geographic location, primary energy source (i.e. DH, electricity, fossil fuels), house area and energy consumption. In broad terms this means that new buildings are expected to have approximately 25 % less energy consumption than the already existing ones [46]. The BBR directives and the primary energy number thus gives an indication about the future energy consumption for both existing and new buildings.

4.4.3 Decentralized Electricity Generation

Presently, the Swedish power generation system consists mainly of large centralized power plants such as nuclear- and hydropower. These power plants have long operating times throughout the year and long-distance transfer of electricity to the end-users. The upcoming expansion of renewable electricity generation challenges the old centralized system with a larger number of, and more small-scale, decentralized plants with intermittent power production [47]. The transition poses a challenge for the future electricity system. As the weather dependent solar and wind power production is becoming increasingly connected directly to the distribution grids, the traditional electricity system faces new challenges in the grids as well as new market actors. New capacity investors and micro-producers can potentially create new demands for the electricity system and change the core structure as well as the conditions for both existing plants and new investments. In terms of the grid stability, the distribution grids must be able to cope with high voltage peaks and bidirectional power flows where "prosumers" both can consume or produce electricity [48]. Simultaneously, several studies indicate that the DSOs can manage the shift from centralized to decentralized power generation without balance and electricity quality problems if leveraging new technology [47],[48]. One of the studies, a master thesis project by Tobias Walla show for example that the DSO can cope with a very large penetration of solar power without facing power quality issues [49]. Since this project focus on the local grid level, only small-scale solar power will be further investigated while large scale solar power and wind are not taken into further account.

Solar power is believed to play a vital part in the transition to an energy system with more renewable power generation. Grid connected photovoltaic [PV] systems stood for approximately 0.4 % of the total Swedish generation 2019, but the market share is continuously and rapidly increasing [50]. The yearly statistics about PV-installations from Energimyndigheten, largely based on data from DSOs, shows that the amount of installed solar power in Sweden has increased largely between 2016 and 2019 from 140 MW to 700 MW [51]. Figure 3 show the recent growth rate. The PV-plants in Sweden be divided into three types based on installed power; <20 kW_p, 20-1000 kW_p and > 1000 kW_p. Most plants (84 %) have installed capacity of less than 20 kW_p and account for 46% of the total installed power [52].

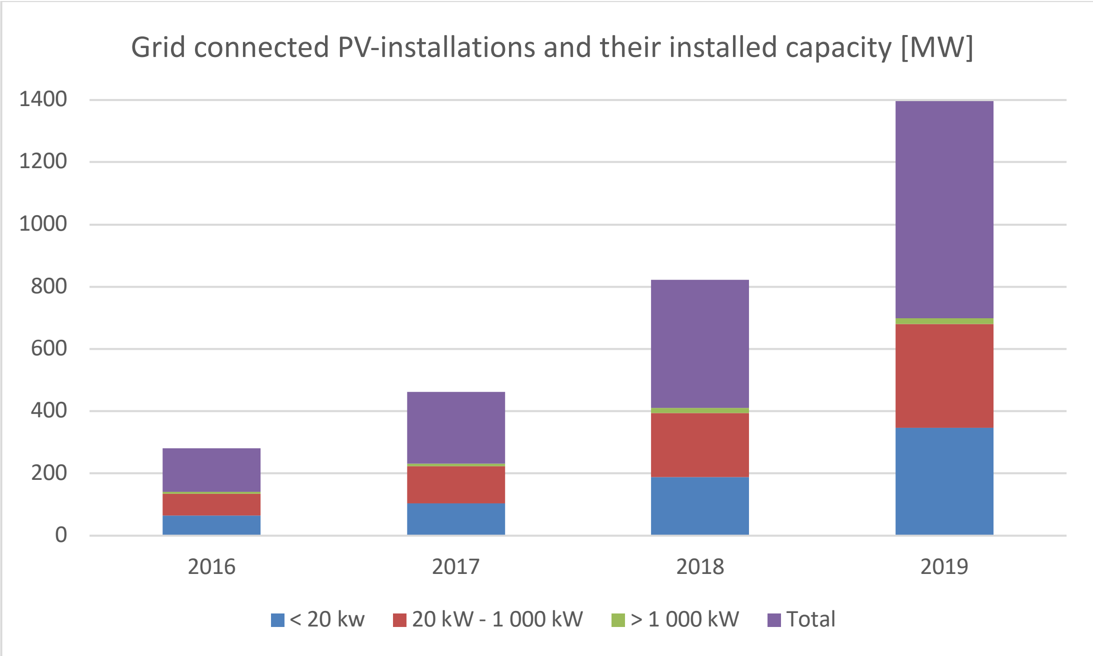

Figure 3 *Amount of grid connected PV in amount and installed capacity [51].*

Energimyndigheten has proposed that the share of PV-production in Sweden could reach 5-10 % of the total power generation and suggests an interval between 7 to 14 TWh in annual production by 2040 [53]. In an article by Johan Lindahl, representing Svensk solenergi, 10 TWh is estimated as a reasonable target for the Swedish solar power production 2040 [54]. Today's 0,7 TWh production is thus thought to increase by approximately 9,3 TWh [51]. There are moreover some obvious strengths and opportunities with solar power as an infinite and clean power source, but also obstacles and weaknesses. Table 4, inspired by an Energiforsk report [55], highlights some characteristics and comments on the influencing parameters regarding an expansion of solar power in Sweden. Currently, Nicholas Etherden at Vattenfall, in dialogue with Johan Lindahl at Svensk solenergi, has made an estimation of solar power standing for 1000 W per capita in Sweden by 2040 [56]. For a substation, that would mean that around 20-30 % of all buildings will have PV-installations. Since the size of PV-plants varies with building type (villa, apartment building or industry), it will however depend on development and pathway of the building stock. Furthermore, a substation can have different fuse types and the number of customers can vary from 1 to 1000 [56].

Table 4 *Opportunities and obstacles of PV production*

Condition	Opportunity	Obstacle	Influences
Renewable resource	X		*Efficiency, location, weather*
Variable production		X	*Location, weather*
Available surface	X		*Solar irradiation, scalability, roof barriers, renovation rate, land use.*
Interest	X		*Energy- and environmental targets. Individual independency.*
Economy	X	X	*Unsecure and heterogenous policy instruments, uncertain sport price, continued cost reduction.*
Regulations	X	X	*Policy- and decision makers*
Electricity grid	X	X	*Potential relief or problem for local capacity.*
System consequence	X	X	*Development of surrounding systems e.g. batteries, other external conditions.*

Theoretically, the potential electricity generation from solar cells, if all available and suitable rooftops in Sweden were covered with PV, is close to 50 TWh - which is equivalent to one third of the total demand [57]. One of the most important limitations with PV-production is the ability to convert solar energy to electricity in a cost-effective way. The interest in PV is continuously growing while the cost steadily decreases. An increased number of suppliers in combination with technological development and higher efficiency of PV components has resulted in a lower production price [53]. Nonetheless, PV-installations are presently relatively expensive even though market-based instruments are in place to reduce costs. The return on investment also depend on the spot price, which per say, is varying and relatively unpredictable, at least in a long-term perspective. The geographical location also affects the output of PV-installations. The solar radiation is higher for locations near the equator and is thus not optimal in Sweden from a global perspective. The radiation in Sweden varies between 750 kWh/m^2 in the northwest to 1050 kWh/m^2 in the southeast per year, measured on a horizontal plane [58]. Worth mentioning is that the radiation also fluctuates a lot from year to year which affect the yearly production. Another factor that is important to consider is that the PV-production curve, with a peak at mid-day, rarely corresponds to consumption pattern for a household. For households, the demand is greatest in the morning and in the late afternoon and evening. Businesses are on the other hand running during the day and are thus more compatible with PV-production since it can consume the generated electricity immediately and does not require energy storage to the same extent as households.

4.4.4 Energy Storage – Batteries

As the share of intermittent power generation is growing larger, the need for energy storage is increasing. Indeed, when the power production is uncontrollable and does not coincide with the electricity demand, energy storage can function as a contributor to maintaining a stable power system. The ability to store the surplus produced for later use when the need is greater than the supply can equalize the energy system and support the constant matching of production and consumption. Energy storage can also increase local penetration and self-consumption from small PV-installations at commercial facilities and at household level [59]. Depending on the type of power generation and the demand, different types of storage technology is required. An IVA report about energy storage states that the most common techniques for energy storage are hydropower, batteries, compressed air and flywheel energy storage [60]. Applications for energy storage varies but can for example be arbitrage, stabilization of conventional electricity generation, capacity firming, storage for non-connected systems, cutting power peaks in the industry or energy storage for household consumption [60]. Table 5, originally from the IVA report, show applications for energy storage categorized after operators and function in the energy system.

Table 5 *Applications for energy storage [60].*

Operators / Function	TSO / centralized storage	DSO / regional storage	Local consumer / household level
Balance in production and consumption	*- Seasonally/ weekly/ daily/ hourly variations - Geographical imbalances - Variations in intermittent production*	*Daily/ hourly variations*	*Daily variations*
Electricity distribution	*-Voltage and frequency regulation -Peak reduction -Power trading -International market*	*-Voltage and frequency regulation -Power trading - Capacity firming*	*-Aggregation of small-scale storage to support distribution -Arbitrage*
Energy efficiency	*Energy efficiency in the global energy mix*	*Load- and storage control for grid efficiency reasons*	*-Increased value of local consumption/ production*

Presently, the most developing and arising energy storage technology is the battery. A battery storage can for example be used in order to decrease grid congestion and delay future grid reinforcements. If the battery storage is used to obtain a more constant production from renewable electricity generation for a given period of time, capacity firming can be achieved. The battery store is then used to store the energy from the renewable sources during periods when they produce the most, whether there is a demand for electricity or not. The energy is then distributed as the production is unexpectedly reduced from the renewable production units in order to obtain a better balance in the electricity grid. [60]

Since batteries can be used for both large- and small-scale applications i.e. in industries or at household level and in EVs. The scalability in producing batteries enables a low threshold for widespread commercialization [60]. The recent fast development of the battery industry also implies that the cost level will fall similarly to the cost development of PV-systems. The energy storage in the EU is currently focused around small-scale applications, arbitrage and peak reduction with upcoming applications such as use in micro grids and home batteries in combination with PV-installations [60]. The growing market of PV-systems has made batteries more interesting as it has the potential to increase the utilization rate of self-produced solar energy. Batteries, as a complement to PV, are presently not a common occurrence on the Swedish market, although energy storage as supplement to self-generated electricity is subsidized and eligible since 2016 [61]. In Germany, the ambitious *Energiewende* program has laid the foundation for a PV+ battery market resulting in that every other PV-installation is now sold with battery storage system [62]. Correspondingly, it is expected that the large investment in R&D of EVs will favor the battery market as great focus is placed on the EV-batteries and the cost is expected to decrease [63]. The lithium-ion battery is a relatively new technology with an increasing market share. Most applications for battery subsidies in Sweden concern lithium-ion batteries even although lead-acid batteries currently have a lower price [61]. By the year of 2025 it is estimated that all EVs will have lithium-ion batteries due to its better performance – a development which will reduce the costs of lithium-ion batteries [63].

4.4.5 Flexibility

Flexibility is a wide concept that more or less means the power systems' ability to manage variations in supply and demand in order to maintain stability and balance [34]. As the Swedish energy system is facing an increased share of renewable electricity generation, flexibility is becoming a key concept and is seen as an important solution to the capacity challenge. With more intermittent power production and less nuclear, it will become more important to utilize all the available flexibility resources in the system, i.e. flexible production, storage and demand to ensure a continuous and secure electricity supply. These flexibility resources can be addressed from either a national or local perspective.

Energy Flexibility from a National Perspective

Table 6 indicates the magnitude of the future national flexibility need for different types of flexibility given a reference scenario from NEPP [64]. The need for regulating power per hour and per week refers to the largest variation of the net load from one hour to another, i.e. how much flexibility is needed to manage the hourly or weekly variations. The excess is the electricity produced from wind and solar power that is exceeding the demand. The peak load has moreover been divided into the need for flexibility for the most strained hour during a so called 10-year winter and as an average during the most strained 24 hours during a 10-year winter. The quantification in **Error! Reference source not found.** shows that the variations in supply and demand increases greatly at 2040 compared to today. The excess increase from 0 to 3 TWh which shows the great need for flexibility to avoid spill. Also, the peak load during cold days is almost 10 times more severe than today.

Table 6 *Quantification of the challenge with flexibility from NEPP [64]*

	Balance (hour)	Balance (week)	Excess	Peak load 1 h	Peak load 24 h
2018	2500 MW/h	7500 MW/w	0	-850 MW	+1650 MW
2040	4400 MW/h	14200 MW/w	3 TWh	-8000 MW	-5500 MW

Demand response flexibility, from here denoted as flexibility, refers to the possibility of changing energy loads during specific time intervals by exposing consumers to the correct signals [65]. Through demand side concerned customers can modify their electricity consumption based on different market signals. For example, consumers such as households or industries can provide stability and balance in the grid through being flexible in their use, i.e. by temporarily increasing/decreasing consumption or utilizing energy storage. There are generally two ways for a customer to capture the value of its flexibility potential. The first is to offer flexibility on different trading markets while the second functions through adapting consumption to signals. According to Energimarknadsinspektionen, the potential for flexibility is greatest for the industry and the household customers [66]. Presently, the industry sector is more prone to adapting flexibility actions due to a higher sensitivity to fluctuations in spot price [66].

The Swedish residential customers account for a large share of the total electricity consumption, especially during the winter. The peak in the residential customers' load patterns pose great impact on the power grid, which causes an imbalance between supply and demand. Customers can provide flexibility through increasing their consumption when the electricity price is low and reducing consumption when the price is high. Amongst household customers, it is mainly those who live in detached houses with electric heating through direct electricity or heat pumps that can contribute with flexibility, making the potential of flexibility highly seasonally dependent [67]. Since heating accounts for the absolute largest share of household electricity consumption, households with DH have less potential to contribute with flexibility. Although, in a future scenario, if batteries are more common and the vehicle fleet is electrified, flexibility in terms of battery storage and EV-charging can concern a wider range of household customers.

Since flexibility among household customers has not yet been commercialized, relatively few studies about customer's motivation for flexibility exists. Energimyndigheten has gathered information from a handful of such studies and made some assumptions on how much different customers are willing to be flexible [66],[67],[68],[69]. However, the results from Energimyndigheten's report resulted in a statement that customers generally lack information about their potential for flexibility [68]. During a study about flexibility where the customers attitudes toward flexibility was examined, it turned out that only half of the asked respondents had a clear perception of the cost of electricity and only one out of four respondents was familiar with the concept of demand flexibility [67]. The study targeted customers with electricity as heating source as potential flexibility contributors. Out of those 50 % were willing to be flexible and participate in a pilot project where their peak load within the time span 17.00-19.00 during the coldest days of the year was reduced by 30 % [67]. The reduced consumption was then moved and spread out over the coming five hours after 20.00 [67]. Household customers could in theory steer their own load with digitalized and smart equipment. Appliances can for instance automatically turn off the heating system for a few hours when the spot price is advantageous, or the grid is congested, only to turn it on at a later time. Much of the equipment that is installed for energy efficiency can thus be used to move, alternatively temporarily increase or decrease the energy consumption. With smart technology flexibility solutions can easily be implemented without disrupting the indoor comfort [68].

Flexibility Solutions for Local Capacity Challenges

Currently, several projects are running targeting increased flexibility in the power system. A Sweco report addressing flexibility as a way to increase the grid capacity, mentions several projects with different initiating actors and diverse driving forces [34]. Among them are projects that targets local marketplaces for trading with flexibility, aggregators and dynamic grid tariffs [34].

Uppsala region currently undergoes congestion in the national grid while continuously receiving capacity requests from various stakeholders, a challenge which is limiting the city growth [70]. The EU-funded project CoordiNet where Vattenfall is involved, has established a local marketplace for flexibility where flexible actors can there bid to temporarily reduce or increase their consumption/generation when the DSO sends a signal to do so [34]. The project has so far combined a total of about 85 MW of flexibility for different customers [34]. All the flexibility can however not be used simultaneously, and it contributes with different impact to different network needs.

With a flexibility market, a local energy system can be used more efficiently through reducing power peaks in the grids. However, it is difficult for small, individual electricity users such as households and smaller businesses to participate in the market themselves. A report about aggregators on the Swedish power market from Sweco, states that aggregation is a prerequisite for capturing the flexibility among household customers [71]. An aggregator remotely controls the electricity consumption in consultation with the customer. If there is a bid limit for the minimum power volume that is difficult for small electricity users to achieve. Instead, they can join a so-called aggregator, which gathers several small electricity users in a joint bid, and through it participate in the trade [71]. For example, Fortum and Fingrid performed a pilot project where they as an aggregator steered the boilers of 100 households and used the aggregated volume as a resource on the balance market [72]. Aggregating multiple flexible sources enables that the total volume can be used as a product on a local market where lack of capacity is an issue. Depending on market model, and energy service (e.g. demand response, production, energy storage), the aggregators can potentially trade and make profit from the flexibility market [71].

Dynamic grid tariffs function as a kind of incentive where for example a DSO send the customers price signals that reflect system conditions in a distribution grid [65],[73]. Grid tariffs are the fee that the customers pay to the utility companies for supplying electricity. A time-based tariff structure can be either static (e.g., tariffs determined in advance) or dynamic. The reason behind designing the electricity grid tariffs more dynamically i.e. making them vary over time, is to give customers incentives to be more flexible. Tariffs determined in "real time" based on the actual system conditions include real-time pricing, variable peak pricing and critical peak pricing [65]. If designing a system with time-of-use varying price signals, they can for example be determined based on the local distribution system balance or on short-term market price signals such as day-ahead or intraday price signals [65]. In Figure 4 visualization of the difference between static and dynamic market signals is presented.

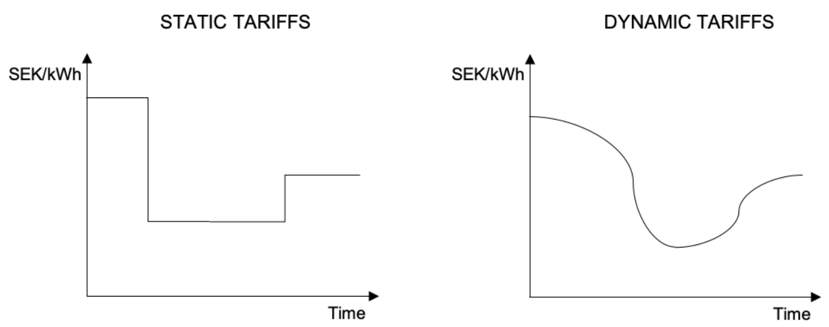

Figure 4 *Difference between static flexibility (left) and dynamic flexibility (right).*

In summary, flexibility cannot be defined as one specific function. Flexibility could be implemented via individual customers or aggregating actors, who trade flexibility, but will rely on smart solutions and economic incentives. It is however clear that some kind of flexibility will play an important role in the future capacity challenge.

4.4.6 Digitalization and Smart Grids

As the societal development become more characterized by digitalization, automatization and smart ICT-solutions, so does the surrounding sectors. The Swedish climate and energy targets pose new demands on the power grid where digitalization and smart grids are thought to play part in the solution. Smart grids can enable integration of renewable decentralized production, increasing flexibility as well as customers functioning as active participants on the electricity market [74]. The concept of smart grids covers many areas such as:

- Integration of renewable and decentralized production.
- Technology for improved transmission and distribution.
- Real-time monitoring and control of electricity grids.
- Advanced Measurement Infrastructure (AMI) and internet of things.
- Customer systems for flexibility and energy efficiency.
- Storage and charging infrastructure for electric vehicles.
- Integration of ICT and cybersecurity.

