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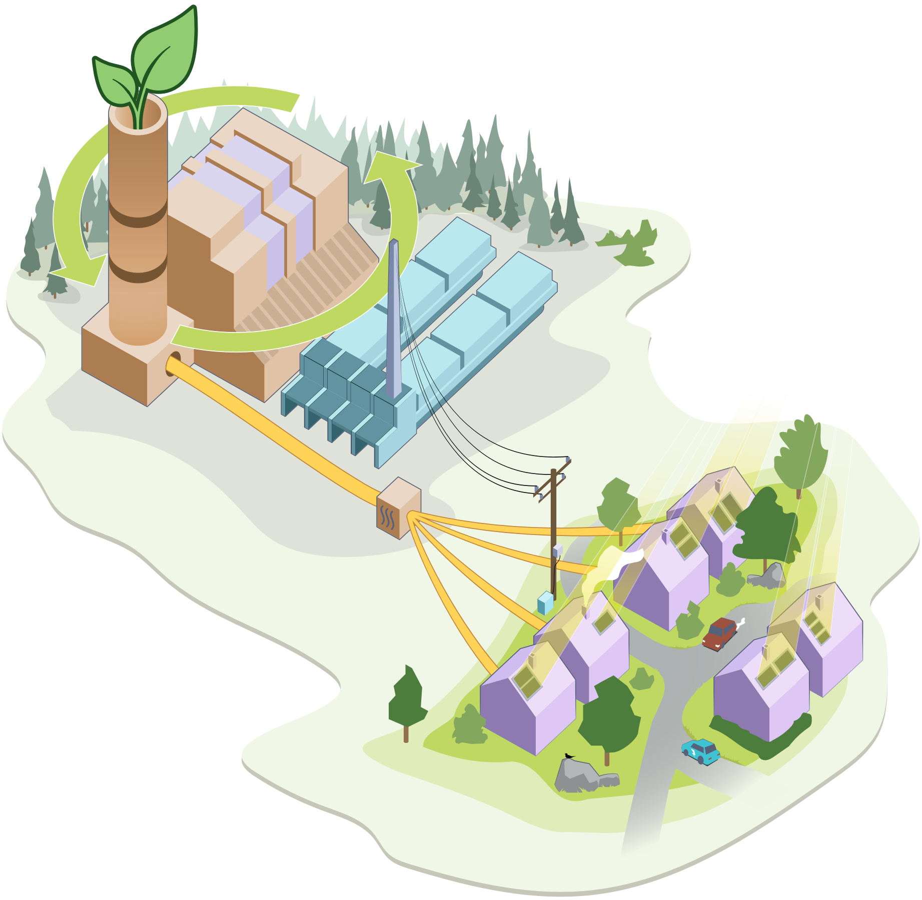
Production planning of CHP plants in transition towards energy systems with high share of renewables

Mahsa Daraei



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Mahsa Daraei

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School of Business, Society and Engineering

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PRODUCTION PLANNING OF CHP PLANTS IN TRANSITION TOWARDS ENERGY SYSTEMS WITH HIGH SHARE OF RENEWABLES

Mahsa Daraei

Akademisk avhandling

som för avläggande av teknologie doktorsexamen i energi- och miljöteknik vid Akademin för ekonomi, samhälle och teknik kommer att offentligen försvaras fredagen den 18 juni 2021, 09.00 i Delta + digitalt via Zoom, Mälardalens högskola, Västerås.

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MÄLARDALEN UNIVERSITY
SWEDEN

Akademin för ekonomi, samhälle och teknik

Abstract

The global energy system is undergoing a transformative change towards renewable energies. The share of Renewable Energy Sources (RES) and bioenergy in the world's primary energy use has increased in the recent years. Based on the EU Roadmap 2050 energy plan, the share of renewables in final energy use in Europe will reach at least 55%, a 45% increase from its share today.

Due to the intermittent energy supply from renewables, their high penetration in energy systems can jeopardize the system flexibility, in terms of the balance between energy demand and supply. Lack of system flexibility could cause energy curtailments, increase system costs, or make renewables unreliable sources of energy. Moreover, the expansion of the renewable energy supply could influence the operational strategy of existing energy systems like Combined Heat and Power (CHP) plants. Therefore, the current study focuses on increasing system flexibility of a CHP-dominated regional energy system with increased renewable power supply. Two flexibility options, including a polygeneration strategy and large-scale energy storage using power-to-gas technology, were modelled. The system is then optimized using a Mixed Integer Linear Programming (MILP) method to investigate the production planning of CHP plants in a renewable-based energy system with higher level of flexibility. Different technical and market factors could influence the results of the optimization model, and thereby system flexibility. Thus, the study is carried out under various scenarios for better understanding of the future challenges regarding energy supply, market prices, and climate change.

