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FLEXIBILITY NEEDS IN 2035'S FINNISH ELECTRICITY SYSTEM

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Executive summary

To achieve climate goals for 2035, the Finnish electricity system will have to reduce its carbon dioxide emissions. Renewable electricity sources, like wind, are intermittent, and there can be an imbalance between electricity production and demand – as demand and supply should always match, there is need for flexibility in the system, that can mitigate this imbalance.

This project was done to Energiateollisuus, who hoped to gain a better understanding on the flexibility needs of the energy system in 2035. Thus, the goal of this project was to get a better understanding of the scale of the flexibility needs in the Finnish energy system in 2035 and determine the impact of various technologies. We aimed to evaluate the flexibility needs in the Finnish energy system in 2035 and to provide answers to the question, which flexible technologies are best suited in terms of total costs and CO_2 emissions.

We evaluated the amount of flexible energy needed in the electricity system 2035. On top of this, we studied possible technologies capable of providing flexibility, and modelled the possible electricity system with flexibility needs and flexible capability ranges of each of these technologies. 112 different scenarios for Finland in 2035 were developed using the modeling tool Energy Plan. The scenarios were based on various pathways of development of Finnish energy system during the upcoming years and they covered a realistic range of possible energy mix.

The general requirements for flexibility in 2035's Finnish energy system were assessed based on numerical residual load analysis, considering flexible power as well as power ramping rates. In all analyzed scenarios, the flexible power required on both supply and demand sides was of the order of 10 000 MW. The value of necessary flexible power was only influenced by the presence of stable baseload power in the power system, coming from sources such as hydro and nuclear power plants.

For the power ramping rates, the differences between different scenarios were minor. Generally, the ramping rates required by Finnish energy system of 2035 are about the value of 100 MW/min both for supply and demand side.

Across all the scenarios, increased amount of baseload generation (hydro & nuclear power) resulted in decreased costs of the system and decreased CO_2 emissions. Industrial P2X held the highest potential for flexibility, but it is important to acknowledge that the modeling done for the project had significant limitations regarding P2X assumptions. Adding P2X into the system increased total energy demand, which partially covered by natural gas power, thus increasing both annual costs and CO_2 emission to the system. Electric vehicles and storage options did not have significant impact on the system.

In our model, it seems like reaching carbon neutrality will still need slightly more than what we considered – out of our modelled scenarios, neither the most probable scenario nor the average of 10 lowest cost scenarios, didn't quite make it to the electricity sector carbon neutrality target in terms of carbon emissions.

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CHAPTER 1
INTRODUCTION

1.1 Introduction

The electricity sector exists within a context of different societal requirements, of which one of the critical ones for today's society is sufficient access to reliable electricity. Energy security is linked to multiple issues such as public health and the environment. The instability of the power system network can threaten society's social and economic functioning. Thus, electricity demand should be met at all times. However, the increase of electricity generation to meet the increasing demand has negative impacts on the environment if the additional electricity generation is done by adding energy sources based on fossil fuels. In general, fossil fuel use needs to be minimized, as carbon dioxide emissions directly cause global warming and the sustainability crisis.

Finland aims to tackle the sustainability crisis by 2035 – one of the targets is to be carbon neutral by the aforementioned year. Currently, Finland's carbon dioxide emissions from fossil fuels and peat use count around 20 $MtCO_2$ (Statistics Finland, 2021). For the energy sector, the goal is to half carbon emissions by 2030, compared to 2018 (Energiateollisuus, 2020). The work to achieve climate neutrality has already started, and for example, the HIISI project analyzes electricity production to be almost non-carbon-based by 2030 (Government of Finland, 2021). Energy consumption, however, is in a crucial role, and there will be some significant changes in the electricity production system by 2030 – one of them being a rapid increase in electricity (Government of Finland, 2021).

Based on a larger number of intermittent sources, the future energy system will need fossil-free flexible energy sources that can compensate fluctuations in intermittent source energy production and keep the future power system dependable, even on windless, cloudy and cold days. Thus, there is a need for a method to evaluate flexibility and the possible technologies that can provide it in the future electricity system.

1.2 Goals

The political decision of Finland to become carbon neutral by 2035 requires the electrical energy sector to lower its carbon emissions. As the role of fossil fuels is already quite modest, lowering the emissions even further is not a simple task. It is therefore the goal of Energiateollisuus try to get a better understanding of the scale of the flexibility need in the Finnish energy system in 2035, as flexibility could become a major bottleneck issue. To aid their understanding, the goal of our project is to simulate multiple possible outcomes of the mix of technologies in the Finnish energy grid in 2035, and to determine the impact of the technologies.

To achieve this, we will determine the total amount of flexibility needed in terms of power and energy in multiple timescales, as well as an investigation of how different sustainable technologies in 2035 will be available to an extent that allows the system to have zero carbon emissions. We are aiming to provide answers to the question of which flexible technologies are best suited in terms of total costs and CO_2 emissions.

1.3 Project Scope

Energiateollisuus hoped to gain an understanding of the Finnish 2035 flexibility needs, and thus the scope of this project will concentrate to the flexibility needs in the Finnish energy system in 2035. Additionally, the project concentrates on various technologies deemed feasible and probable in the future energy system of Finland, so it does not include all possible flexibility options.

The forecasts are based on the literature available as of year 2021 and techno-economic assumptions covered in detail in further sections of this report.

The concept of flexibility needs in the power system is relatively new, being the result of recent advances in decarbonization of power grids, driven by ambitious climate mitigation policies implemented in the European Union. There is no strict definition of flexibility needs or standardization of different areas covered by this concept. However, for the sake of this paper, the authors propose to define flexibility needs as: "*The aggregated sum of installed power of different flexible and dispatchable power sources in the energy system, including the supply side, the demand side, and energy storage, along with the prevalence of different power levels dispatched during a specific time period, required to balance the power supply with the demand*".

The flexibility needs in the power system are the result of the mismatch between baseload power supply and fixed power demand. The numerical value of such a difference for a specific timespan is called residual load. In this project, the flexibility needs of the system are quantified based on the analysis of residual load throughout one year with a temporal discretization of one hour.

To achieve the numerical results, the Finnish energy system is modeled hour by hour, considering baseload power generation, flexible power generation, fixed energy consumption and flexible energy consumption available in 2035. Energy storage serves as both flexible power supply source and flexible demand source. Additionally, the presence of interconnections with neighboring countries is included into the model.

In this project, 112 different scenarios for Finland in 2035 have been developed using the modeling tool EnergyPLAN. The scenarios are based on various pathways of development of Finnish energy system during the upcoming years. The scenarios cover realistic range of possible energy mix, including economy driven implementation of energy storage technologies, distinctly dependent on uncertain technological breakthroughs, while also taking into consideration politically driven decisions regarding future of hydropower and nuclear energy. In this report, the authors compare the scenarios in terms of total system costs and total CO_2 emitted, as these factors are the main indicators of the success in the energy transition towards climate neutrality. Some of the scenarios assume very optimistic situation, while others are more conservative. The authors decided to highlight the scenario which holds the biggest probability of being implemented and compare it with the rest of them.

The results obtained with the modeling also allowed the authors to discuss the benefits and drawbacks of different technology mix and to present the most beneficial direction of future power system development for Finland.

CHAPTER 2
2035 ELECTRICITY SYSTEM

2.1 Electricity Demand

Forecasting the future total demand of electricity is very difficult. If we look at recent years, total electricity consumption in 2020 was approximately 81 TWh (Tilastokeskus, 2021a). However, this consumption was the lowest in 20 years, and compared to for example the year 2019 it was lower by approximately 6 percent. This was due to 2020 having both a warm winter and a lower electricity demand in the industry. It is likely that electricity demand will increase, as Finland aims for carbon neutrality by 2035, greatly due to electrification – electrification is a good solution for decreasing greenhouse gas emissions in many sectors, providing the sector itself can fully decarbonize. Electrification can substitute many processes based on combustion of fossil fuels and which are thus carbon intensive, for example processes in heat production, industry, and transport.

There are many estimations made for the electricity consumption of year 2035. Fingrid has estimated in their Network Vision (2021a) four scenarios for the future electricity system. In these, the total electricity demand varies from 105 TWh to 145 TWh. Another estimation from Sitra (2021) is that the electricity consumption will be approximately 120 TWh in 2035. All these projections are above current electricity consumption and thus it seems certain that electricity consumption will increase. However, the rate of the increase is uncertain.

The most uncertain sector for electricity consumption in 2035 is industry. Industry already has the greatest sectoral share of electricity consumption in Finland but many industrial processes in steel and petrochemical industry directly use fossil fuels. An effective way to decarbonize these processes would be electrification: taking the example of steel production, the conventional production method requires coal, but the same reaction could also be achieved by hydrogen. Many existing processes in the petrochemical sector also use hydrogen. At present, hydrogen is generally produced from natural gas, but the required hydrogen could be produced from water with electrolysis. This power to X method, is examined later. In addition to using hydrogen, some industry processes might electrify directly. Also for example, steam cracking process in petrochemistry might be directly electrified in the future (Layritz L. 2021).

Electricity will also be used more for heating in the future. Currently, coal still plays a role in district heating, but the role will decrease, since use of coal for energy is banned from 2029 onwards in Finland (Valtioneuvosto, 2019). The replacements for coal-fueled CHP plants are planned to be waste heat and heat pumps, which already produce some of the district heating in Helsink. For example Katri Vala heating and cooling plant uses wastewater heat and heat from return water from district cooling.

2.2 Generation

Power systems consist of power generation (supply) and consumption (demand). In accordance with Finland's Low Carbon Roadmap (AFRY, 2020), electricity generation capacity surge is necessary, since the industrial sector decarbonization will take place and cause an enormous increase electricity consumption. In addition, Sitras' Enabling Cost Efficient Electrification in Finland Report (2021) delivers that the electricity supply in Finland should be boosted since the electricity demand will grow by over 20% in 2035.

Finnish generation capacity will reach around 45 GW in 2035 from below 20 GW in 2020 (Sitra, 2021). This over 50% capacity addition is covered mostly by the wind sector under the assumption that wind generation costs hover below decarbonized generation technologies. In addition, a drastic increase in wind power, needs addressing issues such as descending public compliance and requirements of the Defense Forces for wind power plants.

On the other hand, the high proportion of intermittent sources in the energy system requires a considerable amount of flexible generation technologies, such as hydro power, peak generation gas turbines and storages. Storages include batteries where it provides relatively short-term supply and Power-to-Gas-to-Power system as long-term storage. Power generation by biomass CHP plants, which comprise approximately 10 TWh/a, also gives leverage to the future energy system, as biomass is a good replacement for coal and peat fired generation.

Beside the current uncertainty of Hanhikivis' nuclear power plant actualization, nuclear capacity in the Finnish 2035 power system will have the maximum of around 5500 MW installed power, as base load. Hydroelectric power generation capacities will continue invariable as the present level.