The concept of smart grids applies to almost all levels of the power system. Within transmission and distribution, smart grids can improve efficiency and reduce energy losses as well as gather real-time information from sensors and devices for a number of functionalities. An Energiforsk report about opportunities for future substations identifies four different types of substations that can become reality in the near future [13]. The substations are divided into different types depending on their ability to be intelligent i.e. think, control and measure. A basic substation is safe, green, cost efficient, do not require maintenance but does not communicate. An intelligent substation is on the contrary autonomous with high precision in distribution functionality and can perform high degree measurements and analysis, take decisions and has activation ability [13]. Regarding the challenges with integration of decentralized renewable energy sources, smart grids can contribute through an automated control and regulation of production and demand. The AMI-technology can moreover give system operators and customers and systems better access to data through the use of smart meters. A smart grid ecosystem is an enabler for capturing the full potential of functions such as energy storage systems, demand side flexibility and smart charging infrastructure for EVs [74].

4.4.7 Market Based Environmental Policy Instruments

Policy instruments is a linkage between the formulation of a policy and the policy implantation. In the energy sector, policy instruments function as tools to steer the energy market in a desirable direction, for example, to guide decisions, overcome problems or achieve objectives. The energy related policy instruments are divided into, financial (e.g. energy tax and PV-subventions), administrative (e.g. building directives and environmental permits) and informative (e.g. municipal energy guidelines). The ideal policy instrument aims towards a set target, is socio-economically profitable, without any negative side effects. Some current policy instruments are; the CO2-tax, the bonus malus system for vehicles, subventions for PV-installations and energy storage, green electric certificates and greenhouse gas emission allowance trading. [75]

4.4.8 Demography

It is easy to imagine that demographical trends have an impact on the electricity demand. A larger population would logically entail a larger electricity consumption per capita. However, due to energy efficiency actions this has not been the case and the consumption has remained at almost the same level since the 1980s [8]. Nevertheless, the population is an important indicator for future energy related planning purposes. The Swedish population, visualized in Figure 5, is predicted to increase from today's 10 million to almost 12 million at 2050.

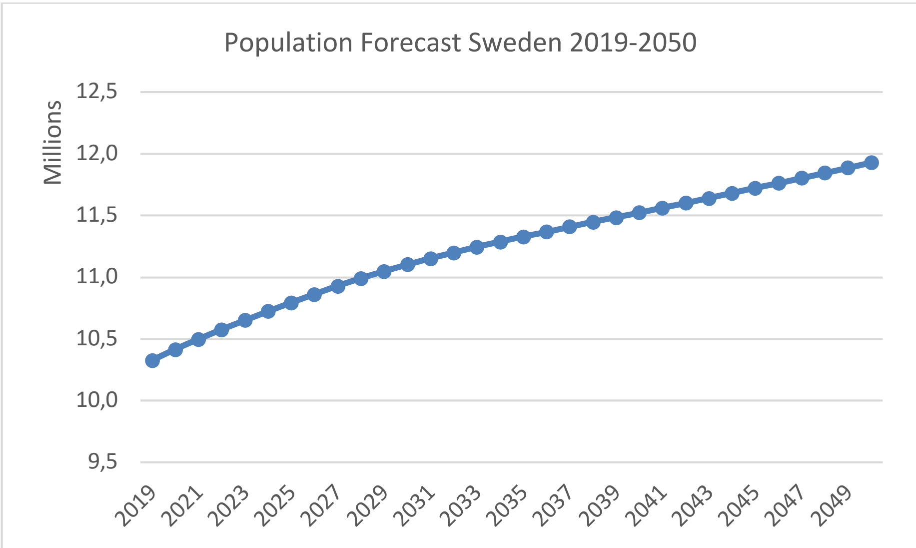

Figure 5 *The Swedish population forecast from SCB [76]*

Before the first industrial revolution, 90% of the people in Sweden lived on the countryside. Nowadays, 85% live in cities and the percentage is increasing. The process of urbanization has gradually put more pressure on the grid and grid power capacity as more customers must share an already dimensioned grid. The relative population development also shows a continuous urbanization, especially in Stockholm with its surrounding area [22]. According to the report about the future electricity consumption by IVA [22], new residential buildings are expected to install electricity-based heat pumps as heating source which in turn increases the power consumption. Also, urbanization means the grid around the rural areas will provide fewer people and thus become more expensive for those who remain [22]. Figure 6 shows the relative population development, the green areas refer to urban regions while the pink and orange areas refer to more rural areas with less population.

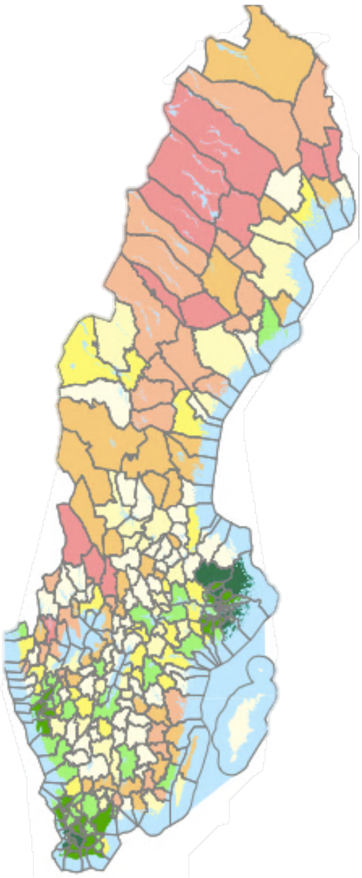

Figure 6 *Relative population development. Green marks heavily populated regions, while pink indicates lest populated regions and yellow and orange the in-between. [22]*

4.4.9 The Impact of Future Climate Change

How the global climate change will impact the Swedish climate exactly in 20 years is hard to predict. On the contrary, it can be argued that weather and temperature have impact on the grid. For example, during an extra cold winter, the heating demand increases and indirectly affect the electricity demand. How widespread effects to expect depends on several factors, including for example global energy consumption and population growth. A climate scenario for 2040 by SMHI shows that the average temperature is expected to increase mainly in the winter, but spring and autumn are also likely to be milder [77]. The snow season is expected to be shorter and heat waves with more than 25°C for several days in a row will occur more regularly. The number of sun hours during the period from June to August is not expected to change significantly. However, more rain during the winters is expected and some data simulations indicate drier summers, which affect the level of water in the hydro power reservoirs. However, trends from the past 15 years suggest increased rainfall during the summer. The sea level is moreover likely to rise, and the risk of extreme weather phenomena is expected to increase. This type of extreme weather can potentially impact the grid through the DEGs' weather sensitivity [77].

5. Theoretical Points of Departure

This chapter introduces theories, relevant concepts and vocabulary that are to be used throughout the whole thesis and in particular in the later discussion.

5.1 Scenario Construction

To envision the future and prepare for the upcoming unknown challenges, it is a necessity to also cope with uncertainty and risk. When faced with complex future challenges that either goes far beyond the reasonable imagination of an individual or when personal biases are too great of a risk, there is reason to systemize the way of approaching the future. One way of doing that is using scenarios as an approach to future challenges. The method or which type of scenario that is most suitable differs and depends on the purpose, what is it that we want to obtain with knowledge about the future. The aim could be to gain understanding, to predict or prepare, or to shape and affect. [78]

According to Börjeson et. al. [79] there are three main categories of scenario studies. The categories are based on the principal questions that the investigator wants to pose about the future; *what will happen? what can happen?* and *how can a specific target be reached?* In addition to these principal questions, two supplementary aspects of the studied system need to be considered to characterize the scenarios. The first regards the concept of system structure i.e. the connections and relationships between the different components of the system, and the associated constraints and conditions. The second aspect is the distinction between internal factors that can be controlled by the investigating actor in question and the external influencing factors. Predictive scenarios usually consist of two main types distinguished by the conditions they pose on possible future events. For instance, forecasts respond to the question *what will happen* on the condition that the likely development unfolds. What if-scenarios on the other hand respond to the question *what will happen* on the condition of some specified events. The question *what will happen?* can thus be managed using predictive scenarios looking at trends, extrapolations, historical data, use of smart algorithms etc. Examples of this is forecast of growth, rate of interest, weather, sources of primary energy and demography to mention some. In summary, predictive scenarios strive to describe the most likely outcome. [80]

The second question *What can happen* is often not treated just quantitively but also qualitative using explorative scenario methods, a concept holding several types of possible scenarios. For example, contextual scenarios, external scenarios and strategic scenarios. The fundamental difference here lies within the possibilities carried by the investigator in question and its capability to affect the development that is to be studied. External scenarios focus on just the external, that lies beyond the investigators control. When internal factors are included and interact with the external, strategic scenarios can be used as a suitable approach. The combination of predicative and explorative approaches is common when studying "what if" scenarios. The point of departure is the predictive approach, assuming that predictiveness exists for a certain event. The explorative approach is expressed as variations in parameters belonging to the predicative approach or trend disturbances that requires adjustments of the predictive model, i.e. new preconditions for continuous prediction. [80]

Lastly, the third question *how a specific target can be reached* is more often answered using backcasting, i.e. a method reaching working from future to present. The most significant difference between predictive and explorative approaches lies not only within the purpose and the questions that needs to be answered but rather in how to cope with uncertainties. Qualitative predictive scenarios often reduce uncertainties early in the process with help from statistical methods and good, reliable data. The explorative approach is more characterized by uncertainties and aims at reflecting them. [80]

5.2 Energy Modeling

Energy modeling is a prerequisite for preparing and a source of strategic insight for energy related future events. The ideal energy model can explain the impact and consequences of today's decision on tomorrow's energy system and its effect on the economy, the society and the environment. It can also describe strategic pathways that enables decision makers and relevant stakeholders to meet future obstacles and challenges. Coping with uncertainties and including transparency is also vital for energy modeling where transparency especially is a necessary condition for reproducible and credible studies [24]. In this context, transparency means that the necessary information to comprehend, and perhaps reproduce, the model results is adequately communicated by the authors of the study in question [24]. There are several ways to construct energy demand models. N. Van Beeck provides an insight on suitable models for a certain purpose through examining differences and similarities between models resulting in a categorization and classification [81]. These nine components of classification are; general and specific purpose, model structure, analytical approach, underlying methodology, mathematical approach, geographical and sectoral coverage, time horizon and data requirements [81].

The *general purpose* reflects how the future is addressed in a model. For example, it could be to predict or forecast, to do explorative scenarios, or to preform backcasting. The *specific purpose* is the focus points of the model such as energy supply/ demand, impacts or appraisal of options.

The *model structure* composes endogenous parameters, i.e. embedded assumptions in the model, and exogenous parameters, i.e. external assumptions to be determined by the user. The model structure can furthermore be characterized by four dimensions. The first is the degree of endogenization where predictive models have endogenous parameters while backcasting or exploring models use exogenous parameters. The second dimension is the extent of details about non-energy components in the model such as financial trade, goods, services etc. More details mean more accuracy for analyzing effects on for example the whole economy. The third dimension concern the coverage of details about the end-users. As for the previous dimension, more detailed information about end-users implies better local accuracy suitable for e.g. models analyzing energy efficiency actions or penetration of EVs. The last dimension concerns the extent of the description of energy supply technologies. In order to perform an analysis of e.g. technological potential of fossil replacements or new supply technologies, thorough details about technologies are required. In summary, the four dimensions illustrate the broadness of the energy sector and point out how one can choose to include a certain extent of details depending on the purpose of the model. [81]

N. Van Beeck furthermore states that there are two fundamental *analytical approaches* of energy modeling; the top-down macroeconomic approach and the bottom-up engineering approach [81],[82]. The top-down model uses high-level information about the whole economy. The approach starts with the big picture and then breaks it down into smaller segments. An overview of the energy system is formulated specifying subsystems but not in detail. Through analyzing the interaction between the energy system and other production factors that affect economic growth, it focuses on the possibilities to substitute different production factors in order to optimize socioeconomic developments. Top-down methods moreover regards technology only as a set of techniques by which inputs such as capital, labor, and energy can be transferred into useful outputs. On the contrary, the bottom-up model requires a comprehensive inventory of technical aspects of the energy system, as well as the energy consumption patterns and how they can develop in the future [81]. A bottom-up approach can visualize more complex systems through piecing together subsystems to an entity. The bottom-up method is independent of observed market behavior and focus on the techniques, performances and direct costs of technological options. The bottom-up method often analyzes individual foundational segments of a system in great detail. These segments are then put together to shape larger subsystems, which then in turn are linked until a complete big picture is created. Bottom-up approaches generally ignore existing market constraints, while top-down methods are based on market behavior. Not surprisingly, the two methods can be combined into a hybrid approach depending on the purpose and the underlying methodologies. Common *underlying methodologies* are econometric, simulation, optimization, economic equilibrium and backcasting. Furthermore, N. Van Beeck brings up some *mathematical approaches* that can be used for energy modeling, among them are linear and dynamic programming [81].

Additionally, N. Van Beck empathizes the importance of the *geographical and sectoral coverage* when deciding energy model approach. Examples of national models are top-down macro-econometric models while regional and especially local can take on a bottom-up approach often focusing at a particular site. Models covering a global or national level generally require highly aggregated data and often comprise a simplification of major energy sectors in order to address macro-economic linkages between those sectors. Models on local level generally require a bottom-up approach using disaggregated and detailed data. The *time horizon* also plays a vital part in energy modelling. Even though there is no exact definition of time horizons, some overlapping intervals less than five years are considered short term, 3-15 years medium term and 10 years or more is considered long term. Even though there is no exact definition of time horizons, some overlapping intervals are identified. Intervals of less than five years are considered short term, 3-15 years medium term and 10 years or more are considered long term. The time horizon is of importance since various social, environmental, economic features behave differently depending on the time scale which per se determines the structure and objective of the model from the very beginning [81].

Lastly, *data requirements* are considered. While some models require quantitative data of cardinal type, others demand ordinal or qualitative values expressed in various units. Moreover, data is not always reliable or available and can be aggregated or disaggregated. For long-term national models, highly aggregated data is often used with a low degree of granularity in technological detail. Detailed data is according to N. Van Beeck only possible in models that are specific for a certain energy sector. A summary of the classification and characteristics of energy modelling is shown in the Table 7 and the parameters used in the later developed model is further presented in section 8.2.1.

Table 7 *Classification and characteristics of energy modeling [81]*

Classification	Characteristics
Purpose	*General: forecasting, exploring or backcasting.* *Specific: energy demand, energy supply, impact, appraisal, integrated approach or modular build-up*
Structure	*Degree of endogenization, description of non-energy sectors, description of end-uses, description supply technologies.*
Analytical approach	*Top-down (economic) or bottom-up (engineering).*
Underlying method	*Econometric, macro-economic, economic equilibrium, optimization, simulation, spreadsheet/toolbox, backcasting or multi-criteria.*
Mathematical approach	*Linear programming, mixed-integer programming or dynamic programming.*
Geographical/ sectoral coverage	*Global, regional, national, local /* *Individual projects, specific energy sectors or overall economy.*
Time horizon	*Short, medium or long term.*
Data requirements	*Qualitative, quantitative, monetary, aggregated or disaggregated.*

5.2.1 Representation of Demand and Consumption

Information about how much electricity is used has always been a requirement at the DSO level in order to operate, dimension and maintain the grid [83]. Traditionally, the power consumption for each load and customer has not been possible to measure and aggregate with high resolution, meaning with great detail. Before investments in AMI and grids modernizations, data was a scarce resource and typical load profiles was generated by segmenting customers into categories. Information such as peak load is of interest from the load profiles, since it is used to design grid capacity and evaluate ability to allow new grid connections. Various mathematical methods have been developed to estimate the peak power load but considering the difficulties with for example approximating one customer's peak load coinciding with other customers, these methods are quite far from exact [83],[84]. The combined peak load of a system and is generally less than the total sum of the individual customer's peak load. To estimate the peak load output and the combined peak load aspect in order to dimension the grid, the Velander formula has been, and still is, a common method to use [5]. The formula estimates the customer's annual peak load in regard to the its annual total power consumption [85],[84]. The formula states that the peak power can be calculated with

$$P = k_1 \times W + k_2 \times \sqrt{W} \quad (1)$$

The equation consists of two parts associated with the annual consumption W. First a linear part related to the constant k_1. Second, a part proportional to the square root of the annual consumption associated with the constant k_2 which has a great impact on low energy consumption and decreases with high use. The two constants depend on the type of customer and location and while the constant k_1 is linked to the average consumption, k_2 is related to individual variations [84]. The Velander formula assumes the loads to be normally distributed and independent of each other. The method has been extensively tested and of good use for the DSO's because of its simplicity and tolerance of low-resolution data. However, the Velander formula does not take the time aspect into account and shows no correlation between customers of the same cluster, it has some obvious disadvantages expressed in overrated power output and exaggerated dimensioning of the grid [5],[84]. The time aspect is important since information about when a peak occurs is interesting. For example, if a peak occurs at winter it can be linked to higher heating (electricity) demand from the customers and a cooling effect on the grid lines implying less losses and more available capacity is. Moreover, the formula tends to not be compatible with new technologies. One example is more EVs on the vehicle market. Through comparing hourly measured consumption values with the power peaks calculated with Velanders', the formula gives an accurate indication of the highest power output. However, since EV charging changes the relationship between consumed energy and power with high but seldom peaks, the formula is not ideal for a future large penetration of EVs [84].

5.2.2 Load Profiles and Load Duration Curves

> "Beyond the increasing amount of data collected, the deployment of smart meters has changed the nature of the metering data from data points to streams of data. Hence, load profiling, that used to be computed on yearly meter reading and information provided by customers, can now be data driven. Furthermore, load profiling can take advantage of the stream nature of the metering data to provide more accurate information" – Le Ray [83]

As the deployment of smart meters becomes a more natural part of the distribution operations, it also enables a change in the paradigm of load profiling. Instead of estimating demand from a handful of arbitrary customers, information from streams of metering data can be summarized and presented with higher resolution [83]. Load profile prediction methods uses typical consumption behavior of loads to visualize an hourly representation of the power consumption.

A load curve, visualized in Figure 7 describes the consumer's electricity consumption for a certain period of time, usually a day, week or year. There are several different consumer types on the Swedish electricity market with varying consumption patterns over the day. The market sector of residential customers tends to use more electricity during mornings and evenings while other sectors such as commercial customers have a higher consumption during the day, typically following working hours. Load curves represent and aggregate these power load variations and the dissimilarities between different sectors result in diverse shapes of the load curves representing a certain sector. Load profiles on the other hand represent a typical customer segment. Load profile prediction is generally done through choosing loads with a certain facility label and then calculating the mean consumption for a certain day of the year. Through grouping customers based on their consumption patterns and comparing load curves, more cost effective and accurate analysis on issues such as peak demand, capacity dimension, planning, electricity prices etc. can be done with high resolution [83]. Conclusions can thus be drawn about when during the day the customer for instance, uses its self-produced solar electricity, charges an electric vehicle or activates several electric components simultaneously. Furthermore, can temperature and geographical location be added when designing models for load curves or load profiles.