The investigation provides an increased knowledge of production planning for the existing CHP plants with increased interaction with renewables. Based on the overall observations of this thesis, the proposed power storage system contributes to the increased system flexibility. However, the study suggests polygeneration and integration strategy as the optimal pathway to increase RES penetration and to support system flexibility, considering future energy developments and changes in energy demand and supply.

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To my mother and father,
Farah and Ali

“Research is to see what everybody else has seen, and to think what nobody else has thought.”

- Albert Szent-Gyorgyi

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Västerås, Sweden, April 2021

Mahsa Daraei

Summary

The share of Renewable Energy Sources (RES) in the global energy supply, especially in the power sector, is growing. The design of 100% renewables-based energy supply in different energy sectors has been the focus of many investigations. According to the Swedish Energy Agency (SEA), wind power development, increased solar power production, electrification of the transportation system, integrated energy supply, and increased interaction of conventional energy systems with renewables are some of the future scenarios to achieve a sustainable energy system.

Energy supply from RES, such as wind and solar power, depends on weather conditions and can intermittently change even over a short-time period. Therefore, the increased share of renewables in energy supply indicates the crucial necessity for flexibility in the system to respond to the imbalances between demand and supply. From the production planning perspective, expansion of the renewable energy supply as well as integration of new energy conversion and storage technologies could add to the complexity of the current energy system. Moreover, several parameters, including trends in energy demand and supply, availability of resources, market prices, and climate conditions, influence the optimal performance of the future energy system. Thus, optimization of such a complex energy system is important and the impacts on the operational strategy of existing energy conversion plants need to be investigated.

Following the increased share of renewable energy supply, the goal of this thesis is to assess the potential of existing Combined Heat and Power (CHP) plants to be integrated with power supply from rooftop photovoltaic (PV) systems. Moreover, given the above-mentioned challenges, the impacts of increasing the use of renewable energy on system flexibility, and the possible directions in production planning of the CHP plants, are investigated. Two cases have been developed and modelled for the system optimization and flexibility analyses. The first case investigates the impact of long-term energy storage, using power-to-hydrogen technology, on the system flexibility. The

second case assesses the potential of polygeneration by integrating bioethanol production and the pyrolysis processes with existing CHP plants. The flexibility of the system in this thesis refers to the energy balance between demand and supply considering the fuel use, energy output, and the interaction with the grid. The optimization is performed in General Algebraic Modelling System (GAMS) using Mixed Integer Linear Programming (MILP) method. For better understanding of some of the future challenges related to changes in energy demand and supply, market trends, and climate change, different scenarios have been developed and investigated. The results of the studied cases are compared and evaluated to find the optimal integration pathway to maximize the renewables' share and minimize the operation costs.

According to the investigation results, potential power supply from the proposed rooftop PV systems can contribute to decreasing the total power imports to the studied system by at most 40%. However, due to variations in PV power supply, imports are still high at night or during winter periods. Moreover, there is a significant overproduction, and thus energy curtailments during summer periods of abundant solar radiation. As the findings suggest, the inclusion of power storage using power-to-hydrogen technology could improve system flexibility. Using fuel cells in the system can further reduce the power import and increase the penetration of renewables in the power supply by around 4%. The polygeneration systems studied in this thesis indicate that the integration of biofuel production with existing CHP plants can increase the total heat and power outputs by 2% and increase the operation time of CHP plants in the system. The integrated pyrolysis process with CHP plants and onsite hydrogen production through electrolysis demonstrates that this system can potentially act as a pathway to improve the profitability of the CHP plants and increase the penetration of renewable resources in the energy system.

The main conclusion of this thesis is that the interconnections between the heating, power, and transportation sectors enable the integration of renewables to the energy system and increase system flexibility. The overall efficiency of the integrated system can vary between 58% and 80% depending on future developments in energy demand and supply. This investigation shows the potential for a fossil fuel-free energy supply by replacing fossil oil with wood as the input fuel to CHP plants. The climate change scenario shows insignificant effects on system performance and the flexibility. However, market trends related to the electrification of the transportation system, increased use of heat pumps as direct heating sources, and variations in electricity prices can influence the operational strategy of the existing CHP plants. Moreover, these trends increase RES penetration in the system while enhancing the power imports and the system costs.