2.3 Flexibility Needs

To estimate the flexibility needs for Finland in 2035 we will make an analysis with the projected 2035 energy production of the non-flexible sources i.e., sources that bids at close to 0 €/MW in the day ahead market, namely wind and nuclear. This will be put against the projected (non-flexible) demand of 2035 to give a view of the need for flexible energy and power over the year. As our focus is on the mid-term flexibility, this analysis will be done over a full year with a time resolution of one hour.

The demand and wind data of 2019 in an hourly resolution have been found from Fingrid (2021) and then linearly scaled to match the expected yearly total of 2035 by AFRY (2020), as seen in Table 2.1. For the baseload nuclear power, we assume a stable production throughout the year which comes to 5123 MW.
Generation technologies which are left out of Table 2.1, are hence considered to participate in the day-ahead market with incentives to be flexible.

Table 2.1 Yearly demand/production

	Year 2035
Demand [TWh]	110
Wind [TWh]	30
Nuclear [TWh]	45

A month of the scaled data can be seen in Figure 2.1 This shows the longest period with a deficit. The 14 days from hour 320 to 660 has a total deficit of 2260 GWh which therefore should be provided by the flexible sources.

Furthermore, the peak need for power flexibility at the most needed hour is 12 and 13 GW for extra production and extra demand respectively. This have been found as the maximum and minimum value of the Flex. need trace on Figure 2.1.

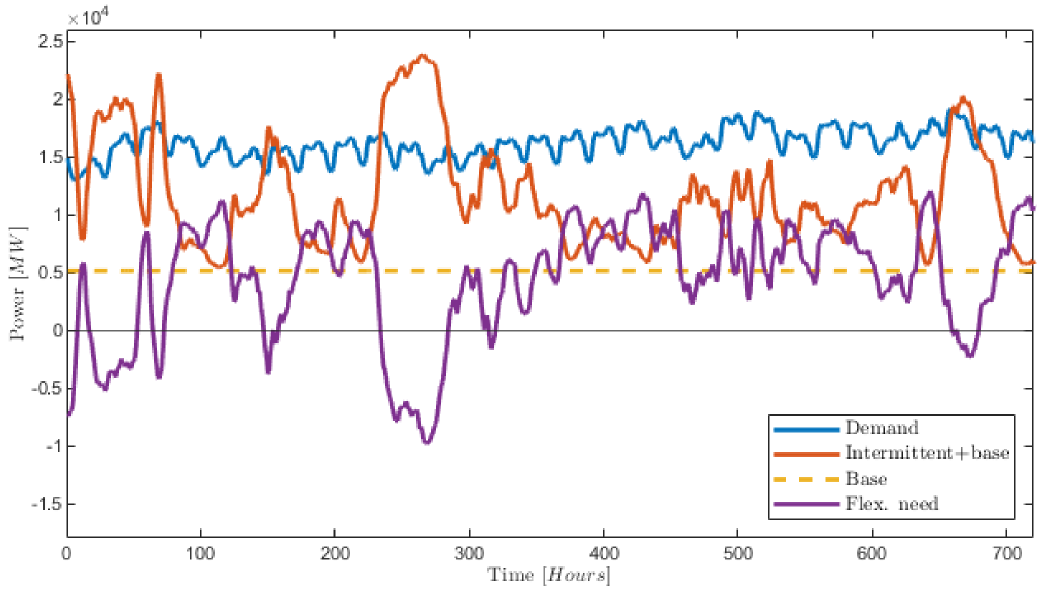

Figure 2.1 Estimation of flexibility need in January 2035

We have now conducted a theoretical analysis which, based on simple assumptions, shows results of the direct need for flexibility in the Finnish energy system 2035. This gives a brief overview of the magnitude of which we are talking about, and we will now go into a model-based analysis which, with a greater number of parameters, provides a more detailed view of the need for flexibility.

CHAPTER 3
FLEXIBLE TECHNOLOGY OPTIONS

3.1 Generation

a. Bio- Combined Heat and Power

Combined heat and power technology is considered as one of the most efficient heating methods since it can effectively produce heat and electricity simultaneously. In Finland, CHP is a primary method for district heat production, while having almost 90% for overall efficiency (ETIP Bioenergy Fact Sheet, 2019). It also has covered 26% of the Finnish electricity demand in 2019 (AFRY Finnish Energy Lower Carbon Roadmap, 2020). Generally, CHP plant fuel can be natural gas, light fuels oil, coal, solid and gaseous biomass, as well as waste fuels. Due to coal ban and tightened climate policy in 2029, many CHP plants are switched to utilize biomass instead of fossil fuels.

The CHP plants that use biomass fuels, Bio-CHP, are a mature and reliable technology. Solid biomass fuels are a combination of forestry materials and forest industry residues while liquid biomass fuels consist of biodiesel or ethanol from sugar and starch crops. The availability of biomass in 2035 should be taken into consideration, as using biomass can bring new problems in terms of sustainability of biomass supply, for instance due to the risk of decreasing forest carbon sinks. Therefore, it is likely, that the sustainability criteria for biomass will be tighter in the future. On the other hand, Bio-CHP has dispatchable generation capacity and high share of domestic fuels, especially in Finland.

CHP plants are often must-run plants which generate power independence of electricity price due to their primary task – heat production. These plants have a capability to respond in changes of the residual demand. Bioenergy is considered as important source of flexibility, as it can be shut down when it is more cost-effective to use the heat boilers since almost all heat networks have adequate heat boiler capacity.

Bio-CHP power availability as flexible technology in 2035 is determined by evaluating the existing CHP plants and the forecasted fuel consumption in power and district heat production. Based on Finnish Energy Authority publication (2021), there are over 100 boilers in CHP plants in Finland until now, including industrial CHP and district heating CHP. In this project, we calculated the maximum power availability in 2035 by assuming that no new CHP plants will be built, the number of plants using biomass remains the same and all the fuel used will be switched to bio-based source. This reasoning is also aligned with our stakeholder interview, namely Fingrid. Based on AFRY's Executive Summary Report of Finnish Energy Low Carbon Roadmap 2020, the rest of the fossil fuel supply is scaled down by and replaced by biomass resources. For the minimum power availability value, we also assume that existing CHP plants will be decommissioned by 10% considering that this year decommissioning rate is 8.8%. The available power data of CHP in 2035 Finnish Electricity System is tabulated on Table 3.1.

Table 3.1 CHP Plants in Finland on 2021

Fuel	2021 Power Maximum
Peat	1360
Industrial wood residues	580
Natural gas	1360
Hard coal and anthracite	990
Forest fuelwood	690
Black liquor and concentrated liquors	1370
Gasified waste	45
Blast furnace gas	90
Heavy distillates	9
Light distillates	1
Biogas	9
Other	360
Total	6864

Table 3.2 CHP plants power availability on 2035 Finnish Electricity System

Fuel	2035	
	Power Maximum	Power Minimum
Industrial wood residues	580	
Forest fuelwood	690	
Gasified waste	45	
Biogas	9	
Others	2293	
	3616	3255

b. Hydro power

Hydroelectric power (hydro power) in Finland consists of run-of river plants (without reservoirs of significant size) and of dammed plants (with reservoirs that can be filled with considerable amount of water). In Finland, there are no pumped-hydro plants, however dammed plants can similarly accumulate water supplies for further use.

The data available from ENTSOE-E Transparency Platform (2021) is, however, blended data of total hydroelectric generation, without differentiation between different types of hydro power plants. Nevertheless, from the energy system point of view the combined generation of all plants can be decoupled into the imaginary superposition of one run-of-river plant and one pumped hydro storage with a reservoir of a defined size.

Consequently, the hydro power generation has been decoupled into daily-averaged baseload generation (which power linearly changes from noon one day to noon of the next day) and the remaining fluctuations, which correspond to short-term daily energy storage. The analysis of the 2019 data resulted in the values of 2500 MW of installed hydro power, 11.5 TWh/a of hydro generation and 10 GWh of storage potential of Finnish water reservoirs. These values were used for the first of two possible pathways of hydro power – as a reference pathway.

The second pathway for Finnish hydropower assumes closing half of the hydro assets. Although, there are no established policies for such actions, this report investigates such hypothetical situation with the purpose of assessing the influence of hydro power on the power system, as well as flexibility related characteristics. Consequently, the second pathway considers 1250 MW of installed hydro power, 5.75 TWh/a of hydro generation and 5 GWh of dammed storage potential.

It is important to acknowledge the existing limitation in the modeling tool used when considering hydropower related results. Although the generation was successfully decoupled into run-of-river generation and storage, in some periods of the year the river “overflows” the dam. This phenomenon happens when the reservoir storage is already full, but there is no additional demand for energy. Dam overflow happens in situations, when the wind generation is strong and stable through long periods of time. The excess energy cannot be further stored, and the export limits have been reached. The result is curtailing of renewable hydroelectric energy, and it is counted by the model as further reservoir charging – or in other words, irreversible loss of storage. In the graphs, this manifests itself as considerably higher amount of energy supplied to the hydro storage than retrieved from it.

c. Gas Turbines

As intermittent energy source capacity increases, gas turbines are needed to ensure the reliability of delivery. Gas turbines are a reliable back up power. They offer power generation with fast response in imbalance situations. Gas turbines can be used always when needed if fuel supply is assumed to be unlimited. Gas turbines are generally more in use during the winter season when there are peak demand hours. According to Sitra’s report, new additional gas turbine power plants are needed for energy transition period. They assume that the installed power capacity of gas fired power would increase from 1.5 MW to 4.5 MW by 2035. However, we have let the model decide how much gas fired power is needed.

Gas turbines are regularly used with natural gas as a fuel. Natural gas is a fossil fuel which means that producing electricity by gas turbines has reasonably high CO_2 emissions. According to the EIA (2021), emissions from burning natural gas are 0.91 pounds per generated kWh of electricity. This is approximately 410 g/kWh. In comparison, the average emissions of Finnish electricity production were only 74 g/kWh in 2020 (Fingrid, 2021). This means that while using natural gas has lower emissions than coal, it is not a low-carbon energy source for electricity. Because gas turbines are reliable source of back-up power, it is discussed that gas turbine power plants could use alternative sustainable fuels instead of natural gas. These could be for example biofuels or renewable fuels of non-biological origin (RFNBO's). However, they are not yet feasible enough. Therefore, for simplification, it is assumed in the modelling that open cycle gas turbines (OCGT) will use only natural gas as a fuel.

3.2 Demand Response

Demand Response is one potential flexibility technology option. U.S. Department of Energy defines demand response as follows: *"Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."* This means that demand response is a method to cut down peak demands or to meet demand for peak supplies in order to balance the electricity system.

a. Industry

Industry is the largest sector by electricity consumption in Finland. Electricity consuming processes could provide demand response capacity that could postpone their electricity consumption if needed. Transmission system operator (TSO) of Finland (Fingrid) has already made agreements with industrial companies for reducing electricity demand if necessary. Many industrial processes can react very quickly to imbalance in the grid. According to Gils H. (2014), the theoretical potential of demand response in Finnish industry is approximately 1200 MW of reduction power. This is in line with AFRY's Low Carbon Roadmap (2020), evaluating the range for 1000 – 1500 MW depending on the situation.