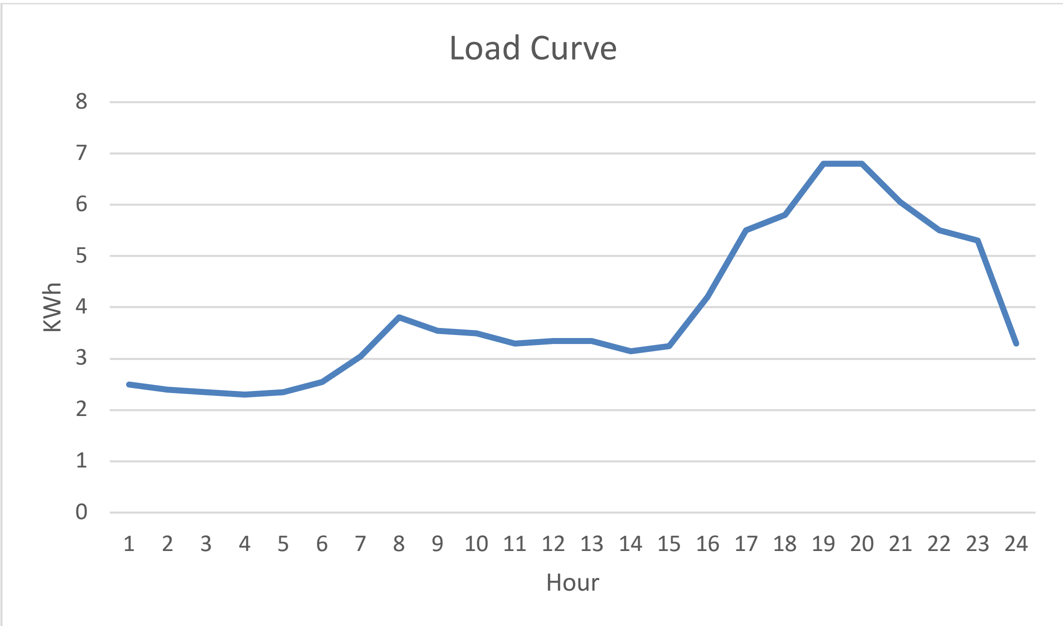

Figure 7 *Example of a household load profile.*

An alternative way to visualize a load curve over a year is to use a load duration curve, visualized in Figure 8. The duration curve shows the, in this example annual, consumption for 8760 hours but sorted in a descending or increasing order. The resulting shape shows the lowest and peak load during the year and how frequent these maximum and minimum values are. An ideal load duration curve for the DSO would consequently be horizontal because the consumption would then be constant and even. The peak is nevertheless important as the load curves are aggregated from different customers connected to the same part of the grid. The aggregated load duration curve of the result can be used to dimension the grid since it indicates the capacity need.

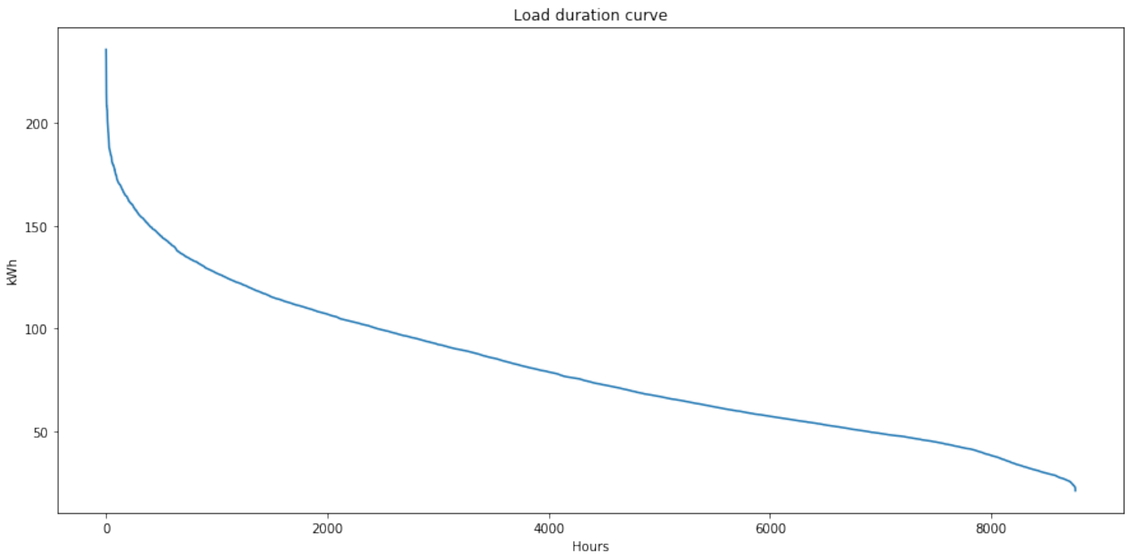

Figure 8 *Example of an aggregated load duration curve of several loads.*

6. Quantitative Method

This chapter describes the method used to build a flexible model that can visualize impact of future energy trends. First, the reasoning behind how the literature review was translated into local level scenarios is described. Secondly, the work concerning collection and construction of data is brought up. Lastly, the development of the model and how the different factors were implemented is explained.

6.1 Quantification of National Outlooks into Local Scenarios

In order to investigate what impact future energy trends might have on the grid capacity on a local level, scenarios based on the literature review were constructed. The scenarios were created to illustrate the local level of national scenarios but also to be implemented in the model in the end. The national scenario reports firstly implied an increased electrification as a result of an extensive decarbonization. This electrification refers to an increase of EVs, electrification of the industry sector and an increase of data centers. Secondly, the national scenarios anticipate population growth as well as a continuous urbanization, but also an increase of energy efficiency that is often seen as a dampening effect of the previous two, in terms of electricity demand. Thirdly, the national reports expect more decentralized intermittent production and energy storage. Lastly, the reports highlight enablers for the future energy system in Sweden i.e. smart grids, flexibility actions and market-based policy instruments.

In order to explore the local level of trends, the scenarios were created around a substation since this usually is a point of departure when working with long-term planning and prognoses at Vattenfall Eldistribution [16]. The constructed scenarios departed from a base case scenario that is supposed to visualize a no-trend state and function as a point of reference. The base case scenario is described in more detail in subsection 6.1.1. Then the four scenarios; *Forte, Legato, Vivace* and *Espressivo,* proposed by Energimyndigheten were used as a foundation for the local scenarios in this project; *Robust, Inclusive, Individualistic*. The factors and trends that were included in the scenarios are; PV-production, EVs, flexibility and energy efficiency accompanied by levels of smart grids and policy instruments. Since the local scenarios were to be implemented in the model, tangible numbers and values were needed. Often the national reports did not include specific numbers but rather stated for example 'a lot' or 'an increase of'. Therefore, the translation into numbers were often derived through discussion, rather than calculation, and can be regarded as subjective. The numbers were also set to differentiate the scenarios and to visualize distinctive characteristics among them. However, it should be remembered that the purpose behind the scenarios is not to describe the most probable future but to produce quantitative outlooks given key assumptions. Additionally, the scenarios intend to show the value and functionality of the transparent method and tool developed. Factors that were not included, but could be added by knowledgeable user, in the model are demography, urbanization, electrification of the industry and an increase of data centers. The energy storage trend is not exclusively targeted but is partly included in one of the flexibility implementations. These were left out for reasons which are further discussed in the section 8.1.6 and Appendix.

6.1.1 Base Case Scenario

The base case scenario was constructed through assembling a scalable substation containing different customer segments. The customer segments are; house, apartment and office. The three segments are sorted on heating source and if they are new or old. The substation is by default created according to the Swedish housing stock which consist of 55% apartments and 45% detached houses, according to SCB [86]. DH is often approximated to cover 50 % of the heating market. In more detail, approximately 20% of the houses have DH as heating source, 50% have electricity and 30% biofuels [87]. Of the apartments, 90% have DH and 10 % electricity as heating source. The same applies for offices where 90% have DH and 10% electricity as heating source [87]. Two offices were also included in the base case with heated area of 100m^2 & 500m^2. Since the collected data for offices and apartments only include buildings with DH, all office and apartment loads in the scenarios are modeled with DH. Besides the residential and office buildings, there are no trends added to the base case substation.

6.1.2 Assumptions About Smart Grids and Policy Instruments

The concept of smart grids as well as governmental policy instruments, i.e. taxes etc. are difficult to both quantify and foresee. These two factors were therefore included as a type of context and solely function as base assumptions within the local scenarios, making it possible to disregard them within the model. In order to make sense of the different types of energy systems in the future scenarios, smart grids and governmental policy instruments will be presented in scales of three levels. The first level means a low development whereas the third level is equivalent to a high degree of development. The three levels of smart grids are stated in Table 8.

Table 8 *Smart grid infrastructure.*

Level of smart grids	Description
1 *Low*	*Similar to the state of today. Substations, measurement equipment etc. has basic functionality, is modern, safe, environmentally friendly, cost efficient, do not require maintenance but does not communicate.*
2 *Moderate*	*A moderate smart grid. Substations, measurement equipment etc. has sensors and high measurement precision. The measured data can be sent to operation centers without remote operation. Substations has continuous measurement of current and voltage per phase and are controllable although it lacks some resources of analysis*
3 *High*	*A high technology smart gird. Substations, measurement equipment etc. is autonomous with high precision and functionality. The smart grid is part of large smart infrastructure with intelligent components that can perform high degree measurements and analysis including decision making and activation ability*

Similar reasoning can be applied to governmental policy instruments, found in Table 9.

Table 9 *Governmental and political influence.*

Level of governmental and political influence	Description
1 *Low*	*Low political influence, individual or local decision making, decentralization.*
2 *Moderate*	*Similar to today: Moderate political influence CO2-tax, bonus malus system for vehicles, subventions for PV-installations and energy storage, green electric certificates and greenhouse gas emission allowance trading.*
3 *Strong*	*Strong political influence, strong focus on R&D on green tech.*

6.2 Data

A major part of the project consisted of collection, construction and preprocessing of data. The aim was initially to work with only time series and data collection to obtain a more accurate view of the capacity need. The ideal conditions for working with a data driven method would include several organized datasets. Firstly, hourly data over a few years from different customer segments such as typical houses, apartments, offices, restaurants, industries etc. would support a good sectoral coverage and time horizon. Secondly, that data should be organized after some fundamental characteristics such as heating source of the facilities (i.e. DH or electricity), age of the building (i.e. new energy efficient facility or old energy intensive building) and location of the facility (i.e. grid area and urban or rural grid). Thirdly, to model future energy trends, datasets comprising consumers with for example PV-installations, batteries and EVs would be essential in order to envision the impact that the trends have on the local grid.

The anticipated datasets for this project was not obtainable for all factors of interest (see 3.4 Limitations). Therefore, some time series were collected while some data was constructed, based on different sources described in 6.2.2. The time series datasets span across different time periods of different lengths. However, for compatibility between the different datasets and to be able to simulate one full year, it was made sure that each time series cover all hours of 2019. Furthermore, all region-specific data, e.g. time series of weather or solar radiation, was limited to be collected or constructed for the Stockholm region to maintain a realistic consistent linking between the time series.

6.2.1 Data Collection

The different load curves and load profiles of different houses and apartments where collected through Vattenfall Eldistribution. Additionally, a dataset with consumption for four anonymous office buildings was collected through a large real estate company. The datasets of the loads contained hourly consumption data which was then cleaned from all-zero loads. Null values were replaced by interpolation. The datasets were moreover scaled down, in terms of separate loads, to facilitate model development. Temperature data over four years was found through SMHI's website [88]. SHMI has free open weather data that spans over decades which can be downloaded using their API.

6.2.2 Data Construction

The data which was needed for the model but not able to be collected was load curves for PV-production and EV-charging. These datasets therefore had to be constructed in order to be included while still upholding the data driven manner of the model.

Office Load Profiles

The data covering office buildings was obtained late in the process of developing the model. In an earlier state, an office load profile was therefore constructed. The load profile was created based on numbers from a master thesis by Ekman and Nilsson [61]. The master thesis states what electricity consumption an average office has per day, including information about the base load made up by heating, cooling and elevators etc. The total daily consumption per day was given and visualized in a load curve. This data was then roughly generalized and assumed to be the same with small deviations over all days of the year. Weekdays and weekends were however differentiated by only consuming the base load on weekends. The collected datasets with consumption for the four anonymous office buildings have consumption of the sizes 21, 25, 64, 69 and 90 kWh/m^2 and year. The office with 90 kWh/m^2 was chosen as a scalable reference load profile since it corresponded to a general consumption for normal Swedish office building [89], [90]. Both the collected and constructed data was included in the model as the constructed office data of a smaller size was a complement to the collected larger office load data.

PV-Production Profiles

PV-production profiles can either be obtained from extracted data of real PV-installations, or they can be created through calculating the solar irradiance and converting it to solar power output. The dataset for PV-production profiles was constructed through simulations in MATLAB in order to obtain hourly values over a year. Temperature and windspeed for a standard year in Stockholm was used within simulations of the MATLAB script, originally written by Duffie and Beckman [91]. Product specific parameters such as panel efficiency, system efficiency and inverter efficiency was obtained from Vattenfall's PV-installation product sheets [92],[93],[94]. Three distinctive simulations were carried out representing three different market segments for PV; a residential house roof, an office roof and the roof of a large apartment building. Azimuth and tilt were set to optimal angles (0° and 40°). The master thesis by Ekman and Nilsson [61] analyzed the same market segments and used roof types of the same size and with nearly the same total installed effect of the panels. The results by Ekman and Nilsson together with the product description of Vattenfall's PV- installations were used to verify the results of the simulation and, by extension, the accuracy of the constructed PV-dataset. Table 10 below shows some of the key numbers from the Vattenfall PV product sheet, yearly consumption of the buildings from Ekman's and Nilsson's master thesis and the resulting total power production from simulations in MATLAB.

Table 10 *Key numbers related to the PV power production simulation in MATLAB.*

	House	Office	Large apartment building
Roof and (PV) size [m^2]	80 (69)	800 (400)	2000 (868)
Total installed power [kW_p]	10,5	66	143
Specified power production [kWh/year]	10 032	62 600	150 000
Number of panels	32	200	434
Simulated power production [kWh/year]	11427	66 254	143 750

The simulations in MATLAB could be performed for different locations, angles, modules, inverters etc. A similar alternative to the MATLAB script is the Python pvlib that analogously provide open and interoperable implementations of PV system models [95]. A more in-depth discussion about the benefits and disadvantages of using the described different methods can be found in Appendix A.

6.3 Modeling

6.3.1 Model development

First, the classes representing different residential loads, substation and grid were developed. Objects of load classes retrieve their consumption patterns from time series data from the respective dataset. For example, an object of the 'house with DH' class retrieves its consumption from a CSV-file containing hourly consumption data of houses with DH. The substation class is at the center of the model, to which the residential loads and offices etc. are added and is it through that object that the consumption is aggregated. The grid class simply aggregates substations. A schematic illustration of the physical aggregation levels and physical substations' relation to the grid is found in Figure 9. Secondly, the classes and methods implementing the different trends were developed. Lastly, a complementary Graphical User Interface (GUI) where the model and output could be visualized was developed.

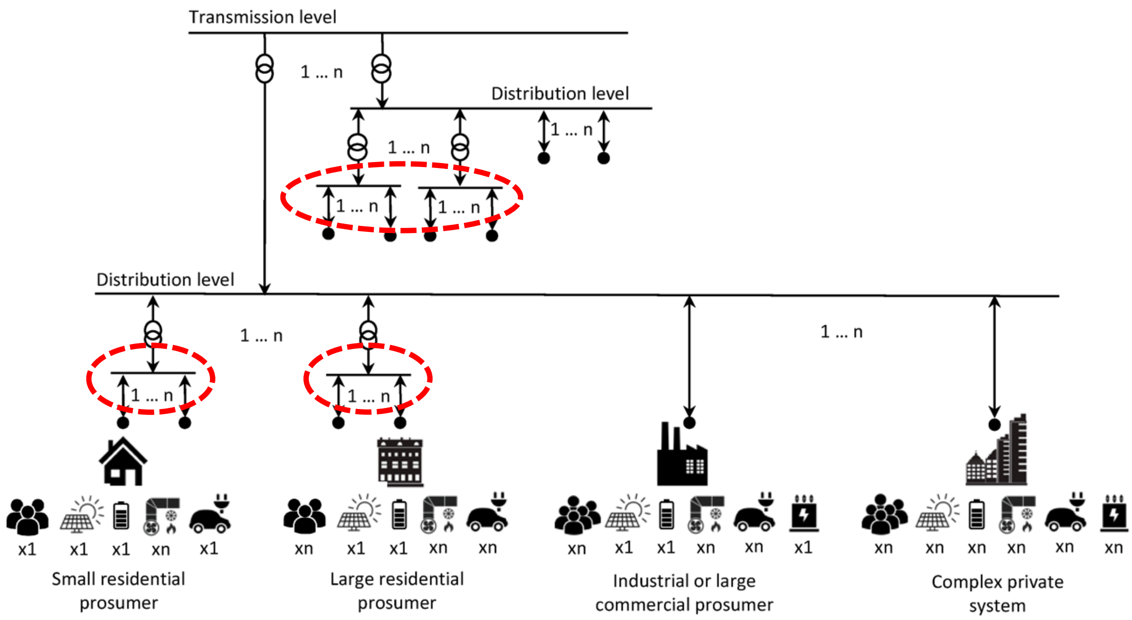

Figure 9 *A schematic representation of the physical aggregation levels and substation market in red [96].*

6.3.2 Modelling Electric Vehicles

Two methods to model EVs were considered. The first method consisted of creating three simple and static EV charging profiles, one for home, one for charging at work and one for fast charging. The charging profiles would not be very realistic since charging does not occur at the same time for all EVs. The second method was to identify other models and integrate it in the model. A spatial model to estimate the charging load of EVs in cities by Mahmoud Shepero was identified as a suitable option and was therefore chosen [97]. Shepero's model only considers light weight private cars and does not include heavy-duty transportation. When looking at number of EVs to include in different scenarios, numbers from Shepero's accompanying paper of 1,7 EV per detached house and 1 EV per apartment is used. Including other charging spaces, the total number of parking spaces (charging places) was estimated to 2,37 per car. The number of parking spaces is not of great importance for the simulation as long as it is more than the number of EVs in order to represent a variation of home, office and fast charging. Shepero's model consist of three different charging possibilities; home and office (charging power 3,7 kW) and other (charging power 11 kW) [97]. To capture the driving patterns and sample the driving distances, Shepero's model uses Markov chains[1] trained from a Swedish travel survey [98]. The EV trend was included through a class which utilized Shepero's model to derive load profiles based on a specified number of EVs and number of parking lots. These numbers are however optional for the user. Additionally, average kWh/km of the EVs is included as a parameter which is then used to draw values from a

[1] A stochastic process in which the conditional probability of the future states depends only on the current state.

gaussian distribution with a specified standard deviation. One final note on the class introducing the EV trend to a substation is that it represents EV charging points and not specific EVs, as it is the charging point that has an impact on the distribution grid and not the EV itself.

6.3.3 Modelling Energy Efficiency

The process of energy efficiency covers a wide range of actions from optimization of existing buildings and processes to new products and artifacts that are more efficient than the old. On a detailed level, energy efficiency in a context of it being a physical concept, could be modeled as decreasing scale factors on appliance use, heating option, the COP-factor of a heat pump that is related to temperature (external/ internal) or isolation to mention a few. This type of more detailed modeling is used in the earlier mentioned case study by Sandels and Widén [31]. On the contrary, when looking from a national perspective it is common to assume that increasing consumption due to population growth is equal to the decrease due to energy efficiency actions [22],[28],[7]. Although this project with accompanying model is targeting the local level, it does not include detailed information about buildings or processes. Energy efficiency is consequently modeled as a Python method that reduces the consumption of a specified number of loads with a specified percentage.