Sammanfattning

Andelen förnybara energikällor i den globala energiförsörjningen, särskilt inom kraftsektorn, växer. Utformningen av 100% förnyelsebaserad energiförsörjning i olika energisektorer har varit fokus för många undersökningar. Enligt Energimyndigheten är utveckling av vindkraft, ökad solenergiproduktion, elektrifiering av transportsystemet, integrerad energiförsörjning och ökad interaktion mellan konventionella energisystem och förnybara energikällor några av de framtida scenarierna för att uppnå ett hållbart energisystem.

Energiförsörjning från förnybara resurser, såsom vind- och solenergi, beror på väderförhållandena och det kan intermittent förändras även under en kort tidsperiod. Därför indikerar den ökade andelen förnybar energi i energiförsörjningen den avgörande nödvändigheten för flexibilitet i systemet för att svara på obalanserna mellan energibehov och försörjning. Ur produktionsplaneringsperspektivet kan utvidgning av förnybar energiförsörjning samt integration av ny energiomvandlings- och lagringsteknik öka komplexiteten i det nuvarande energisystemet. Dessutom påverkar flera parametrar, inklusive trender inom energibehov och energiförsörjning, tillgången på resurser, marknadspriser och klimatförhållanden den optimala driften av det framtida energisystemet. Således är optimering av ett sådant komplext energisystem viktigt och effekterna på den operativa strategin för befintliga energiomvandlingsanläggningar behöver undersökas mer.

Efter den ökade andelen förnybar energiförsörjning är målet för denna avhandling att bedöma potentialen hos befintliga kraftvärmeverk (KVV) att integreras med kraftförsörjning från solceller på taket. Med tanke på de ovannämnda utmaningarna undersöks dessutom effekterna av hög andel förnybar energiförsörjning på systemets flexibilitet och möjliga riktningar i produktionsplaneringen av kraftvärmeverk. Två fall har utvecklats och modellerats för systemoptimering och flexibilitetsanalyser. Det första fallet undersöker effekterna av långvarig energilagring med kraft-till-vätteknologi

på systemets flexibilitet. Det andra fallet utvärderar potentialen av polygenerering genom att integrera bioetanolproduktion och pyrolysprocess med befintliga KVV. Systemets flexibilitet i denna avhandling hänvisar till balansen mellan energibehov och energiförsörjning med tanke på bränsleförbrukning, energiproduktion och interaktionen med nätet. Optimeringen utförs i General Algebraic Modelling System (GAMS) med Mixed Integer Linear Programming (MILP) -metoden. För att bättre förstå några av de framtida utmaningarna i samband med förändringar i energianvändning, marknadstrender och klimatförändringar har olika scenarier utvecklats och undersökts. Resultaten av de studerade fallen jämförs och utvärderas för att hitta den optimala integrationsvägen för att maximera andelen förnybara resurser och minimera driftskostnaderna.

Enligt studieresultaten kan potentiell elproduktion från de föreslagna solcellssystemen bidra till att minska den totala kraftimporten till det systemet med maximalt 40%. På grund av variationerna i solelförsörjningen är importen fortfarande hög på natten eller under vintern. Dessutom finns det en betydande överproduktion och därmed energibegränsning under sommaren när det finns tillräckligt med solstrålning. Som resultaten tyder kan energilagring med kraft-till-vätteknologi förbättra systemets flexibilitet. Att använda bränsleceller i systemet kan ytterligare minska kraftimporten och öka penetrationen av förnybara energikällor i strömförsörjningen med cirka 4%. De undersökta polygenereringssystemen i denna avhandling visar att integreringen av biobränsleproduktion med befintliga KVV kan öka den totala värme- och effektutmatningen med 2% och därefter öka driften av KVV i systemet. Den integrerade pyrolysprocessen med KVV och väteproduktion på plats genom elektrolys visar att detta system potentiellt kan fungera som en väg för att förbättra kraftvärmeverkens lönsamhet och öka penetrationen av förnybar resurs i energisystemet.