However, not all of the potential of demand response in industry has been utilized. Shoreh M. et al. (2016) have stated that the main barriers for industrial demand response are financial, regulatory and knowledge based. Financially, companies don't get enough persuasive incentives by demand response. Industrial companies have had other financial factors to consider operating their processes than the flexibility needs of electricity system. In addition, evaluation of the benefits for the companies of demand response is not clear. Few main regulatory issues are utility reconstruction and limitations on market regulations. As it comes to knowledge-based barriers, companies do not have the knowledge or understanding about the topic. One other knowledge-based barrier Shoreh M. et al. (2016) state is that it would be an administrative burden, demand response would need experts to work on it and consume a lot of working time.

As industrial processes are being electrified, the potential of demand response in industry starts to increase. Many companies are already investigating the possibility for demand response or how to increase it. For example, UPM (2021) announced that they have launched an energy optimization and trading service *Beyond Spot* which gives industrial companies a possibility to operate their electricity consumption flexibly. In AFRY's Low Carbon Roadmap, the benefits of industrial demand response are found to be the potential for increase and smaller investment costs when comparing to additional generation or storage. Pöyry (2020) has stated that the electricity consumption could increase up to 50% by 2035 and the new investments are more likely to be flexible. As a result, it can be assumed that the industrial demand response could be up to 1800 MW by 2035. Many industrial applications can be flexible only short amounts in total. In a case study of demand response for a steel mill (Tang W. et al., 2020), the maximum demand response time was limited to 9 hours a month. This would mean 0.17 TWh of flexibility in a year.

b. Power to X (P2X)

In 2020, the National Hydrogen Roadmap for Finland has been developed by Business Finland, a public organization under the Finnish Ministry of Employment and the Economy (J. Laurikko, 2020). The document defines Power-To-X (P2X) as synthesis of chemical products through low-carbon hydrogen produced with low carbon electricity and/or captured carbon. According to the authors, such hydrogen is going to play a key role both in combating climate change and reaching the goal of Finland's national carbon neutrality by 2035.

In recent years, hydrogen economy has been a highly debated topic, with significant differences in the vision of future adaptation. As an example, (IEA, 2021) in their report *Net Zero by 2050. A Roadmap for the Global Energy Sector* used very optimistic assumptions about future hydrogen demand, for which they have been widely criticized. Furthermore, (European Comission, 2020) in their report "A Hydrogen Strategy for A Climate-neutral Europe" stated power system backup, transport and even heating sectors as possible hydrogen consumers, including individual hydrogen boilers. Some of the energy experts remain sceptical about utilizing hydrogen in such wide set of applications (Liebreich, 2020). In this report, the authors decided to limit estimated hydrogen applications in Finland only to industry due to lack of expected incentives for hydrogen use in other sectors.

Currently in Finland (as of 2015), total industrial hydrogen consumption equals 5 TWh/a or about 150 kt/a. Compared to 281 TWh/a of total final energy use, hydrogen represents a 1.8 % share. It is almost entirely fossil fuel-based, however it represents an existing market, which with accurate policies and incentives can switch to, and become a consumer for "green" low carbon hydrogen produced with P2X.

Most of Finnish existing industrial hydrogen consumption is related to petrochemical industry – about 130 kt/a. It is used for the purposes of production of transport fuels (J. Laurikko, 2020). Another example of existing industrial consumer of hydrogen is chemical industry (10 kt/a), where different chemicals, mostly ammonia and methanol are already being produced. In the future (2030 onwards), green hydrogen-based steel production is expected to also enter the market, as a Nordic and US based company SSAB is planning to replace blast furnaces in Raahe steel mill with electric arc furnaces, therefore needing hydrogen for iron ore reduction. The additional hydrogen consumption attributed to steel is estimated as 120 kt/a. Total utilization in 2035 in Finland has been estimated as 300 kt/a of hydrogen.

From the flexibility point of view, industrial P2X sector can potentially become one of the most significant demand side response consumers. Flexible hydrogen generation is an enabler to deploy, and successfully manage, more variable renewable power in the energy system. In the modelled scenarios, two pathways of flexible P2X are considered. In the first pathway, there is no P2X consumption from the energy system at all. This is a reference situation, reflecting "business as usual" situation, where hydrogen is still produced by fossil fuels. That assumption would be also valid, if all industrial P2X is considered to be generated from off-grid power sources, such as renewable or nuclear sources.

The second pathway assumes the total Finnish hydrogen consumption of Finland in 2035 (300 kt/a) to be generated by flexible P2X, operating at full power during minimum 25% timespan of the given day. This is equivalent to the condition of oversizing each of electrolysers in industry 4 times, while developing necessary infrastructure to allow for diurnal hydrogen storage. Flexible P2X consumers are assumed to operate on an incentive-based scheme, which means that the benefit for becoming such a flexible consumer is assumed to be a static reduction in electrical tariff equal to 30 $\frac{EUR}{MWh}$. The capacity factor assumption finds justification in P2X economy estimations by (International Renewable Energy Agency, 2020).

The projected use of hydrogen in Finnish industry in 2035 is 300 kt/a, which translates to about 16 TWh/a (J. Laurikko, 2020). Based on all the presented assumptions, the total industrial P2X power available for DSR is therefore calculated. The maximum DSR power of P2X is obtained as 7.2 GW and as such has been used in the modeling.

c. High Performing Heating, Ventilation and Air Conditioning (HVAC) Systems

Heating, ventilation, and air conditioning (HVAC) systems are accountable for supplying thermal, cooling and fresh air comfort in building. Overall, this system is used to regulate operation in order to maintain the desired temperature. One of the HVAC systems is heat pump. Reserve process of natural heat energy transfer is done by heat pump by absorbing heat from a cold space and releasing it to a warmer one. In addition, heat pumps can work reversibly by transferring warm indoor air to the outside. It requires external energy, such as electricity, to transfer the heat. Heat pump has emerged to become a mature technology. It is also grown to replace district heating as well as oil and electric heating. It operates a reversing valve to shift the flow of refrigerant from the compressor through the condenser and evaporation coils. The diagram of heat pump's working principle is shown on Figure 3.1.

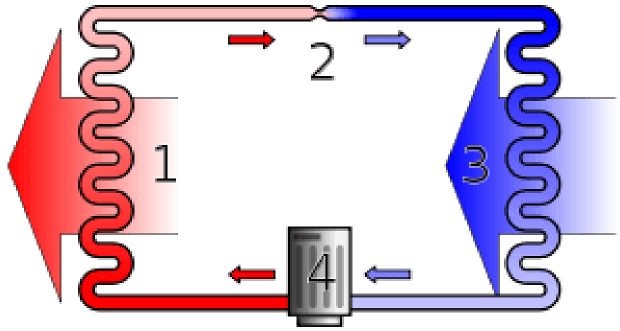

Figure 3.1 Heat pump working principle diagram (greenenergysolution.org)

Heat pump also can contribute into demand side flexibility. Due to their notable share in electricity consumption and coupled to accessible thermal storage in most buildings, heat pump is suitable for demand side management since it supports for modifying the electricity demand to generate heat. For instance, it can encourage foresight of electricity prices stability without sacrificing thermal necessity. Moreover, starting from 2021, the government aims to cut the electricity tax of district heating producing heat pumps by reducing the taxes from 22.5€/MWh to 0.5€/MWh (Finland Ministry of Finance, 2021). It will assist more the integrated system models to solve balancing problem.

Based on case study done by Patteeuw et al. (2015), an integrated operational model of a typical electric power system and a variable electricity demand for heat pump usage in buildings' electric heating systems showed a convincing approach about integration effect of the demand response on the supply and demand side. They examined the residual electricity demand from the integrated model with several variable such as fully (100%) participated in the demand response program, partly (50%) or not at all. It assumed that partly and not participating consumers were not disclosed to hour-to-hour fluctuation of the electricity price. Their model also assumed that RES-based electricity generation accounts for 20% of the supply electricity and projected carbon price by 2030. The result showed that non-demand response participant would give residual electricity demand of 22.96 MWh, partly involved would give 27.12 MWh and fully participation of consumers would give 27.28 MWh for one day period. For this project, based on the model, minimum and maximum availability of heat pump demand response can be achieve from the deviation of partly participation and fully participation with not at all participation, respectively. We are also projecting the power that will be available in 2035 Finnish Electricity based on Sitras' report on Enabling Cost-efficient Electrification in Finland and Finlands' Ministry of Economic Affairs and Employment report on the National Energy and Climate Strategy for 2030. The results are tabulated on Table 2.3

Table 3.3 Heat pump demand response power availability on 2035 Finnish Electricity System

	Value
Availability	18.12% (Minimum) and 19% (Maximum)
Power	1.23 TWh/year

d. Electriv Vehicles Charging (Smart charging)

Electric vehicles (EVs) represent an uncertainty in~~to~~ the future electric system, as they can both create significant additional electricity demand and work as a grid flexibility solution. Optimally, the idle time of parked EV’s in combination with their battery storage capacity, could make EV’s and attractive flexibility solution for the power system, where each EV is a small grid-connected storage unit with the potential to provide a wide range of services to the system. However, simultaneously, uncontrolled charging could increase peak stress on the grid. (IRENA, 2019).

By 2030’s, the global EV market is projected to expand, which will then become a challenge for the balancing of electric demand and supply (IEA, 2021). Electric vehicles are expected to grow in number by 2035 due to policy support and improvements in both EV technologies and infrastructure (McKerracher et al., 2021). For EV’s to become a flexibility solution rather than an additional cause of peak stress, smart charging is needed – meaning the adaptation of EV’s to both the conditions of the power system and the needs of vehicle users. Emerging innovations in smart charging need both the implementation of technologies as well as business models and regulatory frameworks. (IRENA, 2019.) Smart charging is not yet widespread – smart charging concepts currently are more time-of use charging with basic controls (IRENA, 2019), though in Finland there are some smart charging applications that provide smart load control in addition to optimizing charging time (Virta, 2019b). In order for smart charging to provide flexibility services, it will need to advance (IRENA, 2019) and it’s large scale deployment is likely needed to avoid congestions in the distribution network (Sitra, 2021).

It is clear, that the number of EV’s will rise both in Finland and globally, especially as sales have been growing at an increasing rate, though the car fleet is slow to renew in Finland (Traficom, 2020) and currently EV’s and chargeable hybrids represent only 1.6 % of vehicles on the road in Finland (Tilastokeskus, 2021b). It is also clear that smart charging solutions will be needed in the 2035 energy system. One solution to support smart charging would be to incentivize it, for example by a power-based tariff component (Sitra, 2021).