6.3.4 Modelling Solar Power Production

The PV production plants are represented by a Python class as well. Objects of this class read their production profiles from the collected dataset. The PV dataset consists of three time series representing production from a house, an office and an apartment complex respectively. Additionally, one scalable time series based on the 10 kW_p – data as reference is added to the model in order for the user to decide installed power. All the time series were constructed as a typical year, meaning that data had to be complemented when simulated over longer periods of time. This was achieved by using the same year multiple time but having the values deviate from the original. This deviation was a percentage drawn from a gaussian distribution with mean zero and a hyperparameter standard deviation. When the PV objects are added to the substation the production data are translated into consumption data, i.e. be multiplied by -1 to become negative values instead of positive.

6.3.5 Modeling Flexibility

To model flexibility, it is important to be adaptable and transparent in order to allow changes in future simulations when more information about flexibility market models is available. Flexibility is not a clearly defined concept and the need for different types of flexibility actions varies for a wide range of situations. It is however clear that flexibility will become more important and there is good reason to simulate it even though the simulation might not reflect actual future flexibility procedures. In the model, flexibility in a substation is simulated through two methods here called *static flexibility* and *dynamic* *flexibility*. The earlier focus on individual customers, while the latter acts on an aggregated substation consumption representing a situation of for example dynamic time-of-use tariffs.

Static Flexibility

Within this method, only residential houses are taken into account while offices, EV charging and PVs were not. Office and EVs will definitely be part of the real flexibility processes and were simply excluded due to the time frame of the project. In this method, whether the household customers are flexible or not is not based on any market signal, such as spot price, signals from aggregators or their own motivation. However, to create some kind of market signal, temperature was used as a reference since the need for power is affected by cold weather. Factors such as low temperatures and an increasing wind-dependent cooling effect, by extension affect the residential's heating systems. An increased demand during cold weather thus show a correlation between outdoor temperature and spot price, which in turn has an inherent effect on the power demand side [99]. Consequently, in addition to the aforementioned assumptions concerning customer behavior and residence, the load peaks are assumed to correlate with cold weather.

Since the residential customers electricity consumption is largely derived from heating, only customers with heating from electricity (e.g. direct electricity or heat pumps) are taken into account. Customers with DH generally have a lower electricity consumption since the DH is not derived from the grid. Customers with electricity as heating source are therefore chosen as potential flexible agents in the model. Out of those a specified percentage are set to be flexible during a chosen number of the coldest days of the year. The load of the flexible agents is then reduced with a specified percentage during the peak load time. The reduced consumption is moved either forward or backwards in time and spread out over a certain period of time. A simple example of how consumption can be redistributed is illustrated in Figure 10. For example, the consumption can be reduced during 17.00-19.00 and moved to be spread out between 20.00-01.00. All parameters of the method that introduces flexibility to the model are set to be adjustable. In spite of that, the method is entitled static since the invented market signal is fixed, making flex occur under the same specified hours.

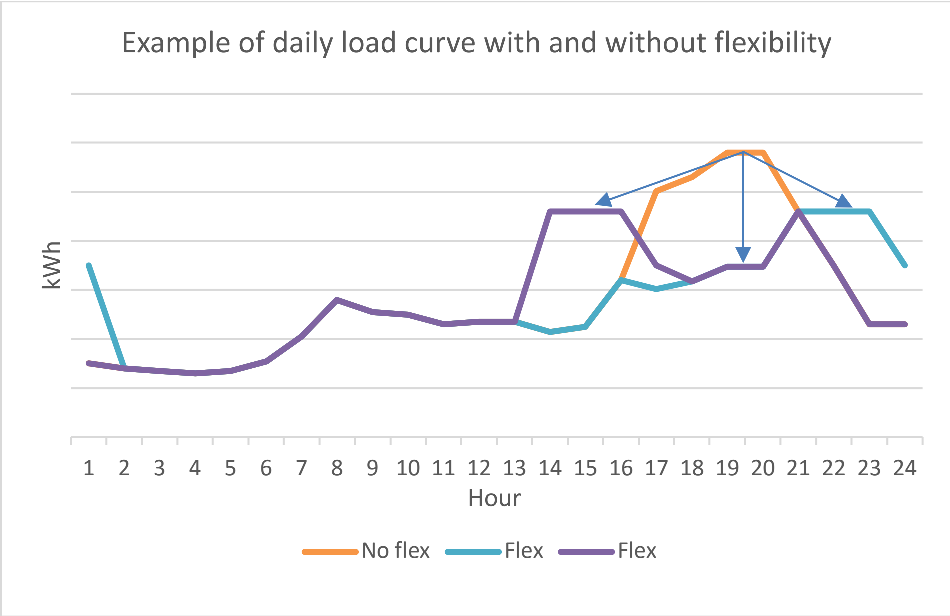

Figure 10 *Illustration of how consumption is reduced during peak and moved backwards and forwards (purple) or only forwards (blue).*

Dynamic Flexibility

The implementation of dynamic flexibility is similar to the static flexibility in the sense that it does not simulate any actual market or process and instead focus on possible results. The dynamic flexibility could as aforementioned represent a time-of-use tariff scheme, where customers can reduce or move their consumption through automatic functions. The signal would in such a situation be time-varying and based on e.g. the balance in the local grid or on market price-signals. The dynamic implementation in the model differs from the static through having this type of *dynamic* response to flexing consumption. Meaning that the flex occurs dynamically based on need, instead of within a predefined time window. Dynamic flexibility is implemented as a method of the substation class, implying that the implementation is limited to optimizing the aggregated load of a substation. The dynamic flexibility method utilizes the SciPy library for optimizing a minimization of max consumption for each day of the simulation [100]. The method optimizes the load given some predefined constraints. These constraints include; 1) a close-to-zero difference of the final consumption sum before and after introducing flexibility, 2) a specified maximal hourly reduction of the consumption, and 3) a specified maximal daily reduction of the consumption. How 2) and 3) are specified is based on if the underlaying systems of flexibility is assumed to be energy storage or flexible agents. For the energy storage, the instantaneous power and the daily energy capacity of the storage is of interest while the assumption of flexible agents focuses on percentages of the daily consumption.

6.3.6 GUI and Implementation of Scenarios

A interactive GUIs, using the ipywidgets framework [101] and Jupyter Notebook [102], was developed for the model. Ipywigdets is an extension to Jupyter Notebook, which is an interactive computational environment where it is possible to combine Python code and output. The four different scenarios were implemented through predefined parameters within model GUI, enabling easy simulation. Additionally, the GUI includes the option the build a custom scenario and run model simulations based upon parameters specified through user input to the interface. Another minimal GUI was developed, using the same tools, for visualizing single load curves in more detail.

7. Model and Results

This chapter states, visualizes and describes the results from simulations of the developed model. The chapter starts off with a section aiming at providing an overview of the model. The chapter then dives deeper into the results of introducing specific trends to a substation. Lastly, the results from simulating a base case substation, which is used as reference, and the four future explorative scenarios are presented.

7.1 Model Overview

The developed model consists of 6 classes, 4 subclasses, 2 minor GUI implementations and a total of 3500+ lines of Python code. A straight-forward simulation of the model within the GUI follows a flow which is illustrated in Figure 11. First, a substation is created. Second, residential loads, offices, EVs and PVs are added. Third, the possible effects of energy efficiency actions as well as static and dynamic flexibility markets are calculated. Last, the results are printed and visualized.

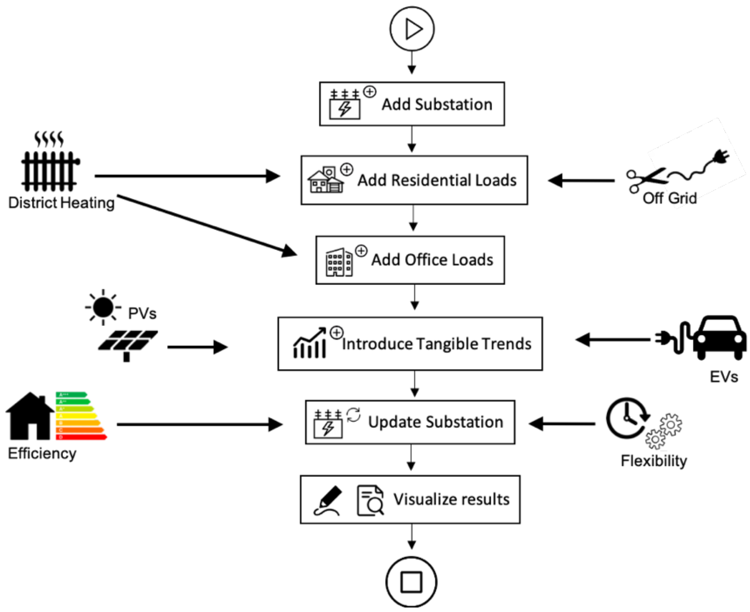

Figure 11 *The flow of the developed model. Where in the simulation the different trends are introduced is illustrated with the larger arrows.*

Due to the limited amount of data, the model is currently only developed for the Stockholm region. The folder structure of the data used can be seen in Figure 12. As mentioned in the literature review, Stockholm suffers from lack of capacity issues which makes it a reasonable area to start with [22]. The model can be expanded to include other regions by adding another folder, carrying the same data structure as the Stockholm folder, to favor scalability. The folders 'Residential', 'Office' and 'PV' all include several CSV-files which are named according to the classes or attributes to which the particular data corresponds to. The 'EV' folder contains transition matrices and distance data, for weekdays and weekends, which are used within the class for EV charging stations.

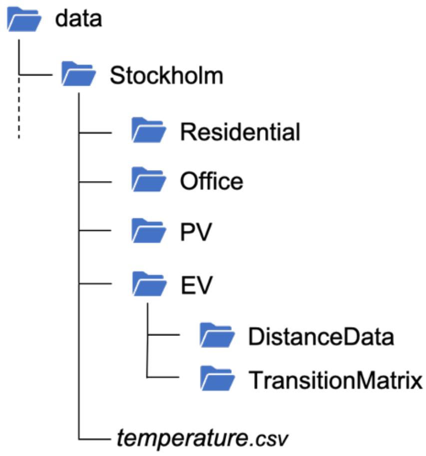

Figure 12 *The folder structure of the data used by the model.*

The purpose behind main the GUI was to create a more graphical and neat way of running simulations of the model. As can be viewed in Figure 13, the interface has two tabs for generating input to the model. In the first, four alternatives of predefined model parameters can be chosen. In the second, all model parameters can be set from scratch to create a custom simulation of the model. Within the second, there is also an option of including alternative time series which is not in the model datasets through uploading a local CSV-file. The idea behind this functionality is to favor the flexibility of the model by the option to add one or many desired custom loads. Additionally, it could be reasoned that the GUI adds flexibility in terms of user base, since less understanding of code in general and the developed model in particular is needed. Once a simulation has run, model output is displayed below the input tabs. The output can also be found in two tabs. One which reflect numerical information about simulation result and one where graphical output can be plotted. The sample of output tabs can be found in Figure 14.

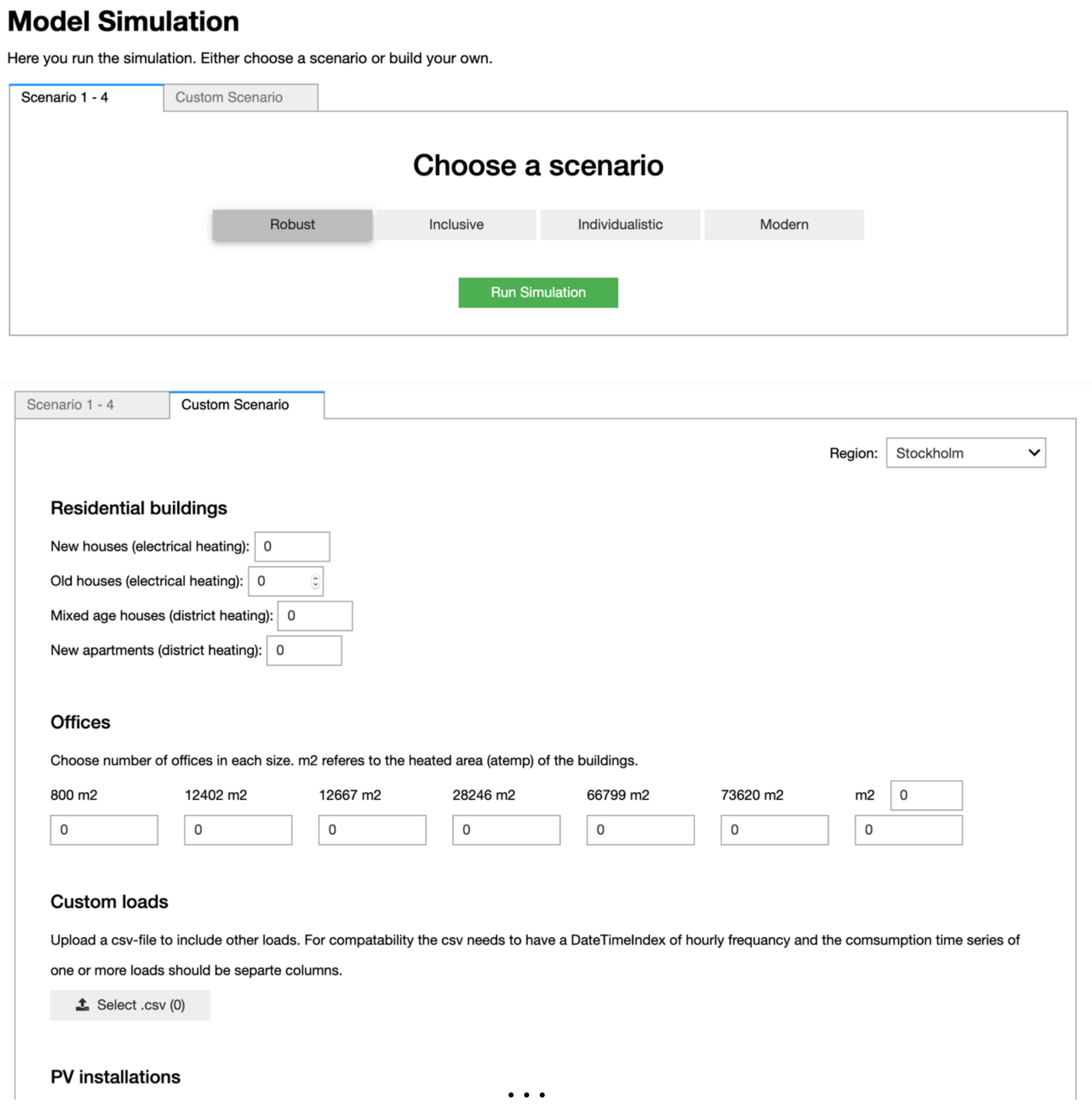

Figure 13 *Screenshots of the two tabs for model input. The upper show the tab for choosing one of the predefined scenarios and the lower shows a part of the tab for creating a custom scenario.*

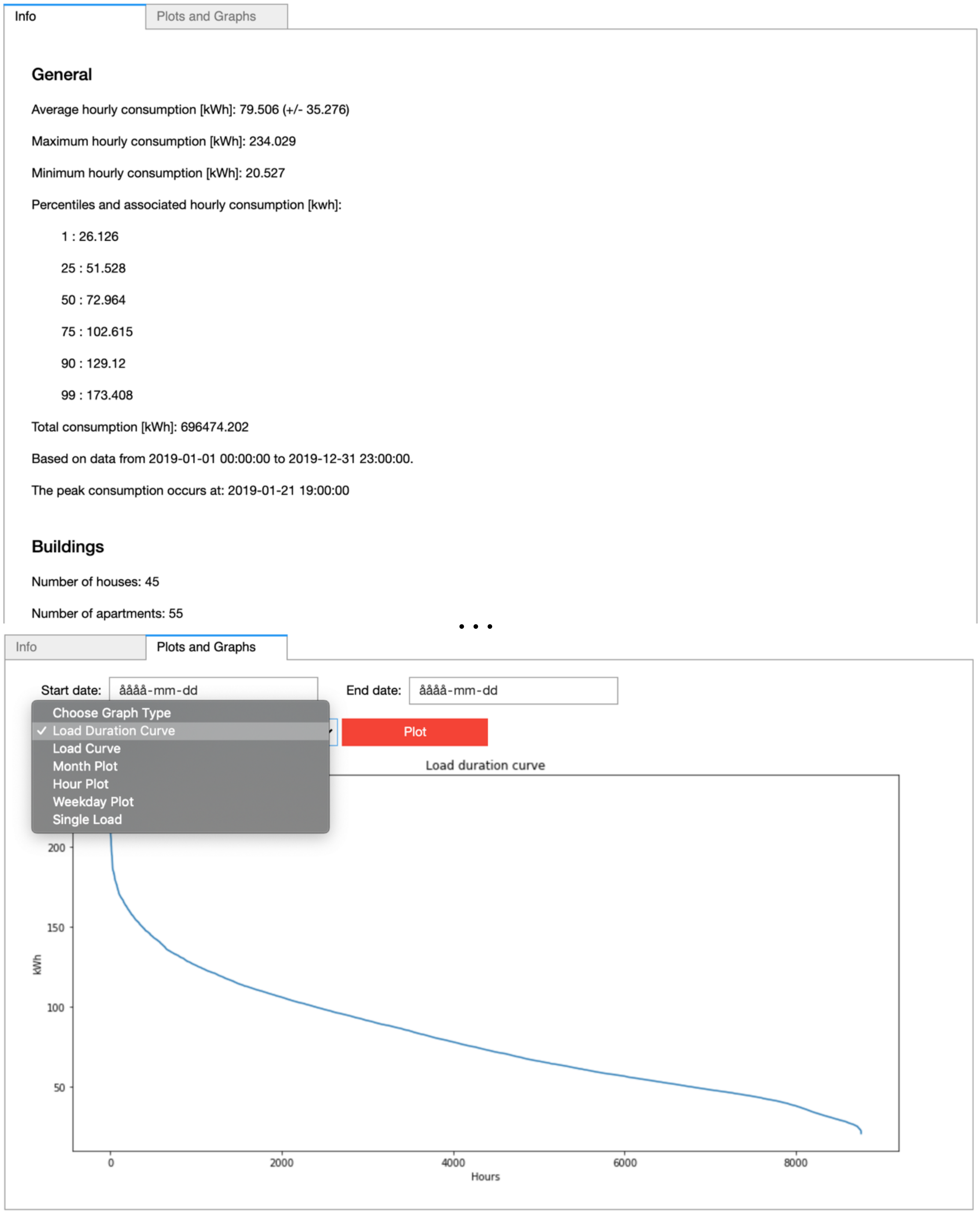

Figure 14 *Screenshots of the two tabs for model output. The upper shows part of the tab for numerical information while the lower shows graphical output options.*

The second minor GUI has no direct link to the model. The purpose behind its development was essentially to favor the 'custom load' functionality within the main GUI and at the same time keeping the interface for model simulation simple. It is supposed to function as a tool for examining CSV-files and visualizing load curves before integrating them in the model. Furthermore, the GUI is meant to assist in making sure a CSV-file is compatible with the model, in terms of delimiter, index format etc. Screenshots of the supplementary GUI are found in Figure 15.