Den huvudsakliga slutsatsen för denna avhandling är att sammankopplingarna mellan värme-, kraft- och transportsektorerna möjliggör integration av förnybara resurser i energisystemet och ökar systemflexibiliteten. Det integrerade systemets totala effektivitet kan variera i intervallet från 58% till 80% beroende på den framtida utvecklingen inom energibehov och försörjning. Studien visar potentialen för en energiförsörjning utan fossila bränslen genom att ersätta fossil olja med trä som insatsbränsle till KVV. Klimatförändringsscenariot visar obetydliga effekter på systemets prestanda och flexibilitet. Marknadstrender relaterade till elektrifiering av transportsystemet, ökad användning av värmepumpar som direkta värmekällor och variationer i elpriset kan dock påverka den operativa strategin för de befintliga KVV. Dessutom ökar dessa trender RES-penetrering i systemet samtidigt som kraftimporten och systemkostnaderna ökar.

List of papers

Publications included in the thesis

This thesis is based on the following papers, referred to in the text by their corresponding roman numerals:

I. **Daraei, M.**, Avelin, A., Thorin, E. (2019) Optimization of a regional energy system including CHP plants and local PV system and hydropower: Scenarios for the county of Västmanland in Sweden. *Journal of Cleaner Production,* 230: 1111-1127.

II. **Daraei, M.**, Campana, P., Thorin, E. (2020) Power-to-hydrogen storage integrated with rooftop photovoltaic systems and combined heat and power plants. *Applied Energy*, 276: 115499.

III. **Daraei, M.**, Avelin, A., Dotzauer, E., Thorin, E. (2019) Evaluation of biofuel production integrated with existing CHP plants and the impacts on production planning of the system-A case study. *Applied Energy*, 252:113461.

IV. **Daraei, M.**, Campana, P., Avelin, A., Jurasz, J., Thorin, E. (2021) Impacts of integrating pyrolysis with existing CHP plants and onsite renewable-based hydrogen supply on the system flexibility. (*Journal manuscript under evaluation*)

V. **Daraei, M.**, Campana, P., Avelin, A., Thorin, E. (2020) A multi-criteria analysis to assess the optimal flexibility pathway for regional energy systems with high share of renewables. *Proceeding of the International Conference on Applied Energy, ICAE 12th*, 1-10 December, Bangkok, Thailand (online).

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Parts of this thesis (Papers I and III) were previously included in the licentiate thesis “Production planning of CHP plants integrated with bioethanol production and local renewables” (Daraei, 2019).

The author’s contributions to the included publications

I. I was the main contributor to this paper. I performed data collection, developed the optimization model, designed scenarios, and wrote the original draft.

II. I was the main contributor to this paper. I performed data collections, the modelling and optimization. I developed the scenarios and wrote the original draft.

III. I was the main contributor to this paper. I performed data collections and data estimations, developed optimization models and scenarios, and wrote the original draft.

IV. I was the main contributor to this paper. I conceptualized the study and scenarios, developed optimization models, performed data collection and analysis, and wrote the original draft.

V. I was the main contributor to this paper. I developed the problem statement and conceptualized the study. I performed data collection and data analysis and wrote the original draft. I was also responsible for presenting the study and findings at an international scientific conference.

Publications not included in the thesis

I. Daraei, M., Thorin, E., Avelin, A., Dotzauer, E. (2017). Evaluation of potential fossil fuel free energy system: scenarios for optimization of a regional integrated system. *Energy Procedia,* 142:964-970.

II. Daraei, M., Thorin, E., Avelin, A., Dotzauer, E. (2018) Potential biofuel production in a fossil fuel free transportation system: A scenario for the county of Västmanland in Sweden. *Energy Procedia,* 158:1330-1336.

III. Daraei, M., Thorin, E., Avelin, A., Dotzauer, E. (2018) Potentials for increased application of renewables in the transportation system: A case study for Södermanland county, Sweden. Energy Procedia, 159:267-273.

IV. Daraei, M., Avelin, A., Thorin, E. (2019) Integration of a rooftop PV system into a regional CHP plant and the impacts on production planning-A case study. *Proceeding of the International Conference on Applied Energy, ICAE 11th,* 12-15 August 2019, Västerås, Sweden.