Despite the uncertainties of EV smart charging future, we decided to include EV’s as a flexibility option for the 2035 energy system. We assumed that smart charging is available and used for most EV’s, with just 15% of EV’s having a fixed charging load (aka they cannot do smart charging), to account for uncertainties in the system. We found this a conservative number, as cars typically spend 95% of their lifetime parked (IRENA, 2019) and the average kilometers driven with an average car in a day in Finland is already well below current EV ranges. On top of this, many charging stations already offer cheaper prices for night time charging (eg. Helen).

In order to estimate the possible flexibility smart charging could bring to the electricity system in 2035, we first needed to estimate the number of EV’s in Finland:

- In Finland the official state target is 250 000 electric cars by 2030 (Työ- ja elinkeinoministeriö, 2016). Regarding the recent boost in electric car sales, we sound this number somewhat low, but decided we would use it to benchmark the lowest number of EVs in 2035 – 300 000 EV’s.

- McKerracher et al. (2021), predict that 15% of vehicles on the road will go electric in 2035 – this is supported by the fact that IEA (2021) assumes EV's to be 12% of the entire car fleet in 2030, assuming a sustainable development scenario.
    - Assuming a similar annual increase in cars as before, about 0.9%, (Tilastokeskus, 2021b), 15% EV's would mean about 900 000 EV's in 2035:
- $5\ 172\ 173\ cars\ in\ 2020 * 1.009^{15} * 0.15 \approx 887\ 425$ (Cars in 2020: Tilastokeskus, 2021b)
    - 900 000 EV's is a high number – the Ministry of Transport and Communications (2021) forecasts that there will be 600 000 EV's in 2030 – but we decided to go with it to be able to model the uncertainties of EV's in 2035.

In order to calculate the available flexible power from smart charging in 2035, we assumed that there will be 11 kW chargers, with a grid connected share of parked cars of 0.6. The assumption for chargers is due to the fact that from 2022 there will no longer be financial support for chargers less than 11 kW chargers (Ara, 2021).

To determine the available power for smart charging, we still needed an average number for car battery capacity. This could be not found in literature, though there were speculations of possible breakthroughs in battery technologies and an upward trend in vehicle average battery size (IEA, 2020). Most battery electric cars are in 50-70 kWh range (IEA, 2020), so we decided to go with an average battery size of 80 kWh after discussing the issue with a representative from Ford – with current battery technology EV's would become too heavy if battery capacity is increased radically; thus instead of major upgrades in battery capacity, it is more likely there will be moderate upgrades. The smart charging power availability on 2035 Finnish Electricity System is tabulated on Table 3.4.

Table 3.4 Smart charging power availability on 2035 Finnish Electricity System

	Value
Availability	24 GWh – 72GWh
Power	3300-9900 MWh/year

We assumed that EV's will consume 3TWh of electricity in 2035. This is slightly lower than Sitra's (2021) assumption, 4TWh, but is based on the average km driven in Finland, 16 800 (Virta, 2019a), and average EV consumption in Finland, 0.2 kWh/km (Virta, 2019a) for a 15% EV share.

e. Electric Vehicles Charging (V2G)

Vehicles to Grid (V2G) is another EV related option in providing flexibility for 2035, where power from an EV battery could also be pushed back to the power grid. V2G potential depends on many things, among them the size of the vehicle fleet and consumer acceptance. IEA (2020) estimates that all being accounted for, 5% of the total electric vehicle battery capacity could be made available for V2G applications during peak times. Calculating from the typical charger power, number of EV's in Finland 2035 and the availability for V2G we get V2G availability, represented in Table 3.5.

Table 3.5 V2G power availability on 2035 Finnish Electricity System

	Value
Availability	Always
Power	165-495 MW

f. Buildings

Demand response also can be applied in the domestic and service sector. The demand management can be adjusted in cross-section processes, for instance, shifting load of heat demand in domestic hot water tank that measures same energy load despite of the timing. Shifting space heating from morning peak hours to a few hours earlier, essentially preheating the building, results in a reduced heat load during the event, possibly no change in actual energy consumption and small changes in indoor temperature during the demand response event (Sami, 2017). There is also load limiting strategy where the load is limited throughout certain occasion by acknowledging there might be slightly difference from favored state before. Light dimming is the example of load limiting.

In this project, the demand response strategies' controls in the buildings is analyzed by focusing on electrical appliances usage at residential buildings, such as refrigerator and freezer unit, washing machines, tumble dryers and dish washers. Each appliances has their own potential to ramp down or up their consumptions. For instance, some applications are better for increasing electricity consumption when there is excess wind power and others are better for lowering consumption for a time when there is no wind.

As what it is, finding out optimal demand response scheduling is a complex problem. But, in a simple way it can be achieved by short-term forecasts for energy prices and energy demand for certain times. The result of power available from buildings demand response energy simulation is 540 MW in 2020 based on the data from Gils H. (2014). We project 2035 flexibility on buildings demand response strategies by rationalizing electricity demand from Pöyry report (2020) which stated that the electricity consumption could increase up to 50% by 2035. The results are tabulated on Table 3.6.

Table 3.6 Buildings demand response power availability on 2035 Finnish Electricity System

Power Capacity (MW)	
Minimum	**Maximum**
290	435

3.3 Interconnections

Interconnectors can also be used as a flexibility option in the energy system. It is assumed that the interconnector capacity will grow in the future and Sitra (2021) has determined the available flexible power from interconnectors in 2035, report as shown in Table 3.7 as maximum capacity. The minimum capacity is from the same report, but an assumption for 2025 – thus it should be easily available in the 2035 electricity system. It is notable, that interconnections to Russia are missing from Sitra's (2021) assumptions and thus also from our flexibility options.

Table 3.7 Interconnector power availability on 2035 Finnish Electricity System

	Power Capacity (MW)	
	Minimum	**Maximum**
FI-EE	1016	1516
FI-SE	3200	3200
FI-NO	0	500

3.4 Storage

Rather than shifting demand or production it is also possible to store the energy from periods of excess production to periods of insufficient production. This is generally done by storage units which buys energy when the price is low and stores it until the price is high where it is then sold back to the grid.

a. Carnot Battery Storage

One of the promising technologies to store electrical energy is by conversion into thermal energy which may be stored in rock-beds and converted back when needed. Heat is generated and pumped through a large bed rock to reach temperatures above 600 ºC. The technology is best suited to store energy for hours to weeks and will therefore integrate well with a high penetration of wind power. The electrical roundtrip efficiency is in the order of 30 to 40 % (Pedersen 2018), which is not beneficial alone but by also utilizing the leftover heat of the output in district heating the technology could function as a combined heat and power plant when discharging. To connect it to district heating the plant needs to be geographically located near cities and preferably on the same premises as a CHP plant. It will take up some space in the magnitudes of a dozen of football fields for Finland but as it is mostly underground other facilities may be placed on top hereof.

b. Solid Mass Gravitational Storage

As we have an increasing need for balancing the system power many new storage types have been developed and explored. One which could have an impact in Finland is to store it as potential energy of solid masses lifted through the abandoned mineshafts. Generally solid mass storage is not economically feasible but studies in the central UK have determined that by usage of already existing mineshafts cuts the capital expenditure and it becomes economically feasible as well (Mortsyn, 2019).

One of the biggest benefits of SMG is the very low OPEX as the electric motors and other parts doesn't require much maintenance when installed, and hence the liftetime is also expected to be above 20 years. Furthermore SMG technology have already shown to be efficient compared to other new storage technologies at 80 % full cycle efficiency (Mortsyn, 2019).

It is also stated by Mortsyn (2019) that the United Kingdom Government Coal Authority Abandoned Mine Catalogue, contains 340 mine shafts that could be converted into gravity storage units with energy capacities above 1 MWh, thus providing 0.804 GWh of energy storage in the UK. Finland has 1000 old mines whereof 600 does not contain hazards at first sight, and it should therefore be possible to get up to 1GWh of total energy storage from SMG.

c. Electrochemical Battery Storage

The last storage option included is electrochemical batteries. For our purpose the different types of chemical batteries have very similar properties, and we will assume the lithium-ion technology since it is currently the most used and developed for grid scale (NREL 2019). An extensive comparison of the parameters of electro chemical batteries in have been made by Benham Zakeri and Sanna Syri (2015). Batteries is today mainly used in frequency stabilisation. However, it is the goal of the owners of the new batteries to also participate in longer term energy markets in the future (Yle, 2020).

Even though we use the lithium-ion technology as base case it is very likely that other technologies get to the market as the lithium-ion batteries with their high energy density is crucial in the transport sector for EVs. A very likely technology would be the Vanadium Redox Flow Battery, which has a low energy density but on the other hand a very long lifetime and a low LCA carbon impact. We will therefore increase the projected capacity to include other technologies, but as we currently only can foresee lithium to be the key player all other technology parameters for the modelling will be based on lithium technology.

Finland is currently a frontrunner in terms of lithium-ion battery implementation for grid connection, as they with the Yllikkälä power reserve one at 30 MWh installed last year now have a total of approximately 50 MWh installed. To predict the installed battery capacity in Finland there are no geographical constraints, however the price and availability of lithium will have a big impact. We have therefore assumed that Finland will follow the European trend which states that the capacity will be 10 times higher in 2028 compared to 2018 (Visual Capitalist). Since we are counting the new large scale

Yllikkälä we may expect a 10-20 times increase in the period 2021 to 2035 for Finland and hence in the range of 0.5 to 1 GWh installed batteries.

CHAPTER 4
ENERGY MODELLING

For energy modelling, we gathered some default data to use in all 112 scenarios. This includes for example the hourly distributions of total electricity consumption and wind power production. Distribution data was gathered from Fingrid's open data (2021). The hourly distribution is then projected with the assumption of total annual electricity consumption and wind power production. Total electricity consumption is assumed to be 110 TWh without power to x and 116 TWh with power to x. Wind power production is assumed to be 61.9 TWh in 2035 based on Sitra's report.

4.1 Ranges of Flexible Capacities

Based on the literature review done on Chapter 3, We can get information on ranges of flexible capacities for each technology which is shown in Table 4.1. It should be mentioned that since each technology has their own power system. The flexible technologies capacity is tabulated on Figure 4.1.