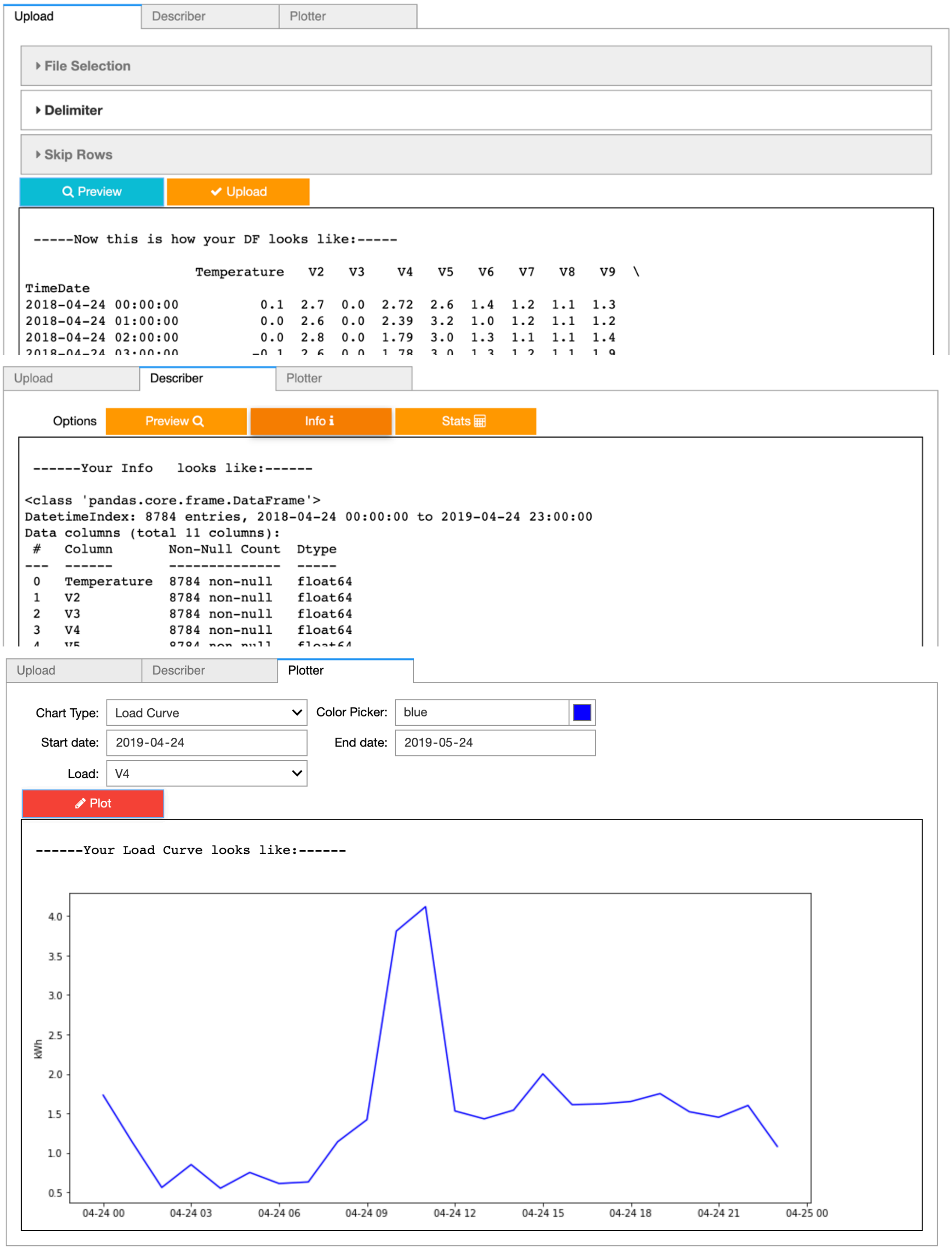

Figure 15 *Screenshots of the three tabs within the GUI for load visualization.*

7.2 Trend Simulations

7.2.1 Results of Integrating Electric Vehicles in a Substation

Simulation results from when EVs were added to a substation show that EVs increases the total consumption. Figure 16 below show an aggregated load curve for a substation with 100 household customers without and with EVs.

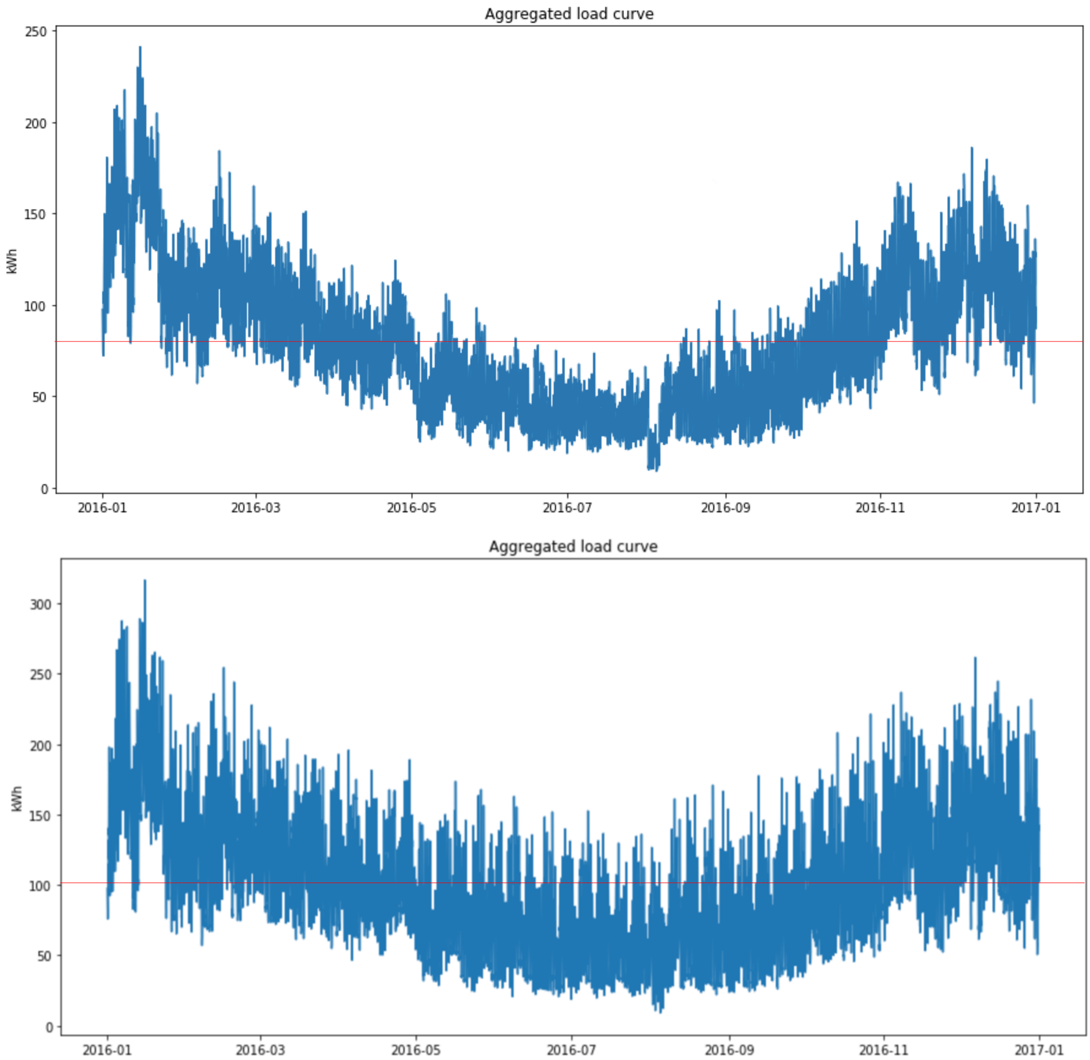

Figure 16 *Load curve for a substation with 100 customers (upper) and load curve for the same substation but with 131 EVs (lower). The red lines mark the average hourly consumption of the simulations.*

The load curve for the substation with EVs shows both a higher average consumption and higher peaks. The EV-curve is thicker, implying a more fluctuating consumption during a full day. In Table 11 below, general information about the two simulations is given.

Table 11 *General information from EV simulation*

General info	Without EVs	With EVs
Average hourly consumption [kWh]:	77.6	101.2
Maximum hourly consumption [kWh]:	241.0	316.6
Total consumption [MWh]:	682.1	888.9
90^{th} percentile of hourly consumption [kWh]:	130.5	164.2
99^{th} percentile of hourly consumption [kWh]:	184.2	227.0

As can be seen from Table 11, the 90^{th} and 99^{th} percentile consumption differs from the maximum consumption, implying seldom occurrences of the highest peaks. The 99^{th} percentile indicates that 99 % of the values are less than that value and that 1 % of the values are greater than the value. In Table 11, the 99^{th} percentile of the simulation with EVs indicates that an hourly consumption above 227 kWh are rare (fewer than 88 out of the 8760 hours).

7.2.2 Result of Integrating Energy Efficiency in a Substation

The results from the simulations of energy efficiency is a direct translation from the relatively simplified modeling method of energy efficiency – a defined reduction of the consumption for one or several chosen loads in the substation. What can be said about the simulations is that the results vary a lot since the model randomly picks loads to decrease consumption on. Meaning that peaks can be neglected if relatively low consuming loads are picked. Accordingly, the results varied largely depending on if for example a large office building or an apartment load was reduced.

7.2.3 Results of Integrating Small-Scale Solar Power in a Substation

Results from model simulations of PV-production go in line with typical production distributions for Swedish PV-plants. The production is high during the summer months and low to nearly non-existent during winter, which supports the accuracy of the datasets even though they are simulated and do not consist of real measured data. However, since the variations in sun hours per year is one of the more important factors when looking at PV-production, it is important to take into account that the output from the used datasets lack variations since it is simulated based on the same year with the same characteristics. Figure 17 below shows the hourly production and outliers over a year for the 10,5 kW_p production profile.

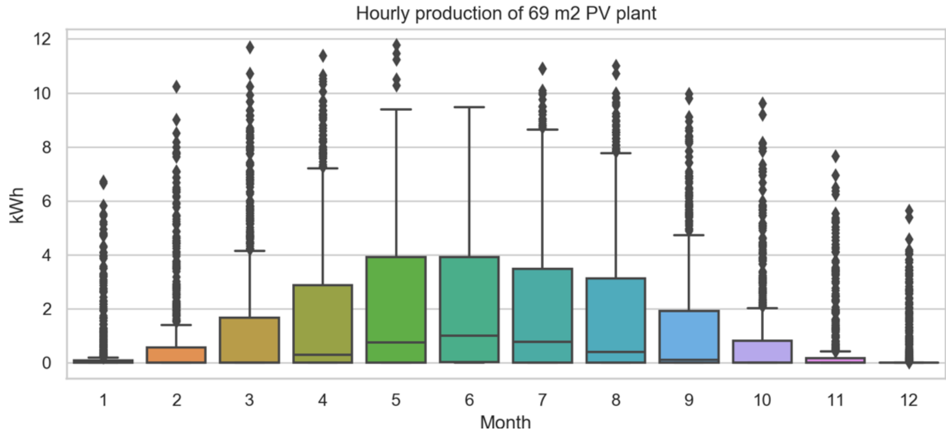

Figure 17 *Power production of a 10,5 kW_p PV-plant over one year.*

In the Figure 18, a substation with a 66 kW_p PV-plant is presented in a load duration curve together with the total consumption for the substation without the PV-plant. The load duration curve visualizes the highest consumption during a year and also a negative consumption for a number of hours. The substation with PV has negative values due to PV-production exceeding consumption, which is a natural occurrence during sunny summer days. This means that the substation transitions from being net consumer to a net producer and thus supplies electricity to the grid. The tails of the load duration curve indicate the highest and lowest consumption in the substation with and without PV. The difference between the highest positive for the two substations is of significant interest for the grid capacity since the substations with PV is less than the substation without.

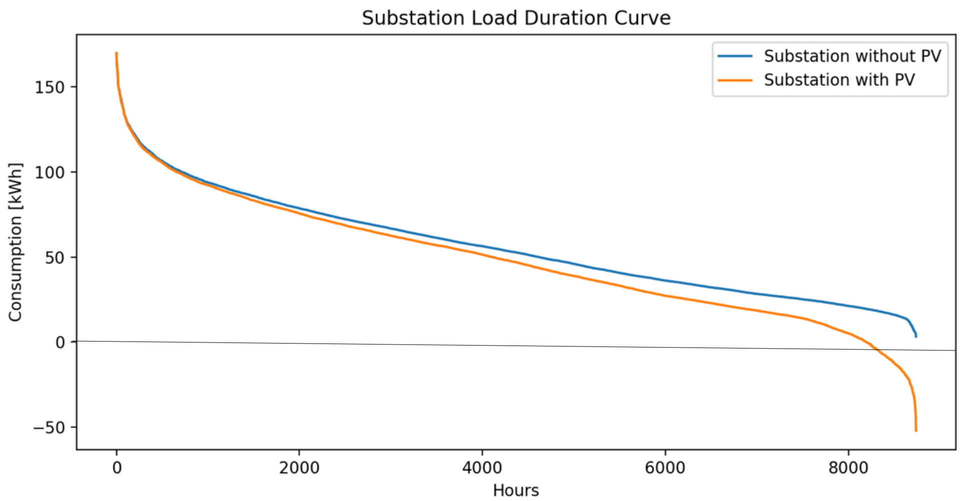

Figure 18 *Hourly consumption from a substation with 60 residential loads, before and after introducing a 66 kW_p PV-plant.*

7.2.4 Static and Dynamic Flexibility in a Substation

The static flexibility trend implementation of the model is not modeling an actual flow or operation of a flexibility market. Meaning that the implementation is static in the sense of the flexible loads not responding to any market driven signals. Nonetheless, it can be argued that the implementation simulates the eventual effects working with flexibility could have on the consumption.

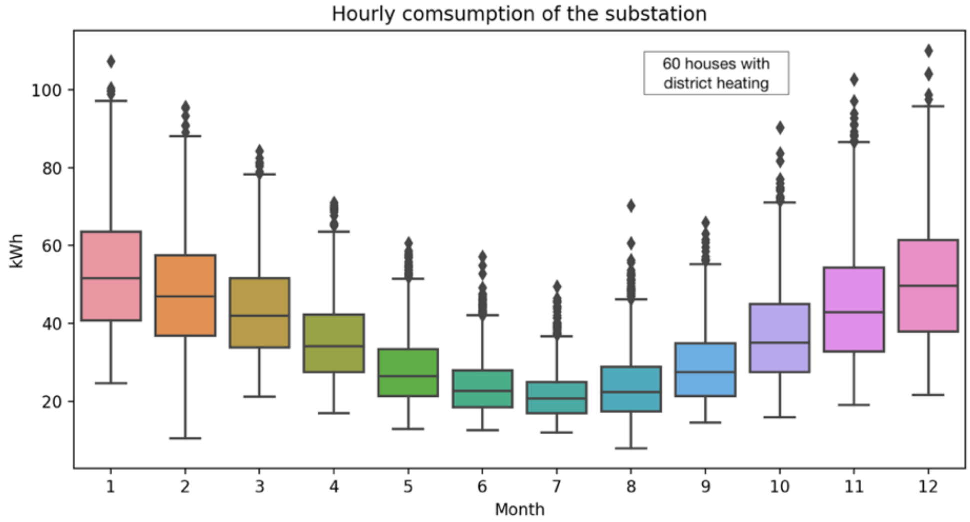

Figure 19 *A boxplot illustrating the seasonality of monthly consumption for 60 houses. The consumption is aggregated over 4 years and the houses* <u>*have*</u> *DH.*

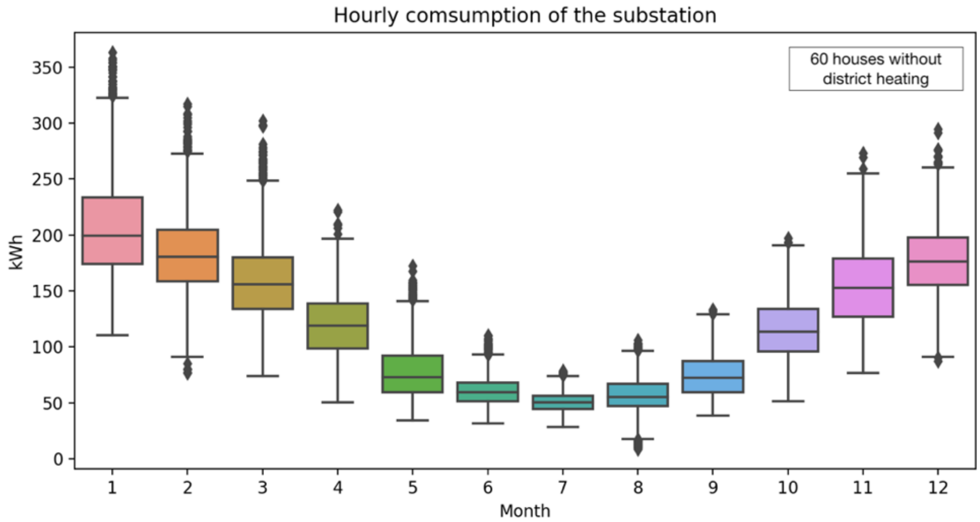

Figure 20 *A boxplot illustrating the seasonality of monthly consumption for 60 houses. The consumption is aggregated over 4 years and the houses* <u>*do not have*</u> *DH.*

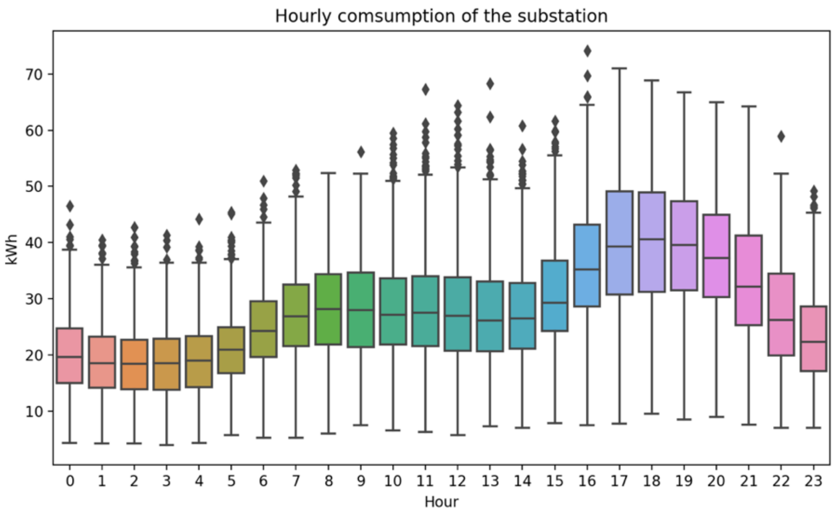

Figure 21 *A boxplot illustrating the hour tendency of hourly consumption of 60 houses aggregated over 4 years. The houses do not have DH.*

As can be seen in Figure 19 and Figure 20, houses without DH both have a higher consumption as well as a larger sensitivity to seasonality. These results support the base assumptions and the decision to, by default, only include houses without DH in the static flexibility implementation. Figure 21 supports the choice to target flexibility during the coldest days of the year, because the highest consumption can be found during the Swedish winter months. It is also in line with the fact that heating makes up the largest part of the energy consumption in houses with electrical heating solution and is directly related to outdoor temperatures. Furthermore, Figure 21 supports focusing the flexibility implementation to the three peak hours of the day. During the hours 17.00 – 19.00 is where peaks can be identified in the consumption over the year, which are also the default hours to reduce within the model.