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Nomenclature

Abbreviations

AEL	Alkaline Electrolysis
AHP	Analytical Hierarchy Process
ANN	Artificial Neural Network
CHP	Combined Heat and Power
COP	Coefficient of Performance
CR	Consistency Ratio
DH	District Heating
DOE	Department of Energy
EVs	Electric Vehicles
GAMS	General Algebraic Modelling System
GHG	Greenhouse Gas
HOB	Heat Only Boiler
HPs	Heat Pumps
HVO	Hydrotreated Vegetable Oil
IEA	International Energy Agency
MCDA	Multi-Criteria Decision Analysis
MILP	Mixed Integer Linear Programming
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
PEM	Polymer Electrolyte Membrane
PV	Photovoltaic
RCP	Representative Concentration Pathways
RE	Renewable Energy
RES	Renewable Energy Sources
SCB	Statistics Sweden
SEA	Swedish Energy Agency
SHF	Separate Hydrolysis and Fermentation

SOEC	Solid Oxide Electrolysis
SVK	Svenska Kraftnät
TSO	Transmission System Operator

Symbols

F	Amount of fuel [ton]
c	Cost [SEK/unit of fuel or product]
pc	Process cost at energy plants [SEK/ton of used fuel]
q	Energy in the form of heat or power [MWh]
conv.	Conversion rate of fuel to energy product [-]
$\propto$	Power-to-heat ratio [-]
HV	Heating value [MWh/ton]
η	Efficiency [%]
Q	Production capacity of the plant [MWh]
U	Operation status of the plant (binary) [-]
Demand	Heat/electricity demand [MWh]
PtG	Power converted to hydrogen [MWh]
GtP	Power produced from hydrogen [MWh]
El	Electricity [MWh]
$\dot{m}$	Inlet energy flow [MWh]
$R_{byproducts\text{-}fuel}$	Ratio of by-products to inlet fuel in pyrolysis [-]
Tank Level	Energy content in the hot water tank [MWh]
PtHP	Power used by HPs [MWh]
E	Mean energy use by EVs per driven kilometer [kWh/km]
D	Driving pattern of EVs [km]
Y	Hourly energy use by EVs [kWh]

Superscripts

F	Fuel
imp/exp	Imported/Exported
F/q,imp	Imported fuel/product
q,exp	Exported product
Waste	Waste heat
Available	Available fuel at the plant
Imp-Limit	The allowed amount of import to the region
Marginal	Marginal CO_2 emissions by power import
Extra	Excess power/heat production in the system
PV	PV systems
Hydro	Hydropower
prod.	Produced (hydrogen)

Used	Used (hydrogen)
Stored	Stored (hydrogen)
max	Maximum limit
min	Minimum limit
Eth	Ethanol
El	Electricity
CH-tank	Charging the hot water tank
DisCh-tank	Discharging the hot water tank

Subscript

f	Type of fuel
p	Type/number of the energy plant
n	Type of product
t	Hours over the year
H_2	Hydrogen
FC	Fuel cell

1 Introduction

The global energy system is undergoing a transformative change towards renewable energies. The share of Renewable Energy Sources (RES) in the world's energy supply has increased by 77% over the ten year period between 2008 and 2018 (IEA, 2020). The most popular renewable resources, which compete with fossil fuels and conventional nuclear energy, are solar energy, wind energy, hydro energy, and bioenergy. The global energy supply from various resources is depicted in Figure 1. The largest increase in renewable energy use occurred in 2017, following a significant increase in the capacity of renewables along with technical developments and reduced costs of solar and wind power (REN21, 2018). The global capacity of the renewables in 2017 was estimated at 178 GW, with a 9% increase compared with installed capacity in 2016. Solar power had the greatest share, accounting for 55% of the total increased capacity. Electrification of the transportation sector in different countries, new policies related to carbon emissions, and other initiatives for energy conservation at national and international levels are other key developments that led to an increase in the RES share (REN21, 2018).