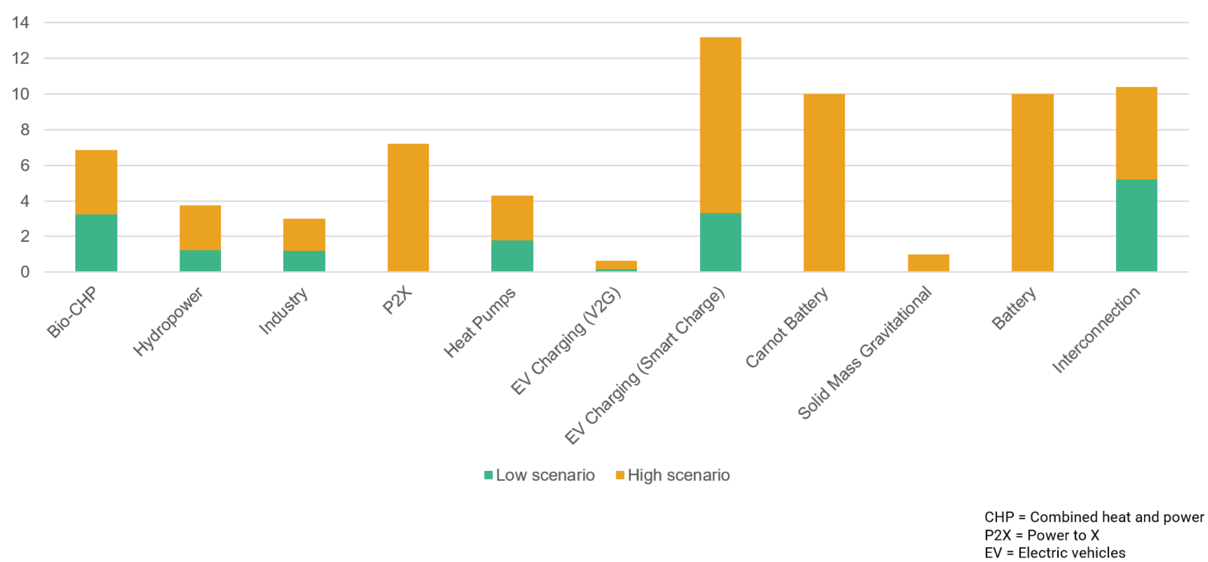

Figure 4.1 Flexible technologies available power by 2035

4.2 Project Approach by Modelling

The empirical part of this project concentrates on investigating how fast and how much each of the flexible technologies can cover by modelling it through EnergyPLAN and Matlab software. EnergyPLAN helps to visualize the operation of national energy systems based on hourly basis. It also gives results of environmental and economic analysis of various energy strategies, where we call it as scenarios. Each scenario is modeled so that they can be compared with one another, rather than just modelling one core solution. The mechanism of the model is determining a general input (i.e. demands, costs, and renewable energy sources) while also generating the outputs such as energy balances and resulting annual productions, as well as total costs of the system. On the other hand, Matlab software helps envision all scenarios to see their tendency, similarities, and/or behavior towards some parameters determined. It also supports the determination of scenarios give the least cost within low CO_2 emissions by providing the yearly distribution of flexible technologies power based on residual load of the scenario model results from EnergyPLAN. The flowchart of the project approach is depicted on Figure 4.2.

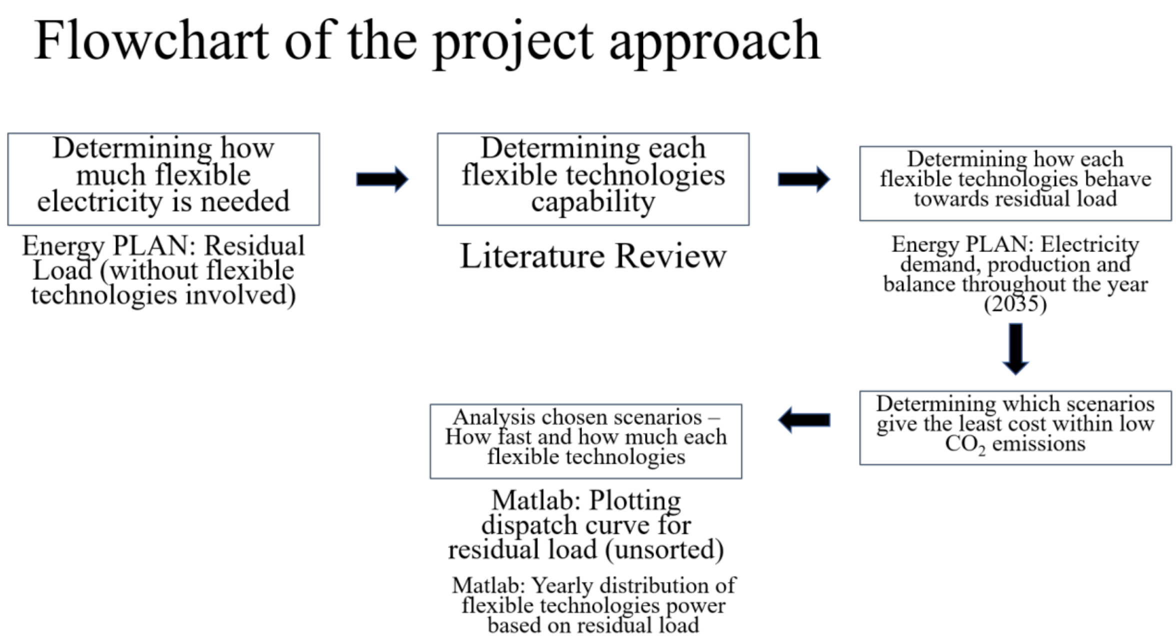

Figure 4.2 Flowchart of the project approach

Based on the flowchart given, how much flexible electricity needed is addressed by simulating EnergyPLAN which derives a residual load curve of 2035 Finnish Electricity System. Parallel to it, literature review study is conducted to determine each flexible technologys capability to cover the residual load. Afterwards, each flexible technology will be derived on how they behave towards residual load using EnergyPLAN. The primary output for each simulation is the system cost and CO_2 emissions where eventually aids to determine which scenarios give the least cost within low CO_2 emissions. Through the medium of Matlab, chosen scenarios can be easily analyzed, how fast and how much each there will be of the flexible technologies by generating the plot of yearly distribution of flexible technologies power based on residual load.

Subject to EnergyPLAN deterministic input/output model, variations of scenarios rely upon every technology variable input availability. Considering their value on ranges of flexible capacities, some simplifications and modifications of variable variation are done in order to lessen the complexity. In a number of situations, it is not possible to quantify all the variables that affect the behavior of the system. As a consequence, there are static and variable parameters for certain technologies. There are 112 scenarios in total that we have developed based on that parametric analysis. The specific values used in the modelling is provided in the Appendix A. It also should be mentioned that this project does not consider solar as one the renewable energy sources since it is insusceptible enough on the electricity system due to geographical features of Finland. The variable OPEX for flexible demand is assumed to be 30 EUR/MWh and did not consider the demand response of buildings because the value is not comparable to other flexible technologies capability.

4.3 Limitations of the Modelling

EnergyPLAN simulation generates a way of evaluating solutions but does not generate solutions themselves, therefore it has several limitations that we should consider. First, flexible demand technologies are assigned with no variable cost. Unrealistic curtailing of hydropower is done instead of selling it through interconnectors because they don’t operate in proper way if the price is too low. There is also limit to simulate only two types of storage at a time. On the general view, Finland is modeled as an isolated island where the interconnector system is simplified. The modelling works only in hourly temporal discretization – doesn’t consider the phenomena in shorter timeframe than 1 hour (i.e ramping rates, frequency balancing). The minimum grid stabilization provided by gas is set to 0 – to maximize all technologies involvement, as other technologies in the future might be able to provide stabilization as well. But, further analysis of fast reaction stabilization need may be needed. In addition, the model did not allow us to use two types of batteries (which is a full potential of our storage sources) at the same time. Regarding OCGT, it is assumed as free variable input where only the economic parameters are put and let the model decide. Lastly, EnergyPLAN is not designed for modelling P2X as a flexible demand technology for renewable electricity.

CHAPTER 5
RESULTS

5.1 Range of Gas Usage, System Costs and CO_2 Emissions in Scenario Results

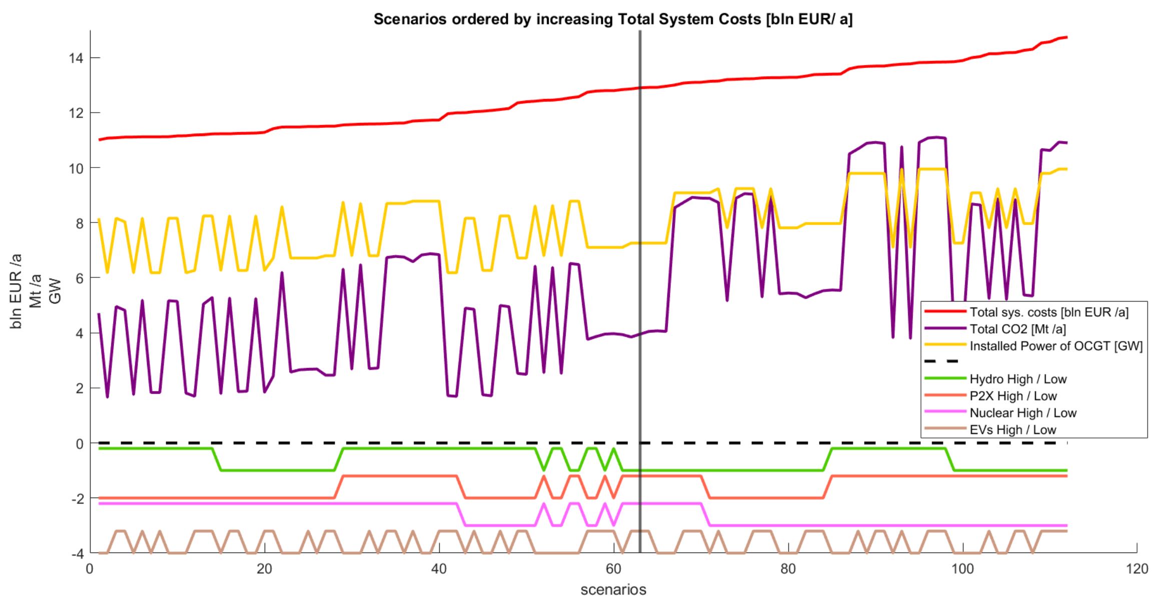

Figure 5.1 Scenarios ordered by increasing total system costs

When our scenarios are ordered by increasing total system costs (Figure 5.1) we can see that CO_2 is not too heavily correlated with total system costs, though both have a slight upward trend and more high emission scenarios are located on the high system cost side. There are however big differences in emissions regardless of system cost - this indicates, that the best scenarios cannot be chosen by total system costs alone, but rather there is a need to take other factors also into account.

From Figure 5.1 we can also see that high nuclear and high hydro are mainly associated with less system costs, whilst high P2X is associated mainly with higher system costs. High and low EV's scenarios are located on both sides (high and low system cost) and thus are likely not to affect system costs.