Example output after implementing the static flexibility in a substation with 100 electrically heated houses, out of which 30 are flexible, is illustrated in Figure 22. The simulating, running over 1 year, shows that the peak hourly consumption of the substation could be shaved from 666 kWh to 632 kWh. In the simulation the flexible loads redistributed 70% of the consumption during peak hours of 50 days. The consumption peak of substations has been moved after every observed run of the static flexibility implementation.

Figure 23 is a graph illustrating an example output of a dynamic flexibility simulation. The load duration curve of a substation containing 100 electrically heated houses, is plotted with and without dynamic flexibility. The results in the graph exemplifies a dynamic flex simulation, where a battery of 100 kW power and 300 kWh capacity on substation level was assumed. The peak hourly consumption of the substation could through flexibility be reduced from 636 kWh to 589 kWh, all the while the total consumption of 7632 MWh remained relatively unaffected.

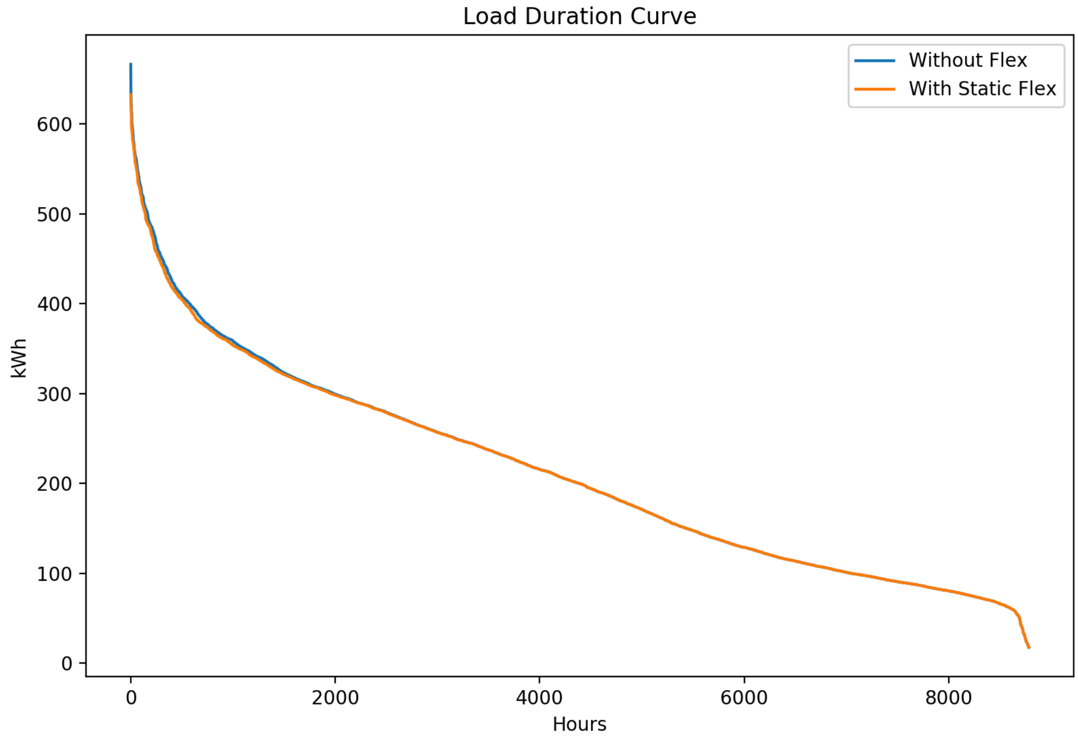

Figure 22 *Load duration curve of a substation with 100 electrically heated houses. Blue indicates the hourly consumption with, and orange indicates the hourly consumption with static flexibility.*

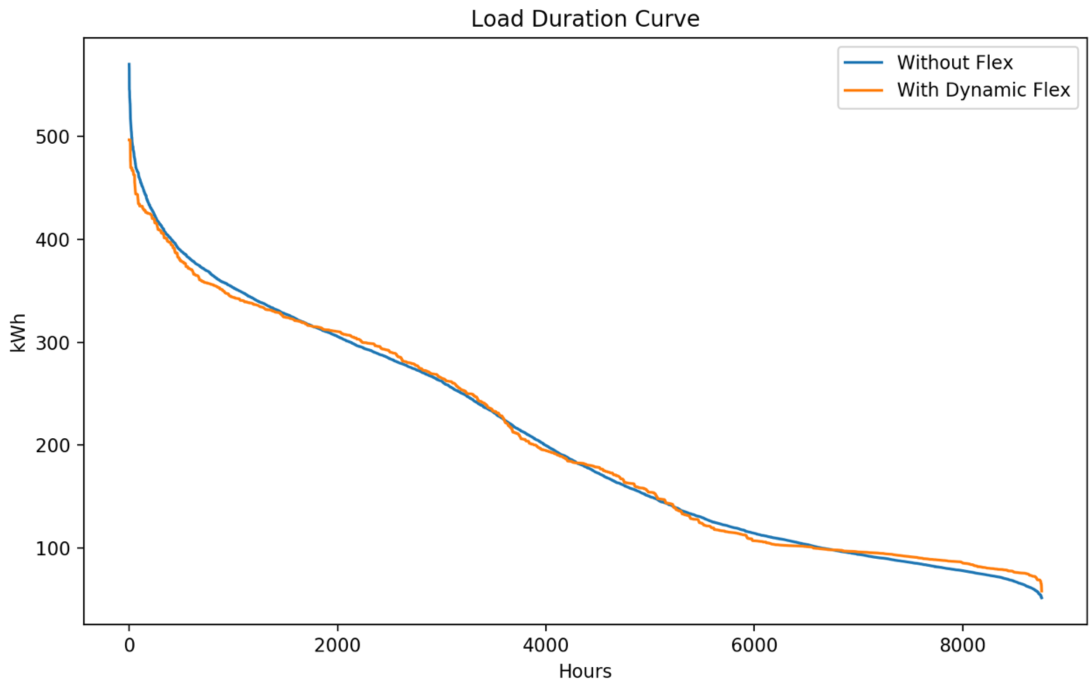

Figure 23 *Load duration curve of a substation with 100 electrically heated houses. Blue indicates the hourly consumption with, and orange indicates the hourly consumption with dynamic flexibility.*

7.3 Model Scenarios

7.3.1 Base Case

The inputs to the model representing the base case scenario of a substation with 102 customers is as follows. The distribution of loads for the base case is modeled as described in section 6.1.1. and comprises 30 houses with electricity, 15 houses with DH and 55 apartments with DH. In addition, two offices of sizes 100 m^2 and 500 m^2 with DH is added to the substation. In the present, the level of smart grids is relatively low and flexibility markets is not yet commercialized among households and office facilities. The level of governmental influence is considered moderate in regard to current policy instruments. The PV-production profiles are set to be 50 % of size small 5 kW_p, ~50 % of size medium 10,5 kW_p and ~1 % of size large 66 kW_p. The dimensions differ from the three earlier presented PV-profiles in order for them to suit a small substation. However, since PV-production is still relatively uncommon and spread out in the country, it is difficult to generalize how much installed capacity or number of PV-installations there are per substation. Also, since the current share of PV-installations per substation is currently very small, the amount of PV-production profiles in the base case is set to be zero. Same goes for the penetration of EVs. Output from simulation is illustrated later in Table 12.

Figure 24 is a plot of the base case's aggregated load of the substation over a year. The plot visualizes the highest and lowest peaks and gives a good picture of the yearly variations in consumption. Figure 25 is a plot of the base case's load duration curve for the substation over a year. The plot visualizes the annual consumption distributed over 8760 hours and sorted in a descending order. The resulting S-shape shows the lowest and peak load during the year and the frequency of maximum and minimum values.

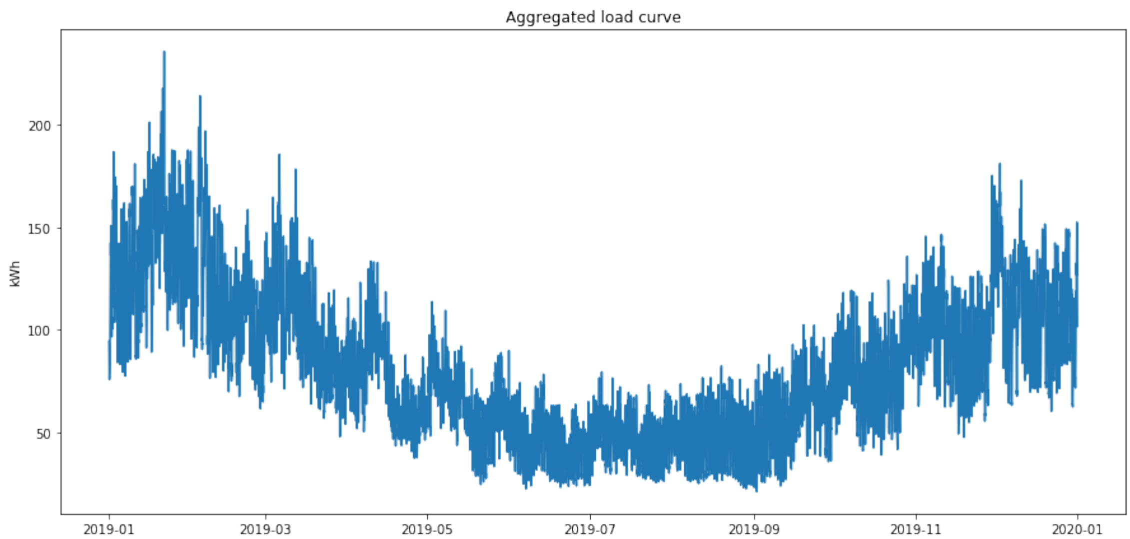

Figure 24 *Aggregated load curve for the base case scenario substation.*

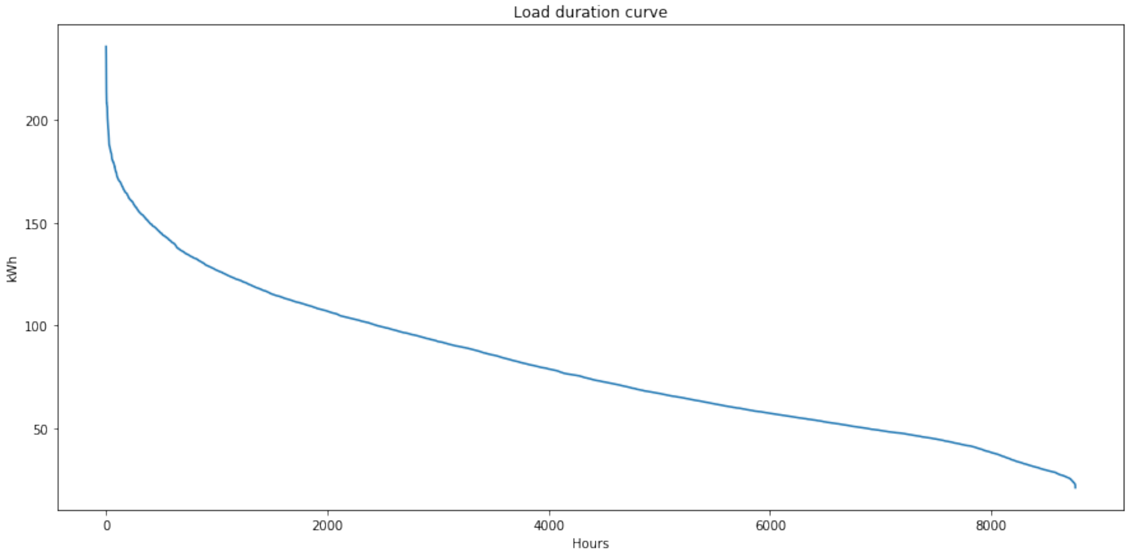

Figure 25 *Load duration curve for the base case scenario substation.*

Figure 25 shows the aggregated hourly load of the base case during a day for the substation. The plot visualizes the highest and lowest peaks during a full day. For example, the consumption is higher during the day than during the night and highest during the peak hours of 16.00-18.00. The outliers capture variations and unique values in the consumption. The last two plots of the base case in Figure 26 and Figure 27 is the aggregated monthly load during a day and aggregated daily load during a week for the substation with electric energy consumption in kWh on the y-axis and month on the x-axis, visualizing the highest peaks during the months of the year. Figure 28 illustrate an evenly divided consumption over all days of the week, simply because of an even distribution of residential loads (which typically have higher consumption during weekends) and offices (which typically have higher consumption during weekdays) in the substation. Figure 24 – 28 are generated through the main GUI and indicates the graphical outputs and information sources available.

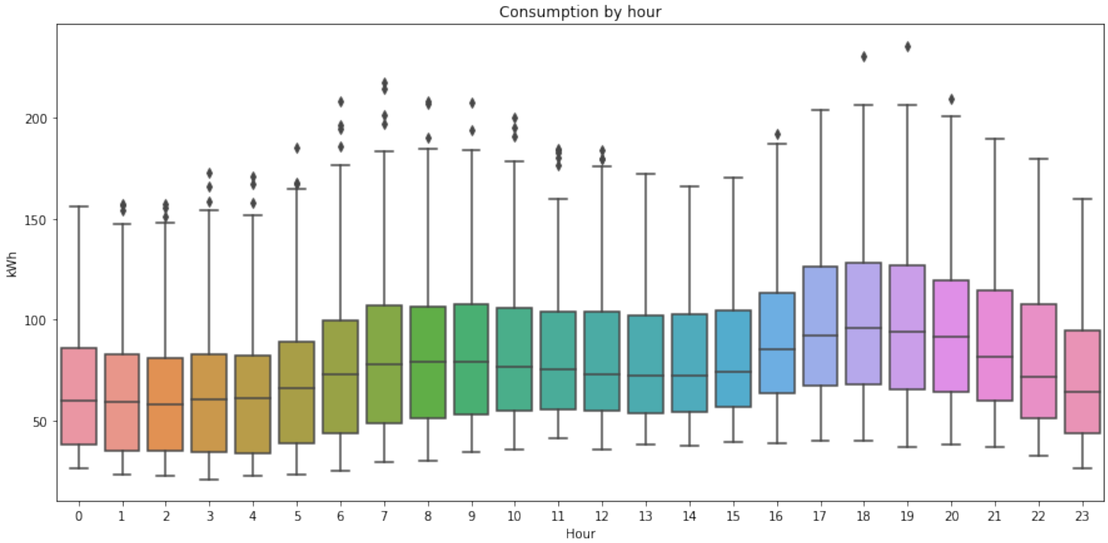

Figure 26 *Boxplot over the hourly consumption of the base case.*

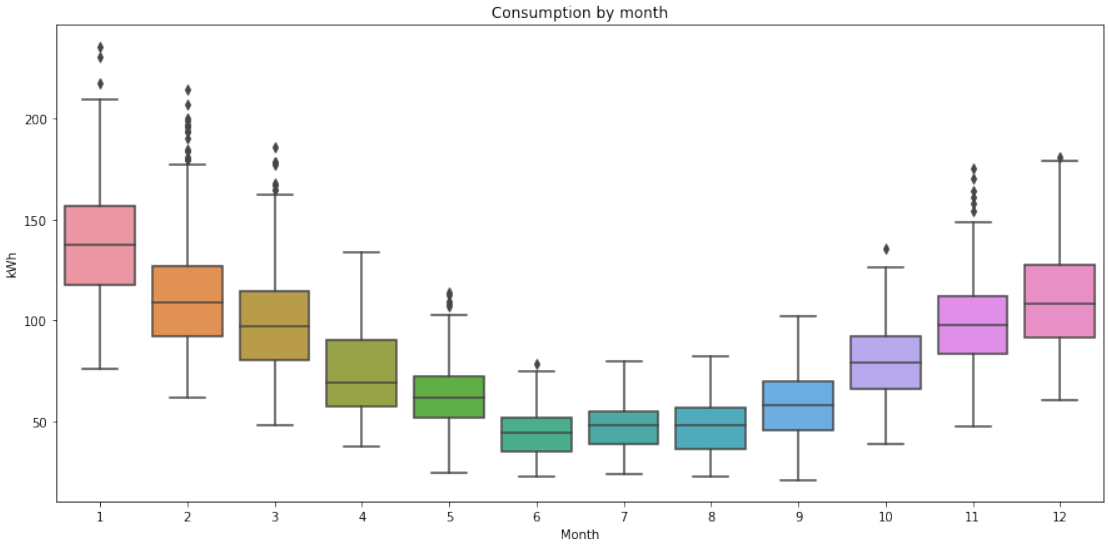

Figure 27 *Boxplot over monthly consumption of the base case.*

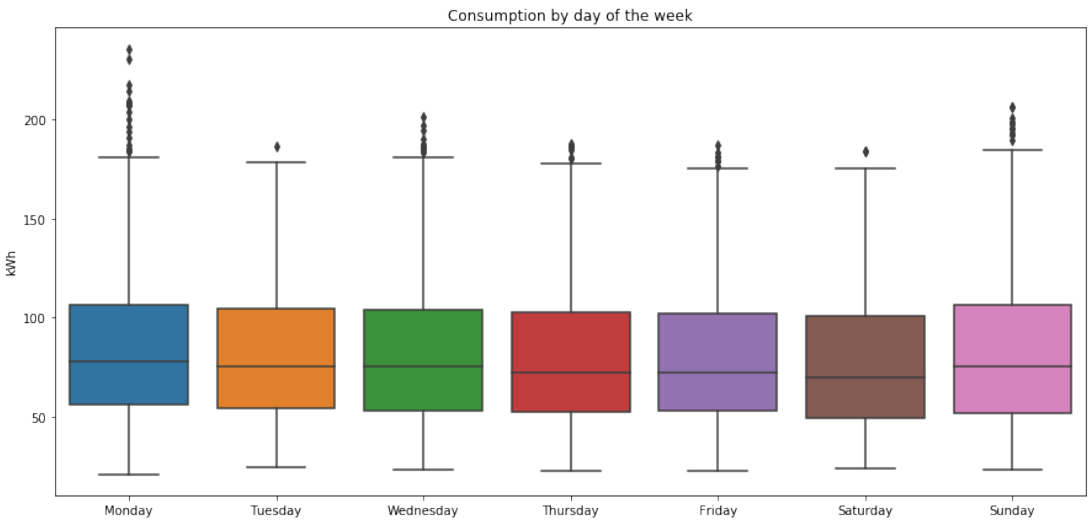

Figure 28 *Boxplot of the weekly consumption in the base case.*

7.3.2 Robust

The first constructed scenario is inspired by Energimyndigheten's explorative scenario *Forte* where the industry and national economic growth is prioritized before environmental objectives. The energy system is centralized with new investments in nuclear which implies the same share of renewable energy sources as today (50 %). The demand side flexibility is similarly reflecting the present state of nearly nonexistent and is therefore set to zero. The PV-production profiles are similar, somewhat higher, than in the base case and is set 0. However, since the industry sector has grown in this scenario, the DH market has grown with it and stands for ~70 % of the market instead of today's ~50 % which modifies the heating sources of the housing stock slightly. Energy efficiency actions have decreased the consumption by 5 % compared to today. Moreover, EVs has increased a little and stands for 5 % of all private cars. The level of governmental green policies is low, and the level of smart grids is low.

7.3.3 Inclusive

The second simulated scenario is inspired by *Legato* where energy is seen as a resource to be shared equally and environmental objectives are very important. The level of governmental green policies is high reflecting a decreased consumption and a very large share of renewable energy sources (100 %). However, ~ 5 % of all buildings have PV-installations since most of the renewables consist of wind power. A moderate level of smart grids has enabled static demand side flexibility to exist in a relatively high extent. The industry sector has not grown but is driven by a circular system implying that the market of DH has increased. Energy efficiency actions have reduced the total consumption of the loads by 30 % compared with today. Moreover, the penetration of EVs on the market has increased and stands for 15 % of all private cars in this scenario.

7.3.4 Individualistic

The third simulated scenario is inspired by *Espressivo* where energy is a mean of individualism and expression. The energy system is decentralized, consist of 75 % renewable production and is characterized by local solutions and self-sufficiency. The level of governmental green policies is low and approximately 5 % of all customers has gone off-grid. The smart grid level is moderate, and flexibility exist on local decentralized markets, as in the *Espressivo* scenario, with flexible agents as underlying system of the dynamic flexibility. The penetration of PV-installations in the substations is close to reach 30 % of all buildings. The interest for taking part of the of the DH market has declined a lot to ~30 %. Energy efficiency actions have furthermore decreased the consumption by 10 % compared with today. Moreover, EVs has increased and stands for 60 % of all private cars.

7.3.5 Modern

The fourth simulated scenario is inspired by *Vivace* where green tech, innovation and digitalization stands in focus. The energy system, with 100 % renewable production, is characterized by a high grade of smart grids and green governmental policies. As the Vivace scenario has a Swedish battery industry in the forefront, dynamic flexibility is highly integrated in the autonomous energy system with energy storage as underlying system. Approximately 20 % of all buildings have PV-installations. The industry sector has not grown but is driven by a smart circular system implying that the market of DH has increased some and reached 60 %. Energy efficiency actions have moreover decreased the consumption by 20 % compared with today. Lastly, EVs has increased a lot and stands for 90 % of all private cars and their efficiency has increased from 0,2 kWh/km to 0,1 kWh/km.

7.3.6 Simulation Results

The input parameters to the model of the different scenarios are summarized in Table 12 and in Figure 29 all the load duration curves from the different scenarios are presented.

Table 12 *Input parameters to simulation of substation according to scenarios*

Substation with 102 loads	Base case	Robust	Inclusive	Individualistic	Modern
Electricity heated houses	30	20	25	50	32
DH heated houses	15	25	20	10	13
Apartments	55	55	55	35	55
Offices	2	2	2	2	2
Energy efficiency[2] [%]	-	5	30	10	20
EVs	-	6	19	79	118
PV-plants	-	-	5	28	19
Dynamic flexible loads [%]	-	-	-	80	-
Dynamic flexible storage [kWh]					150
Static flexible loads [%]	-	-	30		-
Off-grid	-	-	-	5	-

[2] Refers to reducing the energy consumption of loads with a certain percent.

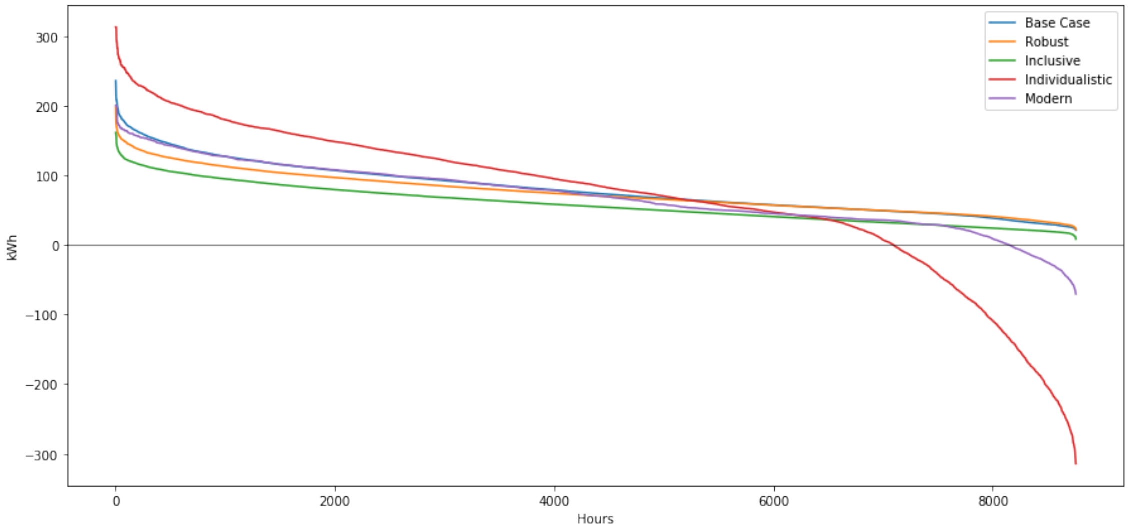

Figure 29 *Example output from scenarios. Five load duration curves from five different scenario simulations.*

The load duration curves in Figure 29 show the highest positive and negative peaks as well as the general spread of the consumption for each scenario including the base case. As can be seen, the scenario *Individualistic* has both the highest positive and negative peak with over 600 hours of reverse power flow. Noteworthy is that both peaks pose impact on the grid capacity in a grid and that the negative peak is greater than the positive peak in absolute numbers. The negative consumption in *Individualistic* and *Modern* can be derived from the integration of PV-production. The *Individualistic* scenario has more hours of reverse flow as well as a higher negative peak than *Modern* which goes in line with the fact that it has a larger installed power of PV. The average consumption in the scenarios is relatively similar but the spread in standard deviation between the scenarios is significant which is expected since some scenarios have both positive and negative peaks while others do not. *Robust* and the base case are relatively similar and in *Inclusive*, the total consumption is less.

In Table 13 some key numbers from simulations of the four scenarios and base case can be found. The percentiles indicate on how seldom a peak occurs which is relevant for grid reinforcements which is often based on maximum peak loads. The 99.9th percentiles of the different scenarios could be an indication of the seldom occurrence of the maximum peaks – which what the grid has traditionally been dimensioned from. It is thus desired that the 99.9th percentile is as close to the absolute maximum peak as possible, as in *Modern,* since this indicates a more optimally utilized grid. Fully utilized grids without overcapacity are desirable from socioeconomical perspectives. A more in-depth discussion about the scenario simulations can be found in section 8.2.2.

Table 13 *Example of resulting numbers from the five different scenario simulations.*

General info	Base case	Robust	Inclusive	Individualistic	Modern
Average hourly consumption (and standard deviation) [kWh]:	80,5 (± 35,4)	75,0 (± 35,4)	53,3 (± 25,4)	69,2 (± 108,0)	70,5 (± 46,2)
Maximum hourly consumption [kWh]:	235,6	197,3	161,1	312,7	199,98
Minimum hourly consumption [kWh]:	21,1	22,1	8,2	-314,2	-70,5
Total consumption [MWh]:	705,6	656,5	509,3	606,1	617,2
99.5th percentile of hourly consumption [kWh]:	184,2	153.9	124,3	262,7	167,9
99.9th percentile of hourly consumption [kWh]:	206.5	167.9	141,1	291,8	199,56
Reverse flow [hours]	0	0	0	1667	612

8. Discussion

In this chapter the results from the previous sections will be discussed and analyzed. The chapter starts off with a section highlighting the identified societal and technological trends in parallel with a more in-depth discussion about how the trends could impact the grid capacity demand on a local level. Throughout that section benefits and shortcomings of the model is also underlined. The chapter then continues with an analysis and classification of the model from a more theoretical perspective to substantiate and provide context. The chapter ends a discussion about the model simulation results and thought on working data driven using time series.

8.1 Future Trends and Their Impact on The Local Capacity

The increase in electricity demand comes from some prospective trends and factors which in turn is mostly a result of the high-level political goal of a CO2-neutral Sweden by 2040-2050. The trends, based on the literature review, can firstly be divided into those which constitute a decentralized power production. Secondly, there are trends that increase the power demand such as electrification, demography and urbanization. Thirdly, there are trends that on the contrary reduces the energy demand such as energy efficiency and energy storage solutions. Lastly, some trends function as enabling factors including digitalization, flexibility, and marked based policy instruments.

Worth mentioning about the trends and their impact on the local level capacity is that when considering the future, it is seldom a question of whether the trends will exist or not. It is the surrounding systems such as infrastructure, digital components and financial incitements that must be in place for the trends to be realized and to which extent.

8.1.1 Impact of Electrification

Both the literature review and model simulations indicate that the electrification trend will increase the capacity demand in local grids. The results from simulating EVs in a substation showed a higher consumption with higher peaks. It is of interest to obtain an overview of the impact EVs will pose on the grid capacity. During an extensive market penetration, EVs can potentially flatten the aggregated load curve for a substation if they are flexible enough and can charge during low consumption hours, for example during the night. If the consumed energy increases but not the capacity need, the local grids instead become more optimally and fully utilized. Such a scenario would require an extensive integration of AMI and smart grids. However, if EV charging is not flexible, the peak hours risk to become even more severe and could cause issues for the grid capacity. Figure 30 is a visualization of redistributing and optimizing the EV load using the dynamic flexibility implementation of the model. Through setting the constraints to maximally reduce 30 kW per hour and maximally 60 kWh during a full day, some of the highest peaks can be avoided.

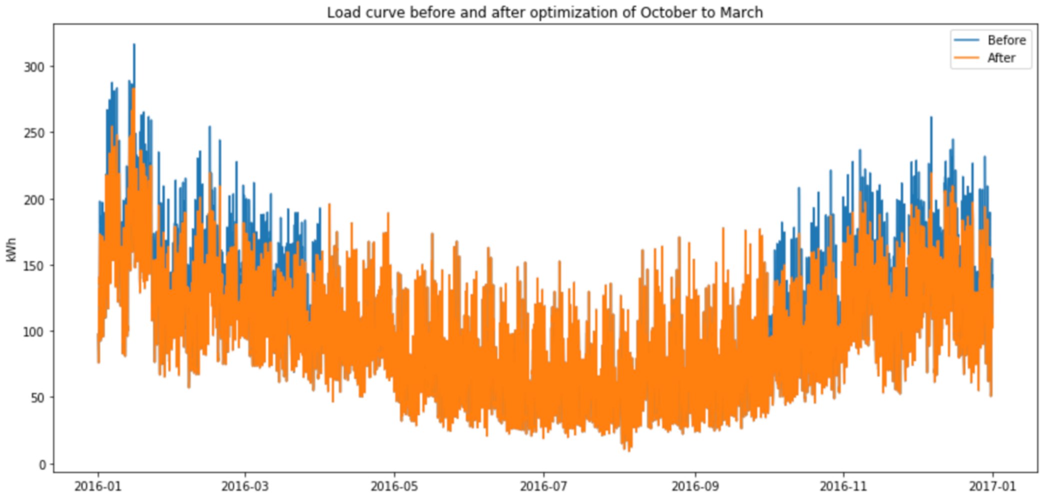

Figure 30 *Peak shaving during winter months using dynamic flexibility on a substation with households and EVs.*

Furthermore, EVs are thought to become a vital part of the transport sector as the official forecasts are pointing clearly in that direction [40]. The rapid growth of EVs in combination with the fact that there are currently very few EVs on the market makes it difficult to imagine a future where EVs dominate the market. Since EVs require major infrastructural changes there is moreover a typical chicken-egg problem in whether the infrastructure in form of e.g. public charging points should be implemented first or if it the citizens should create a demand through purchasing EVs. Additionally, it might not be realistic to assume that all customers have EVs in the same extent as people have fuel driven cars today, but it still gives a good indication of the impact that EVs might pose on the grid capacity in the future. On the contrary, it is not the numbers in the forecast about EVs that are important in this context, it is the method and the tools used to overview and plan for the future that are fundamental. Most of the parameters concerning EVs in the model are adjustable and simulations can easily be redone using other assumptions.

8.1.2 Impact of Energy Efficiency

Energy efficiency is a process that will likely continue to pose impact on the local grid level. Mainly because the energy use has not gone up in decades due to the increased consumption being compensated by a steady trendline of energy efficiency leading to decreased consumption. As the national scenario reports tend to simplify energy efficiency largely through equating it to the increasing consumption due to population growth and by so, neglecting it. End-user oriented reports on the other hand tend to dive deep into details about processes, materials or appliance usage. Given the hybrid nature of this project, none of those approaches are ideal. Population growth are not reflected on a local level making a top-down method unfitting, likewise the granularity in the data is not high enough to use a bottom-up method. Energy efficiency thus remains difficult to model and quantify. In the model, energy efficiency was modeled as a reduction of consumption in percentage. Even if this implementation is an extensive simplification of the trend, it is an attempt to include it in the model. However, since the parameters and the model are adjustable, energy efficiency could in a future development of the model with more detailed data, both take more detailed processes into account as well as take population growth.

8.1.3 Impact of Decentralized Electricity Generation

The DEGs is one of the trends that are frequently discussed when it comes to impact on local grids. More decentralized generation implicate new market actors and bidirectional flows in the distribution grid from e.g. local power plants or small-scale solar "prosumers". This project is delimited from regarding wind power as well as voltage variations and power flow issues, suggestions for a future implementation of wind power in the model can be found in Appendix. On the contrary, small scale solar power production has been included in the model since the transition to a 100% renewable energy production generally incorporates plans for an expansion of PV-production. The past few years expansion and increase of PV-installations has progressed with a remarkable pace. However, there is also a risk with a fast speed market development, both economically and technically. There is good reason for including PV-production in a model with the purpose to quantify and visualize the impact future energy trends could have on the local distribution grids. Firstly, the results from the simulation go in line with existing evidences about PV production which supports the functionality of the model [91]. Secondly, there is high value in illustrating the yearly variations in production together with other components and factors in, for example a substation. Thirdly, there is a winning in presenting information such as the minimum consumption which due to self-use of solar power can be really negative.

In terms of the capacity need, PV-production on its own is not likely to add any utility since it almost only produces electricity during the summer months, and it is generally during the winter months that lack of capacity is a problem. During summer months, the exception is PV-installations in combination with offices and similar since they have the same but inverted typical patterns. Meaning that offices have higher consumption during the day when most solar power is produced. From a self-sufficiency perspective, the model thus functions as a good tool to experiment with sizes of offices and dimension of installed capacity for PV. However, in the model, PV-production is equal to a negative consumption implying that maximum production i.e. the minimum consumption can be negative in a larger magnitude than the highest positive peak. Meaning that over a year, a substation can have e.g. a positive peak of 250 kWh during winter and a negative peak of -255 kWh during summer. Since the grid is often dimensioned after the maximum positive peak, and not the negative, such a result naturally affects the future capacity planning. In order to solve the capacity challenges with negative peaks, flexibility or energy storage solutions must be present for optimizing and balancing the production and consumption.

Additionally, the decision of which origin the data that represent PV-production should have is of importance for valid simulations and results. Synthetic data such as the simulated PV-production profiles used in this project has some advantages and disadvantages depending on the purpose, compared to real measured data. For instance, if it is desired to simulate PV-production in a long term-perspective, then synthetic data can be profitable since it enables adjustments in for example PV-panel efficiency parameters. In that way, it is possible to simulate PV-production with the assumption that the PV-technology has improved. On the contrary, for more short-term simulation, it can be argued that real measured data captures the real variations, such as angles, location and temperature, better than the synthetic data, giving more realistic results.

8.1.4 Impact of Energy Storage

Rather than focusing on the extent of batteries that will exist 2040, the literature review instead revolves around technology and price advancements of energy storage. It is far from clear how the different technological storage solutions will continue to develop but there is much potential within the area. It could be argued that energy storage will most likely play an important and expansive role in the future Swedish energy system. The applications on a local level is again visualized in Table 14 where the bold marked applications are related to the grid capacity need and included in the model.

Table 14 *Model integrated applications for energy storage on a local grid level.*

Operator / Function	DSO and regional storage	Local consumer / household level
Balance in production and consumption	***Daily/ hourly variations***	***Daily variations***
Electricity distribution	*Voltage and frequency regulation* *Power trading* ***Capacity firming***	***Aggregation of small-scale storage to support distribution*** *Arbitrage*
Energy efficiency processes	*Load- and storage control for grid efficiency reasons*	*Increased value of local consumption/ production*

In the model, the capacity firming relates to the dynamic flex with energy storage as underlying system. The static flexibility is correspondingly visualizing the effect of managing daily and hourly variations but is not modeled with energy storage but through moving the consumption backwards or forwards in time. The static flexibility could easily be extended with a for example battery that charges up during the night and discharges during the peak load hours. As for the current high prices, using energy storages such as batteries for arbitrage reasons can reduce the payback time for the battery and can for example function as an extra feature during summer in addition to providing flexibility services during winter. Continuing on the same theme, the economic parts of batteries are an important aspect for long-term predictions. Without financial incitements, it is difficult to envisage a future with batteries as a cornerstone in the energy system. Same goes with surrounding systems such as smart grids and AMI, as well as policy’s and regulations.

8.1.5 Impact of Flexibility

Flexibility is one of the most interesting upcoming trends because of its frequently mentioned potential and future importance, in combination with the fact that it is still rather undeveloped. As previously mentioned, flexibility is a wide concept that is linked to several technical and societal functions and sectors. How different flexibility markets and actions will look like is not possible to say at this stage and there are many possible outcomes. Hence, modeling flexibility is not a trivial task and that also constitutes the foundation for the decision to construct two different flexibility methods. Together, the two methods provide a more holistic picture of potential flexibility actions through focusing on both static and dynamic flexibility.

The static flexibility simulations give an indication about the eventual effects that flexibility could have on a certain load. There are however some clear disadvantages with the static flex implementation. Firstly, the static movement of peaks implies that some peaks risk to be missed if not occurred during the specified hours. Secondly, there is the correlation with cold weather which is a great simplification of a real market signal. Thirdly, there is no coordination between the different loads leading to that peaks sometimes are just relocated instead of flattened. On the contrary, the dynamic flexibility gives a good picture of the potential value that can be captured if the loads are aggregated optimally. The question is how realistic the dynamic flexibility is seen to the instantaneous signal and response that it requires to function. It is not realistic to totally disregard how much flexibility each unique load contributes with, and thus it is essential to specify more detailed constraints. Additionally, it can be argued that both flexibility implementations are unrealistic since the optimizing of consumption is based on the actual consumption. In a real-life situation, it is not possible to work with the actual consumption, since the flexibility actions takes place before the usage of electricity. Therefore, prognoses and predictions will have to be used instead, which introduces more sources of error.

Most types of flexibility strategies are strongly linked either polices and market functions, or the development of smart grids and AMI since components and equipment must be integrated in a larger communicating system. In a digital utopic future society, it can be imagined that all buildings and facilities are equipped with smart technology and connected to intelligent substations. All components would then dynamically adapt to each individual customer’s behavior, be connected to a smart grid network and make intelligent decisions according to flexibility- and electricity market signals. However, the present state is far from being that interconnected. Depending on what type of flexibility strategy that is to be implemented, different types of governmental policies and infrastructural investments are required, as well as various grades of progressions within metering infrastructure and digitalization. For example, while local dynamic time-of-use tariffs require a high level of AMI and a smart grid infrastructure, the steering of boilers in households can function through existing technologies.