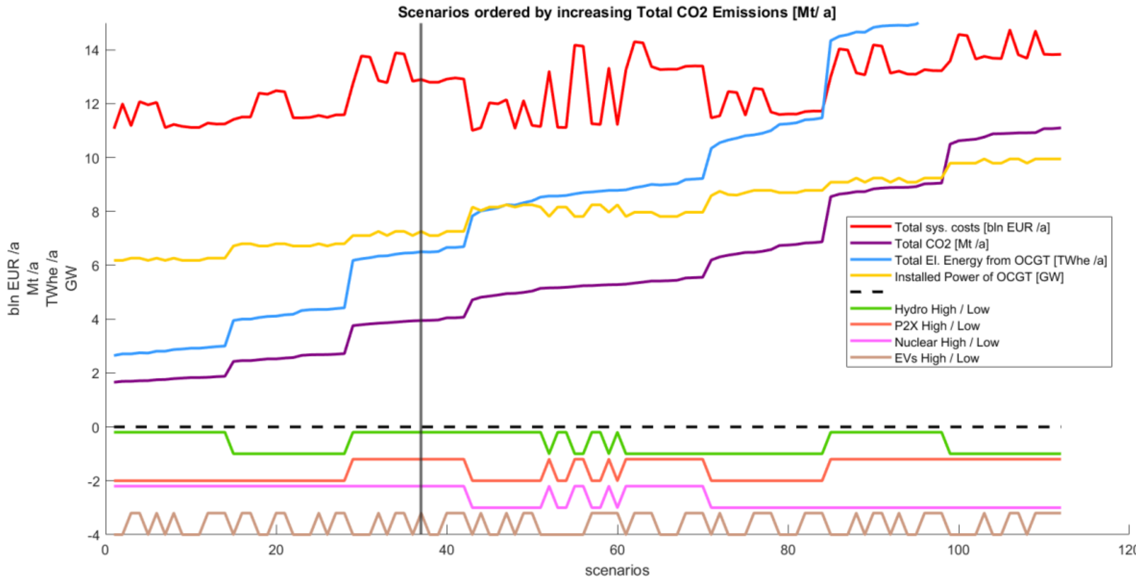

Figure 5.2 Scenarios ordered by increasing total CO_2 emissions

Figure 5.2. represents scenarios ordered by increasing total CO_2 emissions and from it we can see that high CO_2 is correlated with the usage of OCGT.

High hydro and high nuclear are more associated with the lower CO_2 emission side, whilst high and low EV can be found in high and low emission scenarios. It is likely that EV's do not make a big difference either way for the CO_2 emissions.

High P2X is mostly located in the high CO_2 emission side. We assume this is due to its similar cost to OCGT – the model uses both OCGT and P2X when prices are high enough and the use of OCGT causes CO_2 emissions. On top of this, high P2X scenarios have a bigger electricity consumption, than the no P2X scenarios, which can further increase the demand of OCGT and thus partly be a cause of high CO_2 emissions in these scenarios.

5.2 Scenario Analysis

When sorting all scenarios by total system cost it is possible to examine the similarities in the scenarios with lowest total system costs. 10 scenarios with the lowest total system costs were examined further:

All 10 scenarios used high capacity of hydro power. This confirms that cheap hydro power can be assumed to be producing electricity still in 2035 at high rate. Almost all (9/10) scenarios had lower capacity for electric vehicles. This might be due to the cost assumptions made for EV's. Only one scenario was using solid mass gravitational storages and Carnot batteries were not used in any of the scenarios. In seven scenarios electrochemical batteries were used but the variable OPEX of the battery seems to not have an affect whether the use battery is beneficial or not. This could mean that electrochemical batteries didn't effect on the system or the total system costs at all. Also, the nuclear capacity seemed to not have affect. The capacity of nuclear production was equally divided, five scenarios with low nuclear capacity and five scenarios with high capacity. Surprisingly, power to x was not used in any scenarios. The reason for it is probably the limits of EnergyPLAN and our assumptions for the price for power to x.

All 10 scenarios had reasonably low CO_2 emissions. However, one scenario had significantly lower emissions compared to other nine scenarios. The CO_2 emissions were only 1.7 Mt CO_2/a, having the lowest emissions from all 112 scenarios. The average emissions of all 10 scenarios were 3.7 Mt CO_2/a. When considering the total system costs and annual emissions, this one scenario can be stated to be the best scenario as a result from the model (see figure 4.3). This particular scenario had variable values as follows: high hydro power capacity, low electric vehicle capacity, no Carnot batteries, no solid mass gravitational storages, variable OPEX of 100 €/MWh for electrochemical battery, high nuclear capacity, and no power to x capacity.

According to realistic assumptions on how the electricity system will look like in 2035, the most realistic scenario is chosen to be the scenario with variables as follows: high hydro power capacity, high electric vehicle capacity, no Carnot batteries, no solid mass gravitational storages, variable OPEX of 100 €/MWh for electrochemical battery, high nuclear capacity, and high power to x capacity. However, the actual capacities might be somewhere in the middle. Capacities used for electric vehicles and power to x are reasonably high and it is not certain that they will actually meet capacities so high. Considering the costs, this scenario is around the halfway point of all scenarios, but still on the high side. Considering the emissions, it barely makes to the best 1/3 of all scenarios. The annual emissions in this scenario are 3.9 Mt CO_2/a.

With the aim to compare the amount of flexibility in Finnish energy system in 2019 and in 2035, the total installed power of dispatchable sources is presented in the Figure 5.3. The projection for 2035 is a result of modeling of the most realistic scenario. The figure includes both supply and demand flexibility.

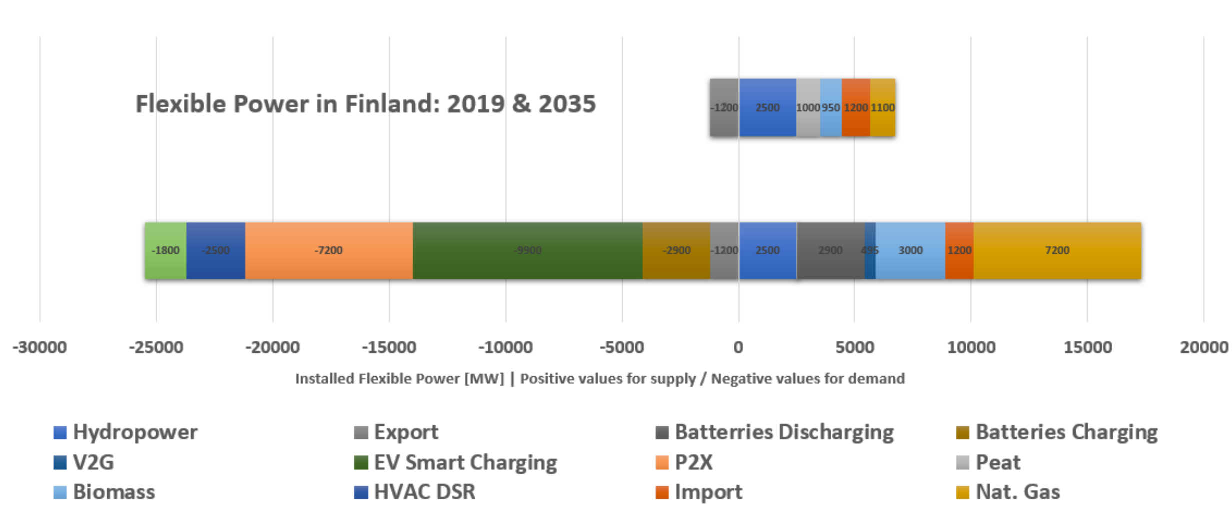

Figure 5.3 Total installed power of dispatchable sources in Finland in 2019 and in 2035

The total amount of flexible power sources is expected to more than quadruple during the next 14 years, from 9500 MW to 42 800 MW. In 2019, the majority of the flexibility was attributed to the supply side (8300 MW), where the biggest contributors were hydropower and coal. On the demand side, the only mean of flexibility was represented by interconnectors (averaged as 1200 MW, as the precise available capacity is changing constantly with high complexity and relations to different market factors).

In 2035, the majority of available flexibility is shown to be provided by the demands side (25 500 MW), mostly by the vast amount of smart charged electric vehicles, as well as industrial power to x. The supply side flexibility is expected to achieve the total value of 17 300 MW, with the biggest contribution of OCGT power plants, which are assumed in this report to be fueled with natural gas. Additionally, electrochemical batteries also have high contribution in the projection, with total installed power of 2900 MW, being utilized tens of times during the year,

All best scenarios evaluated have high capacity for hydro power. The scenarios with the lowest costs didn't use power to x at which explains the difference in total electricity consumption between the best scenario based on the model and the best scenario based on literature review. However, the best scenario based on the model results is not as realistic because it does not use power to x at all and it has low capacity for electric vehicles.

The capacity and usage of OCGT's was left for the model to decide. Only economic parameters were fixed. In many scenarios, OCGTs are used significant amount for peak demand. There are several reasons for reasonably high gas usage in the scenarios. First, the basic principle of the model is to cover the rest of flexibility need with gas. Other technologies were insufficient to cover the whole demand. For example, storages have physical limitations of energy capacity. The focus of this project has been examining flexibility on minimum of hourly basis. Electrochemical batteries are more. effective in short term. Secondly, the limitations of the model affected to the results. EnergyPLAN didn't allow to use two types of batteries at the same time. Because of this, full potential of storages was not possible to be analyzed.

Even though OCGT's are designed to operate for peak demand hours, the total amount of installed power and produced electricity was reasonably high. As mentioned earlier, OCGT's were assumed to use only fossil fuels. This has increased CO_2 emissions for many scenarios. Sustainable fuels could be used to replace natural gas. Biogas is one potential alternative. The limitations of biogas are the price and limited amounts of raw materials. However, production of biogas is increasing and already in 2017 heat and electricity was produced 500 GWh from biogas (Gasum, 2021).

Scenarios with lowest total system costs had annual emissions of 3.7 $MtCO_2$/a and the most realistic scenario had 3.9 $MtCO_2$/a, which means that there is no significant difference according to emissions. The emissions are on average above the energy energy sector agreement to reduce half of the emissions from 7 $MtCO_2$ to 3.5 $MtCO_2$ by 2030 (Energiateollisuus, 2020). The average emissions were 87 CO_2/kWh in 2019 (Fingrid, 2021b). Total electricity production was 66043 GWh (Tilastokeskus, 2021). Therefore, the emissions from Finnish electricity production were already approximately only 5.7 $MtCO_2$ in 2019.

The total generation and consumption of the 2035 Finnish energy system is presented in the Figure 5.4. The supply side is shown on the top of the Y=0 axis, while the corresponding demand is placed below the same axis.