8.1.6 Impact of Non-Included Trends

There are trends that have not been implemented in the model due to their complexity and the difficulty to reflect them on a local level, especially in a substation. These trends are however important to keep in mind and further investigate in order to maintain a holistic view of future trends.

In terms of electrification, industries, data centers and heavy-duty EVs were not included in the model. This choice was made for three reasons. First, each industry is unique and not one load profile can be generalized to represent industries within the model in a good way. Secondly, the model only takes local grids into account, departing from a single substation. Large energy intensive industries and data centers are generally connected to a higher voltage level, they can potentially pose great impact on the local grid capacity, but only if they are located on a local substation, which most likely will not occur. Modeling an energy intense industry with electricity consumption equal to the city of Västerås, would moreover surpass the modeled substation even if several substations were aggregated to a larger grid. However, if a specific industry is of interest it could be included in the model through the custom loads functionality. Thirdly, as for the heavy vehicles, the implemented spatial model for EVs only took light weight EVs into account. Heavy-duty transportation was excluded partly for that reason but also due to the scope of the project.

The climate changes 20-30 years from now might pose an indirect impact on the grid capacity. Extreme weather in terms of longer periods of drought or heavy rain can affect both the hydro power and the intermittent electricity production which are directly related to the grid but not necessarily to the capacity. Milder winters can on the other hand decrease the heating demand and thus put relief to the grid capacity. In the future can therefore the data sets be updated to capture these changes in consumption.

Urbanization is causing increased pressure on grids in cities and around. The depopulation also means that the grid around the rural areas will provide fewer people and thus become more expensive for the reaming inhabitants. This could result in an increased drive for end-users to disconnect themselves from the electricity grid, at least during the summer, and become self-sufficient. Both population growth and urbanization naturally affect a local substation but is close to impossible to quantify and implement in a realistic manner in the model.

8.2 Combining the Scenarios and the Model

8.2.1 Theoretical Analysis and Classification

It should be remembered that the intention of the study is not to predict the future but to produce quantitative views and insights given key assumptions. In extension, the aim of the scenario construction was to gain understanding of and create long-term preparedness for how future trends could impact the local grid. Since forecasts about the future energy system and the electricity demand tend to have low accuracy looking at 20–30 years, it was suitable to pose the question of *what can happen,* rather than *what will happen*, as this project's time horizon is long term. A question of *what can happen* is often, as in this case, approached by using a combination of qualitative and quantitative methods and through combining predictive approaches with explorative. Here, the qualitive part mainly consisted of the literature review, while the quantitative parts consisted of quantifying the identified trends and the model implementation.

The constructed scenarios could be described as predictive in the sense that they strive to describe the most likely impact on the grid, while they could also be described as explorative since the different scenarios are ways to express "what if" and a range of possible outcomes. The predictive approach is largely derived from the reports and forecasts that suggest different future pathways and developments of identified trends. The explorative approach on the other hand, which has Energimyndigheten's four scenarios as a point of departure, function as a way to express key assumptions or variations in the trend parameters belonging to the predictive approach. Likewise, how uncertainties are coped with could be described as a combination of a typical predictive and typical explorative approach. Predictive, in the sense that the method uses real measured data and works with energy consumption in a data driven manner to reduce uncertainties within the simulations. Explorative, through constructing distinctive scenarios which aims to reflect and be characterized by the remaining uncertainties. Since including transparency is an essential factor within energy modeling, being transparent during the project and throughout the thesis has been a high priority. The assumptions made have been declared in the literature review, the qualitative method and in the results. Necessary information in order for the simulation to reproducible has been put forward to a future user. Hence, the method can be regarded as transparent.

The developed model aims to utilize the analytical method of bottom-up engineering. Although, it is worth mentioning that while it is the local level that is investigated, the degree of granularity in the modeled scenarios, is limited. For example, in Sandels and Widéns report, a more detailed picture of how the effect of i.e. heat pump efficiency coefficients and isolation in houses could change with time was given, implying a more bottom-up oriented method than the one used in this project. Nonetheless, a bottom-up method implies *piecing together subsystems into larger systems* which in this case refers to loads being aggregated into a substation which in turn is aggregated to a larger substation. This type of modeling method requires good access to disaggregated data. The more detailed and organized data that can be accessed, the more accuracy in the model. The method in this project can thus be seen as an attempt to a bottom-up method with room for more details in a future development on the model. Worth mentioning is that utilizing scenarios goes more in line with a top-down method. Yet, the distinctive difference lies in the classification of the model itself, which is bottom-up. One last note on the local grid focus is that the local grid is a matter of specific energy sector rather than a geographical area. However, in terms of geographical coverage – areas with local capacity challenges is where the model could leverage the most utility.

The investigator, Vattenfall Eldistribution as a large DSO on the market, has capability to affect the development to a certain extent. Through acting as an encouraging enabler and providing innovative and simple business solutions such as solar power systems or charging points for EVs, Vattenfall can steer the development, but not control it. There are thus both internal endogenous factors to take into account as well as external exogenous factors. An example of exogenous factors are climate change and urbanization. The model moreover strives for a low degree of endogenization to favor a flexible model structure. A high exogenous degree is instead targeted, allowing the user to explore parameters rather than predefining them (endogenously) within the model. In Table 15, a summary of the nine classification components and the model's relation to each component is reflected.

Table 15 *Classification of the developed model. Identified components indicated in bold.*

Classification	Characteristics
Purpose	*General: forecasting, **exploring** or backcasting.* *Specific: **energy demand,** energy supply, **impact**, appraisal or modular build-up*
Structure	***Degree of endogenization**, description of non-energy sectors, **description of end-uses**, description supply technologies.*
Analytical approach	*Top-down (economic) **or bottom-up (engineering)**.*
Underlying method	*Econometric, macro-economic, economic equilibrium, **optimization**, **simulation,** spreadsheet/toolbox, backcasting or multi-criteria.*
Mathematical approach	***Linear/ dynamic programming**, or mixed integer programming.*
Geographical/ sectoral coverage	*Global, regional, national or **local*** *Individual projects, **specific energy sectors** or overall economy.*
Time horizon	*Short, medium or **long term.***
Data requirements	***Qualitative, quantitative**, monetary, aggregated or **disaggregated.***

If focusing on the model, the general purpose is to explore while the specific purpose concerns electricity demand and grid capacity impact. The combination of the two establishes few limitations in width and thus more in depth. As a consequence, all the different trend implementations as well as constructed scenarios have room for improvement. The key finding within the project is how the combination of the scenarios and data driven model can function as a method, rather than any exact numbers or any certain lines of code.

8.2.2 Lessons Learned from Local Scenarios

The main reason behind using local scenarios was to bring added value to the model and enable the functionality of it being a tool for exploring effects on the future grid capacity. When viewing the model as a method to answer questions of "what if ", and at the same time keeping in mind its shortcomings, some noteworthy results was found when simulating the scenarios. However, the relevant findings within the outputted results are primarily the tendencies rather than the specific numbers. For example, when introducing an increased number of EVs in a substation, it is of interest to note that the simulation results show the need of *more* capacity, but not exactly how much more.

Starting with the scenarios *Individualistic* and *Modern,* these two scenarios have the widest variation in consumption. The maximum negative consumption can be derived from PV-production but also from the shortcomings of the dynamic flexibility, which is found within both scenarios. Despite the flexibility being in place to reduce the negative consumption in order to lower high peaks, the result still show many negative values. Most probably this is due to the inability of the simulation to redistribute consumption between days, meaning that the flexibility implementation only optimizes consumption on a daily basis and is not 'smart' enough. However, the dispersed distribution in the load duration curve shows the need for flexibility solutions and further possibilities to reduce peaks. Nevertheless, the values of the 99.5^{th} and 99.9^{th} percentiles indicate that the flexibility implementations still show great potential to flatten load duration curves if better implemented. This is especially true for the *Modern* scenario, which also has the most generous amount of flexibility available compared to substation consumption.

Regarding the introduction of PV-production in the scenarios abovementioned, it is of interest to see how the impact of a trend on national level is not necessarily equal to the impact on a local level. For example, the national predictions and estimations about the future penetration of PV from Johan Lindahl and Nicholas Etherden [56] suggest a percentage of 20-30 % of all buildings. Since the substations in the scenarios are of relatively small size, the PV-production was set to be less than 20 % in all scenarios, otherwise the PV-production would dominate the entire consumption of the substation in question. Despite that, the scenarios *Individualistic* and *Modern* show large negative values, indicating on the future challenge of balancing the high PV-production and low consumption during summer with the high consumption and nearly non existing PV-production during winter. This result problematizes the usage of national "per capita" estimations about future trends on local level substations and underlines the difference between national and local impact of a trend. Noteworthy, is that the negative peak of the *Individualistic* scenario is greater than the positive peak in absolute numbers. Hence, it is the negative peak in *Individualistic* that determines the capacity need of the scenario.

On the contrary, there are cases where the national scenario or outlook is directly reflected at the local level. The *Inclusive* scenario is similar to the *Legato* scenario, by Energimyndigheten [29], since they are both characterized by sustainability, less consumption and hence pose less stress on both transmission and distribution grid levels. In contrast, there are also cases where the local scenario contradicts the national scenario upon which the it is based, such as in the case of *Robust*. The *Robust* scenario simulation show a decreasing in consumption compared to the base case while the national *Forte* scenario, by Energimyndigheten, instead show an increase. One possible explanation for that is that large industries, which have an increasing impact on the electricity demand, has central role in *Forte*. The increase in demand due to electrification of the industry is however not translated into the local substation in *Robust,* since large industries rarely are connected to the local grid and hence does not affect an increase in consumption at a local substation. Another possible explanation is that the rest products from the industry were assumed to favor DH as heating option in *Forte*. Since the DH system does not impact the electrical grid capacity, it resulted in a decreased consumption on local grid level when implementing more DH usage in *Robust*.

The opposite situation can be found within the results from simulating the scenario *Individualistic*. While not taking into account whether it is realistic or not that customers goes off grid, *Individualistic* illustrates that the willingness to be connected to centralized systems constitutes a difference in terms of grid impact. In *Individualistic* 5 percent of the substation customers have gone off grid but the consumption peak and average are still the highest of the simulated scenarios. This result can partly be concluded from the individuals' opposition to be connected to the DH system, which in turn poses extra pressure on the electricity demand derived from the heating option. In summary, there are differences between the national scenarios and the local scenarios depending on the different trend's impact on local the level.

8.2.3 A Data Driven Approach for Grid Planning

What could be found through all scenarios, including base case, is the detailed information which is possible to generate through data driven model simulations. When departing from time series and hourly measured data, the data driven method can provide valuable insights for the DSO to proceed with in regard to long term planning of local grids. For example, looking at percentiles of consumption could enable other ways of working with grid dimensioning which perhaps could incorporate more uncertainties and informed risk decisions. Rather than focusing only on the maximum peak load, the percentiles can tell how frequent the peak occurs which constitutes as an additional parameter to take into account when planning and deciding about the future grid design. An additional advantage of working with time series is the visualization of the yearly variations which is of great importance in a country with distinctive seasons like Sweden. The transition to more intermittent and decentralized power generation in combination with a seasonally altering consumption emphasizes the necessity to obtain a good view of when and how frequent peak values occur. The time aspect here is essential and is a consequential benefit from using time series. It can for example be argued that utilizing time series is decisive when working on flexibility solutions in order to capture the values of reducing *real* peaks rather than expected peaks. The obvious disadvantage of using time series is that it requires accurate and existing data. When data is not obtainable, either out of practical reasons or if future not yet existing trends are desired to be modelled, then time series have to be made up, which often diminish the variations of reality. However, through constructing a surrounding infrastructure, as in this project, imperfect or simulated data can later be replaced with real data.

Moreover, traditional grid dimensioning methods are not well-suited enough for new trends such as batteries, flexibility and EVs. As mentioned, the peak consumption has traditionally been estimated with methods such as the Velander formula and later from using standardized power estimations [83],[85],[84]. Using Velander constants and estimations for grid planning is however not compatible with a large expansion of EVs due to the fact that the charging of EVs changes the relationship between consumed energy and power with high but rarely frequent peaks. The formula which compares yearly consumption with power peaks, will thus give an inaccurate view of the electrical energy consumption in relation to the power peaks. For example, to include EV charging in the long-term grid planning, use of standardized power estimations or constructing new Velander constants can be applied that takes EV charging into account. However, since hourly measured data is obtainable, working with time series seems like a more practical and useful option. Time series eliminates the problem of comparing the sum of the total maximum consumption with the peak consumption for each individual customer. Visualization through time series also allows a higher resolution for decision making when looking at the capacity challenge. For example, can information about when, to what extent and how frequent the highest peak occurs be useful when deciding about new connections. If an outstanding high peak occurs only once per year, then the grid reinforcement could realistically be dimensioned after other criteria's than the absolute maximum peak. Simply, instead of approximating standard power estimations, actual consumption data can be used for the same purposes and possibly give more accurate insights. This project has emphasized a wide and high-level discussion about future trends' impact on the grid capacity. However, the developed model itself has enabled more in-depth and comprehensive analysis through utilizing time series. A knowledgeable user could through small changes and especially better access to data, achieve useful and powerful calculations for future analysis.

The digitalization of the energy sector has enabled the implementation of methodologies utilizing real measured data for load analysis. Vattenfall Eldistribution has an endeavor to improve the quality of both long-term planning and simulation tools as the desire is to plan electricity grids as optimal as possible. Through maximizing the benefit of investments and prioritizing the right projects, uncertainty margins based on costly model errors can be reduced. Implementing efficient data driven models can thus provide a substantial positive impact on grid operation and planning. It could be easy to imagine a trade-off between privacy and working in a data driven manner. However, since the use of data within this method is anonymized, privacy remains a challenge of the data collection rather than the model or the analysis. Nonetheless, future data driven implementations will have to continue to strive for an optimal balance between regulations and opportunities, as data still yield benefits for both the business as well as the individual customers and the society.

9. Conclusions

Rapid societal changes are currently putting pressure on the power system, where lack of capacity is among the most urgent problems. Especially in urban fast-growing areas is lack of capacity a challenge. Whereas societal development happens fast, reinforcing the grid takes a long time. Seen to the Swedish DSOs responsibility to allow new connections and enable societal development, there is a need for enhancing a more proactive way of planning the capacity that takes into account upcoming trends. Against this backdrop, this project has addressed the grid capacity through time series. More specifically, a data driven and scenario-based method targeting *what can happen* has been derived.

Where the traditional ways depart from standardized power estimations, a model developed alongside the thesis utilizes information in time series. To cope with the long-term time horizon of grid planning, the model is built to explore the effects that different scenarios could have on the local grid capacity. A low degree of endogenization in combination with a bottom-up approach was chosen to favor a flexible model structure as well as scalability.

The trends identified to pose impact on the future grid capacity are electrification of different sectors, energy efficiency actions, decentralized electricity generation, energy storage solutions, flexibility, smart grids, urbanization and climate. The subfactors of these trends which are concluded to especially impact the capacity at a local level, and hence are included in a developed model, are; PV-installations, EVs, individual flexible customers, aggregated flexible markets and energy efficiency. The non-included trends are still thought to impact the capacity but are not directly reflected on the local level. They are thus important to include and further observe in order to maintain a holistic view in terms of future grid dimension and reinforcement. Even though more time series data, higher data granularity and improved trend implementations would improve the model, some benefits of the developed model could still be found. The thesis concludes that the impact of a trend on national level is not automatically equal to the impact on a local level. Similarly, a long-term increase of the national electricity consumption does not necessarily worsen the local capacity challenges.

Although the project has emphasized a wide and high-level discussion, the developed model itself has enabled more in-depth grid analysis through using time series. The model shows potential as a method to provide both detailed and accurate information about hourly consumption – information which is used to dimension grids. Furthermore, the communication of comprehensive, necessary and reproducible information about the model and its simulations, enables a transparent method for continuous development. Additionally, the model generates graphical output which enables visualization and could favor more transparent decision making.

In conclusion, since the relevant data is already being collected – it is high time to capture the value of working data driven. Addressing grid capacity through time series could assist in being one step closer to keeping up with the rapid pace of today's society.

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Appendix: Future Work

This appendix depicts suggestions on future work and continuous development of the model. The aim of the project was to develop a flexible, transparent and data driven approach to visualize and gain understanding of the impact of trends on the grid capacity, meaning that most modules in the model are only briefly touched upon and some potential modules are not included at all.

Data Coverage

A prerequisite for further development of the model is a larger and more detailed data coverage. In order to work with time series and data driven models, good access to data is a necessity. The data should ideally be unaggregated, detailed and organized. It is easier to start off with unaggregated data in order to obtain a comprehensive view and conduct relevant analysis.

Development of Model

The design and usability of the GUIs were not priorities and hence are areas of improvement. Additionally, there are several disable features which should be added to the model as well as taken into account in the analyses in order for the method to be well grounded.

- The PV-production profiles used in this project were simulated in MATLAB using a script that calculated the produced electricity based on information about temperature, wind speed and specifications about the solar panels such as inverter and efficiency. There are two main approaches of implementing PV-data as time series in the model. The first is to collect real measured PV-data and the second is to construct data through using a bottom up method i.e. calculating irradiance and then converting it to solar power, similarly to the data generated in MATLAB. The choice depends on the desired outcome. If one wants to preform long-term forecasting and modify the efficiency values of the panel and inverter parameters, then the backcasting approach is perhaps more suitable. A more compatible way of preforming a bottom-up simulation is to use the already developed python library, pvlib [95], that can easily be implemented in the developed Python model instead of MATLAB. On the contrary, real data can provide more realistic and detailed result in the simulations. Using real time series from PV-production will capture the yearly variations in sun hours as well as the variations in azimuth and tilt angles.

- Decentralized wind power is an important part of the power grid and should be implemented on an aggregated level of substations when further developing the model.

- Industry, data centers and heavy-duty transportation are trends that should be implemented in the model. It would be highly interesting to expand the EV-module and for example visualize flexible charging vs. nonflexible charging for both light weighted EVs and heavy-duty EVs. Moreover, eventually add real data that reflects an actual electrified transport sector. Furthermore, the already existing EV charging station class of model should differentiate the different charging station types in order to enable different behaviors depending on type. For example, for the home charging to be flexible while the fast charging at other stations is not.

- In terms of the flexibility implementations and flexible agents, there are lots of areas of improvement. Making sure the implementations are more realistic and include more details about flexibility markets. Including modelled market signals, would for example be desirable. Additionally, the industry and service sector will be important player on future flexibility markets and should therefore also be included in the model implementations.

- Integration of financial- and market related functions. Flexibility is only one trend that is largely dependent on market signals, governmental policy instrument and spot price. Through including financial- and market related functions, modules that takes into account for example dynamic power tariffs can be included.

- The energy efficiency trend was greatly simplified in the model of this project and could be develop further. For example, energy efficiency can be modeled according to the characteristics of a certain substations, i.e. if the substation is located in an urban or rural area substations with new or old houses.

- Implementation of both rural and urban grid is desirable since there are differences especially in terms of DEGs and urbanization. This is also connected to the benefits with expanding the data and regions incorporated within the model.

- A differentiated grid analysis where several local grid characteristics are included as well as more loads based on different fuse levels such as restaurants, small service facilities and small industries would make the model more comprehensive.

- Lastly, there should be an accompanying power flow analysis to the developed model in order for the method to be more complete. A power flow simulation with voltage analysis should be taken into account when simulating future trends such as PV-installations and EVs since those trends pose great impact on the voltage level and power quality, especially in rural grids.