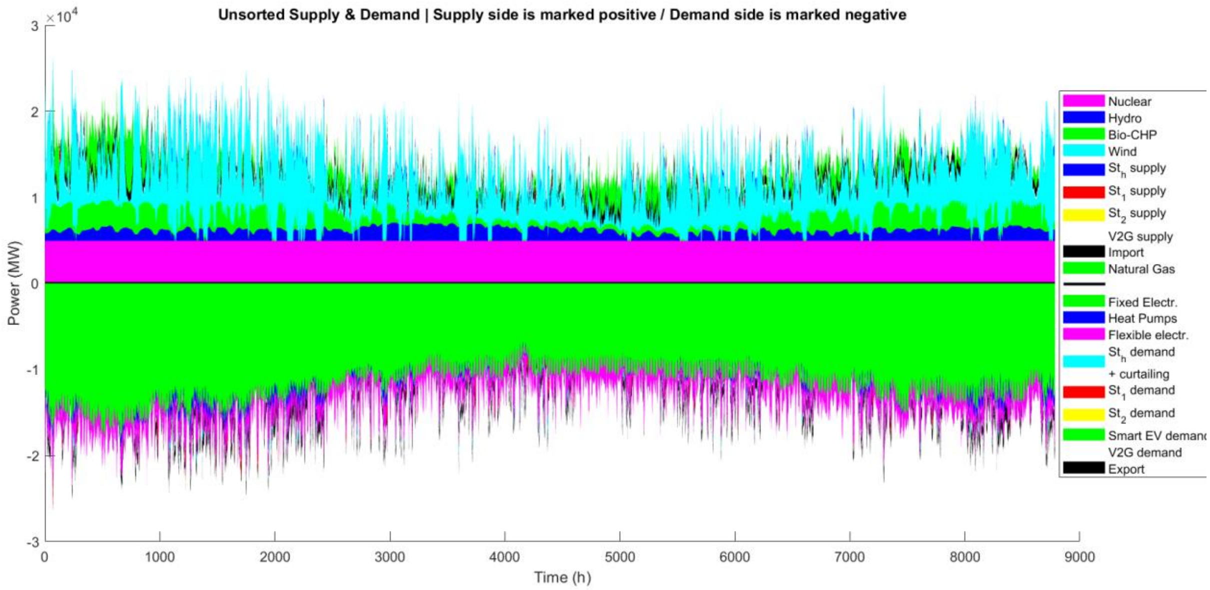

Figure 5.4 Total generation and consumption of the 2035 Finnish Energy System

From the figure it can be acknowledged that the vast majority of the electrical demand in 2035 is still fixed. Most of the public and private consumers have their work and life patterns which are predetermined by practical and cultural factors, therefore they cannot be easily modified. If we pay attention to the supply side of the figure, the role of baseload power, such as nuclear and hydro can be appreciated. Being the result of inflexible demand, such baseload sources can fill a considerable part of the necessary power supply, stabilizing the energy system significantly.

However, the role of flexible demand should be also noted. The flexibility of part of the consumers is a direct reason, for which that high amount of wind power is able to be present in the energy mix. Without these consumers, much of the wind power would need to be curtailed, driving up total system costs. What is more, as a result more flexible supply would be needed to cover that additional energy demand, which would undoubtfully lead to increase consumption of natural gas.

To visualize better the contribution of the flexible power sources, the same graph has been modified, so that only the flexible contribution is shown in the Figure 5.5.

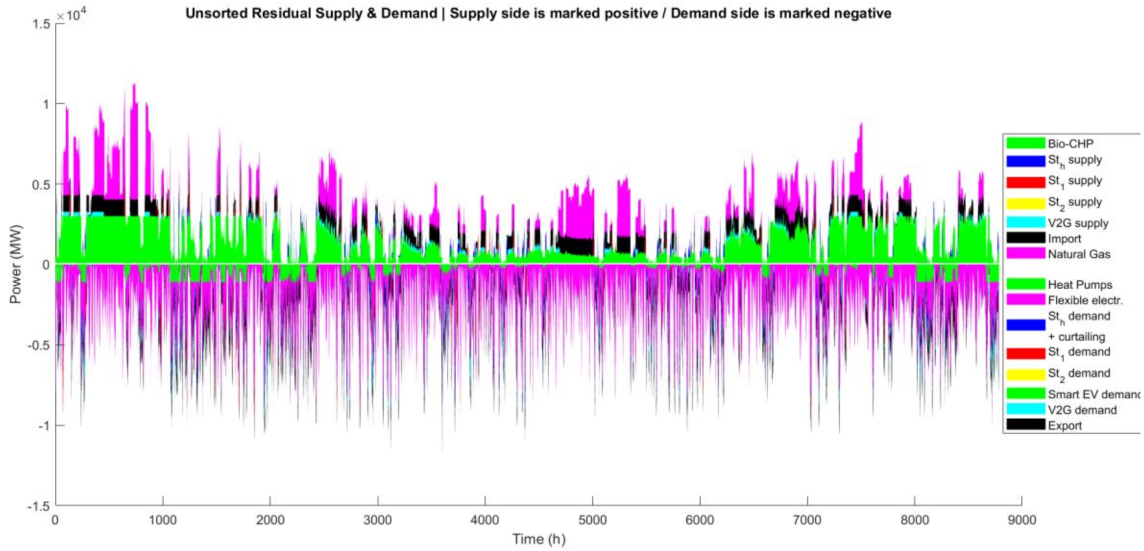

Figure 5.5 Total flexible generation and consumption of the 2035 Finnish Energy System

The figure shows that flexible demand has its limitations. This is due to diurnal operation characteristics, coming from physical constraints of energy storage, such as daily hydrogen storage on industrial sites or daily shifts of consumption of heat pumps. Flexible supply, however, shows its capabilities in longer time periods, such as couple-days long periods of operation. It is especially visible, that bio-CHP has its role in covering winter demand in both district heating as well as power in the energy system. Also, bio-CHP shows significant correlation to natural gas usage at times of significant requirements of residual load. OCGT power plants fuel by natural gas have their significant role throughout different seasons of the year, covering periods of poor wind power, which can last up to 14 days (see Figure 5.4).

The authors recommend further studies on feasibility of hydrogen storage in longer term than 1 day, such as 1 week. In theory, hydrogen storage in underground caverns might open that opportunity, providing great benefits to the energy system with long term flexible demand of power to x.

Figure 5.6 presents the magnified area of the Figure 5.5. It can be seen that different means of short term energy storage also have their contribution both on supply and demand side, e.g., batteries provide up to 2900 MW of peak flexible demand as well as supply tens of times during the year.

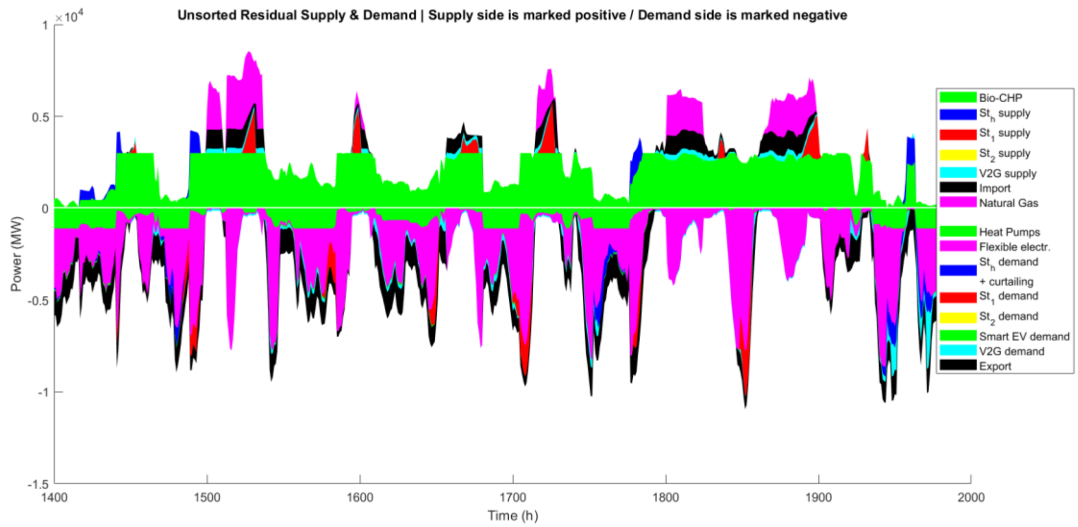

Figure 5.6 Magnified flexible generation and consumption of the 2035 Finnish Energy System

Another way to present the bulk results of the most probable scenario for Finland in 2035 is by the yearly distribution of residual load, which is covered by different power sources. Figure 5.7 is the result of sorting the hourly data presented in Figure 5.5 by increasing residual load.

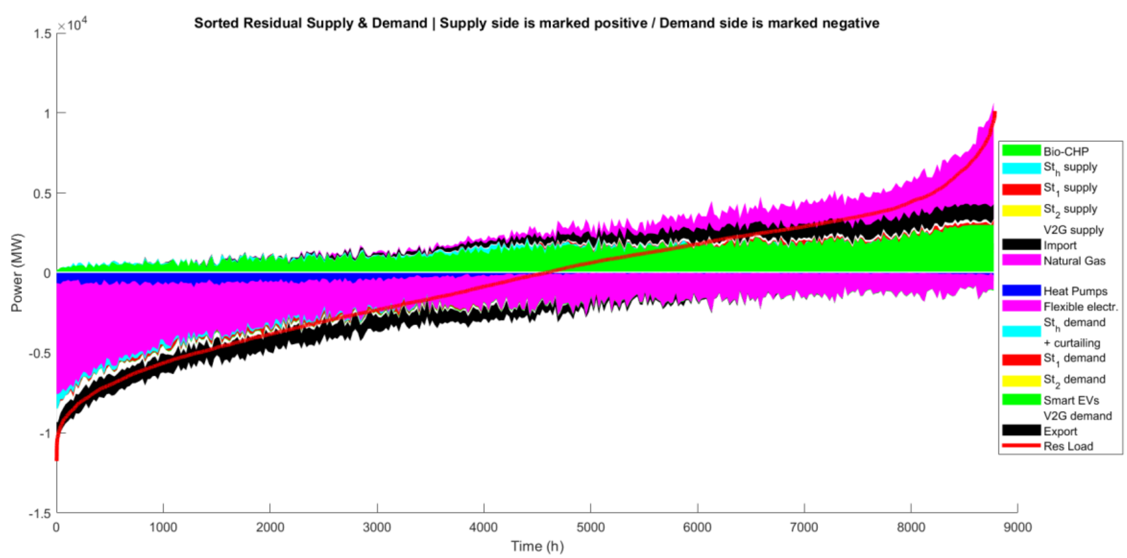

Figure 5.7 Flexible power dipatch in the most realistic scenario

The figure illustrates the contribution of each of flexible power sources in the function of residual load. It can be noticed, that natural gas is used mostly in periods with very high residual load required to be covered. Contrarily, hydropower reservoir storage, being the source with 0 marginal costs of usage, is being dispatched mostly in the moderate residual load situations. It is worth noting that the figure displays incorrectly the demand of hydropower storage. This is due to limitations of the model, which made some decisions to curtail hydropower in overgeneration situations instead of using full interconnector capacity.

Another finding is that, although different means of energy storage contribute highly to peaks in necessary supply or demand, their bulk role in terms of terawatt-hours in the energy system is very limited. Most of the flexible energy supply still comes from bio-CHP, imports and OCGT plants in 2035. When it comes to flexible demand, it is mostly covered by industrial power to x together with individual flexible heat pumps (purple), district heating heat pumps (dark blue) and exports.

Figure 5.8 gives an idea about the needs for total ramping rates necessary in the Finnish energy system in 2035. Different sources have different ramping rate characteristics (see Appendix B) and not only need to be able to cover a certain power demand, but also follow the changes of power demand in the system.

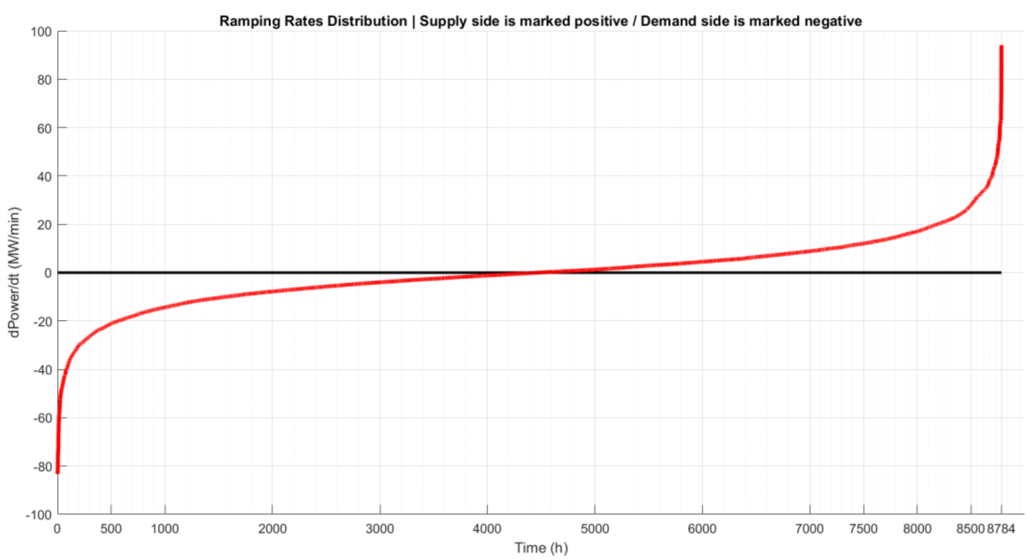

Figure 5.8 Total ramping rates required to cover the hourly flexible power fluctuations in the Finnish Energy System in 2035

The highest absolute values in the order of ~100 MW/min are not high or should not be considered challenging by any means. To put them it into perspective, with 7200 MW of installed OCGT power, given average ramping rates of 12% P_{nom}/min, we could expect 864 MW/min of flexibility provided by OCGT plants alone, covering all of the demand with significant margin. However, it is worth noting, that the analysis in this report was conducted with hourly temporal discretization. It can be expected, that when short term fluctuations are considered, the requirements for the ramping rates could increase significantly.

CHAPTER 6
CONCLUSIONS

Flexibility becomes an increasingly important aspect from the point the Finnish energy system. The increased penetration of variable renewable sources, which is necessary to achieve ambitious climate goals, requires vast utilization of flexible energy technologies both on the supply as well as demand side.

In this report, the general requirements for flexibility in 2035's Finnish energy system have been assessed based on numerical residual load analysis, considering flexible power as well as power ramping rates. In all analyzed scenarios, the flexible power required on both supply and demand sides was of the order of 10 000 MW. The value necessary flexible power was only influenced by the presence of stable baseload power in the power system, coming from sources such as hydro and nuclear power plants.

When it comes to power ramping rates, the differences between different scenarios were minor. Generally, the ramping rates required by Finnish energy system of 2035 are about the value of 100 MW/min both for supply and demand side, which is not a challenge from the system point of view. However, further studies should be undertaken on shorter-term system analysis, in temporal discretization of seconds or minutes, to investigate the necessary ramping rates with more precision.

Most of the flexible supply is covered by natural gas in all scenarios. The required installed power of OCGT has been estimated between 6 and 10 GW, with the value of 7.2 GW estimated for the most probable scenario. Natural gas power plants are used with particularly low capacity factor, utilizing more than 50% of its installed power only during 600h throughout the year. It is recommended for further study to assess the feasibility of preparing half of the OCGT plants to work with P2X – derived electro-fuels such as e-ammonia or e-methanol. Although these fuels are expected to be 4-5x more expensive than natural gas, the increase of total energy system costs could be acceptable. This is due to certain superior properties of liquid e-fuels in relation to natural gas, including practicality of long-term storage in a liquid state instead of underground caverns, as well as energy security considerations of domestic fuel production instead of imports.

The role of flexible power consumption, although not big in terms of bulk energy numbers, is significant. This is because it allows to utilize the peaks of wind power generation, which leads to reduction of total system costs and lower consumption of flexible supply, such as natural gas. The authors recommend further studies on hydrogen storage in periods longer than 1 day. With underground caverns hypothetically allowing storage periods of 1 week, the benefits of flexible industrial P2X could be multiplied, further reducing the need for natural gas.

From all investigated flexible demand technologies, industrial P2X holds the highest potential with 17 TWh/a of daily flexible energy consumption. It is very important to acknowledge, that the modeling presented in this report had significant limitations regarding P2X assumptions (see modeling limitations subchapter). Adding P2X into the system increased total energy demand and was partially covered by natural gas power, increasing both annual costs and CO_2 emission to the system. The authors didn't include mitigated emissions from industrial sector, which in the broader context are expected to provide a worthy payback of CO_2 emissions, as well as savings in mitigated CO_2 allowance procurement. In order to assess these external benefits, further analysis in this matter is recommended.

The presence of Carnot batteries (with very optimistic price assumptions) did not result in any benefits from the system point of view. The implementation of such storage did not lower the total CO_2 emissions, while only increasing the total system costs. Considering the possible pathways of flexible EVs, there were no visible differences between scenarios with higher or lower amount of such vehicles both in terms of CO_2 as well as total system costs. When it comes to solid mass gravitational storage, the situation was similar: within given assumptions of small scale implementation, there was no distinction between scenarios with or without such storage, therefore the benefit is not seen as significant.

Electrochemical batteries were included into the model in order to investigate their theoretical potential. Different assumptions were used, including extremely optimistic - practically unrealistic from today's technological development point of view. The goal was to assess the influence of possible technological breakthroughs on the system. In achieved modeling results, the influence of batteries is not significant, despite the high amount of installed power and capacity. Both total system costs as well as total CO_2 were barely affected by the presence of batteries and their different price ranges. It is worth noting that utilization of electrochemical batteries holds a much bigger challenge than only high performance, low price and high durability – that challenge is the aspect of critical raw materials value chains and recyclability. Therefore, authors express serious doubts on feasibility of mass implementation of bulk electrochemical storage in grid scale as a component of the energy systems.

Across all the scenarios, the increased amount of baseload generation (hydro & nuclear power) results in both decreased costs of the system and decreased CO_2 emissions. One of the characteristics of flexibility is that by nature it has its price, therefore a target energy mix should be properly assembled of stable baseload sources, cheap intermittent sources and efficiently managed flexibility sources on both supply and demand side of the system.

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APPENDIX A
SUMMARY OF FLEXIBLE TECHNOLOGIES CAPACITY

Table A.1 Summary of ranges of flexible capacities for each technology

Technology	Available Power [MW]		Availability of Output / Input	Ramping rate [% Pnom/min]	Min. uptime & downtime	Notes
	Min.	Max.				
Generation						
Bio-CHP	3255	3616	14 TWh / year	3-6	8 hours	Flexibility parameters refer to hard coal “post flexibilization” plants
Hydropower	2500	2500	11.5 TWh / year	15	0	-
OCGT (nat. gas)	1500	4500	-	8-15	10-60 minutes	
Demand Response						
Industry	1200 MW	1800	0.17 TWh / year	20-100	0	-
P2X	0	7200	15.8 TWh / year	100	0	Daily storage for industrial hydrogen assumed, capacity factor of electrolysers ~25%
HVAC	2500 (20% of HVAC power)		1.23 TWh / year	100	0	Daily load shifting
Buildings	290	435	Always	100	0	Daily load shifting
EV Charing (V2G)	165	495	Always	100	0	Daily load shifting
EV Charing (Smart Charing)	3300	9900	24 – 72 GWh / day	100	0	Daily load shifting
Storage						
Solid Mass Gravitational	0	1000	1000 MWh of total storage capacity	100	0	-
Interconnectors	4216	5216	-	100	0	

APPENDIX B
DEVELOPING SCENARIOS

The values presented in this section were used directly for modeling purposes in EnergyPLAN software tool.Some of the values are not physically correct, as they are a result of simplifications along the way (such as levelizing all nuclear power costs to CAPEX or levelizing all electrochemical batteries costs to var. OPEX).

Table B.1 Value input in the modelling for developing the scenarios

Technology	Scenario Version	Values	Description of variables	Other static values	Description of other static values
Hydropower	1	0 | 1250 | 5 | 5.75	Pump-back power [MW] | Dammed power [MW] | Capacity [GWh] | Yearly Demand [TWh]	50	Fixed OPEX [kEUR/MW/y]
	2	0 | 2500 | 10 | 11.5			
EVs	1	165| 3300 |24 | 1.5	V2G power [MW] | total EVs charging power [MW] | Capacity [GWh] | Flexible EV demand (TWh/y)	50	Variable OPEX [EUR/MWh]
	2	495 | 9900 | 72 | 3			
Carnot Batteries	1	0	Installed Power [GW] |Capacity [GWh]	500 | 0.5	CAPEX [EUR/kWh] (20 Years of operation) | cycle efficienciy
	2	10 | 40			
Solid Mass Gravitational	1	0	Installed power [MW] | Capacity [MWh]	1000 | 0.9	CAPEX [EUR/kWh] (20 Years of operation) | cycle efficienciy
	2	1000 | 1000			
Electrochemical Batteries	1	50	Var. OPEX (LCOE derived) [EUR/MWh]	10 | 40 | 0.9	Installed power [GW] | Capacity [GWh] | cycle efficienciy
	2	100			
	3	200			

Nuclear	1	3300	Installed power [MW]	7 | 0.22	CAPEX [mln EUR/MW] (20 Years of operation) | Fixed OPEX [mln EUR/MW/y]
	2	5500			
P2X	1	0	Installed power [MW] | Flexible demand [TWh/y]	50	Variable OPEX [EUR/MWh]
	2	7200 | 16			

For the rest of the technologies, other static values were assumed. They are presented at Table A.2.

Table B.2 Static input value in the modelling

Technology	Values	Description of variables
Wind	19500 | 61.9	Installed power [MW] | Yearly production [TWh/y]
Bio-CHP	3000	Installed power [MW]
Industrial DSR	1800 | 0.17	Installed power [MW] | Flexible demand [TWh/y]
HVAC DSR	2500 | 1.23	Installed power [MW] | Flexible demand [TWh/y]
Interconnectors	5200	Installed power [MW]
Gas (OCGT)	10	Installed power [GW]
Emission Trading System	120	CO_2 price [EUR / tCO_2]