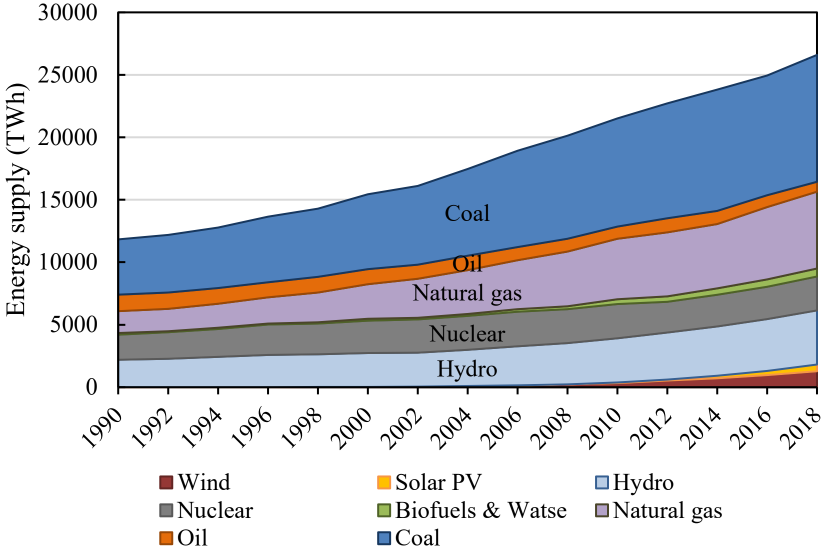

Figure 1: World's electricity generation by source, 1990-2018 (IEA, 2020).

There have been many agreements, policies, and scenarios set by governments, national, and international organizations, to reduce Greenhouse Gas (GHG) emissions and promote rapid transition towards a renewable energy system. Following the Paris Agreement, for example, the EU has set a target of reducing GHG emissions up to 95% below 1990 levels by 2050 (European Commission, 2012). As reported by IRENA (IRENA, 2019), transformation from fossil-based system to a system where renewables account for 65% of the energy supply in 2050, could lead to 41% of the expected reduction in GHG emissions. A further 13% reduction can be achieved by the transportation system and power sector electrification strategy. Based on the EU energy roadmap for 2050 (European Commission, 2012), the total renewable share of gross energy use would reach at least 55% by 2050, with about a 45% increase compared to the current share. The share of different sources in electricity generation in EU countries in 2018 is provided in Figure 2. Nuclear power had the largest share in Europe, and hydropower accounted for the greatest share among RES.

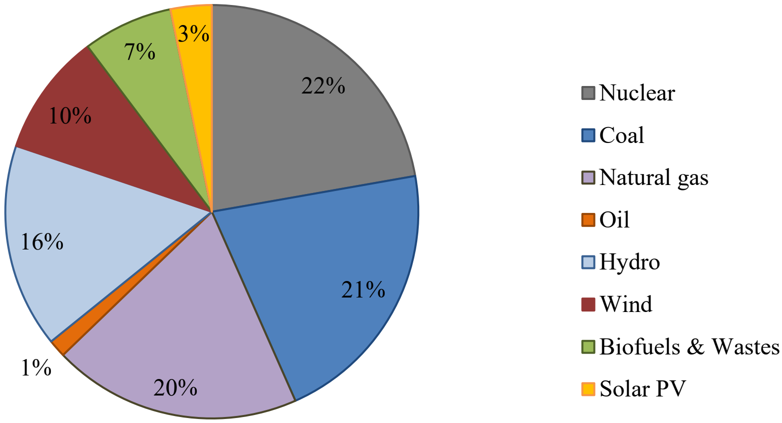

Figure 2: Fuel share in electricity generation in Europe in 2018 (IEA, 2020).

Following the EU roadmap 2050, a common target for fossil fuel-free energy supply has been set for countries across Europe. In most of the countries in the northern Europe, wind power is an important energy source that can potentially meet a large share of the national electricity demand with negligible GHG emissions. With the significant reduction in the levelized cost of solar power generation, solar energy is also expected to supply a great amount of the electricity needs in central and southern European countries (Göransson et al., 2019). The share of wind and solar energy in Germany is continuously growing and it has reached 35% of the national power supply in 2019 (Fraunhofer ISE, 2019; Jentsch et al., 2014). Denmark has set a target of achieving a 100% renewable energy supply with zero net emissions by 2050 (Danish Energy Agency, 2014; IRENA, 2019). Moreover, a fossil fuel independent heat supply by 2035 is within the target set by the Danish government (Heinisch, 2014). The entire power system of Norway is already based on renewable sources, with over 99% production from hydropower (IEA, 2020; REN21, 2018). In Sweden, 100% renewable power supply and phasing out nuclear power are some of the energy targets to be achieved by 2045 (Energimyndigheten, 2019).

Given the status of the energy systems in different countries and the review of studies on energy systems, a 100% renewable electricity supply is technically feasible using a variety of existing and developing measures and technologies including power storage, electric vehicles, vehicle to grid, and large-scale Photovoltaic (PV) systems (Connolly & Mathiesen, 2014; Dominković et al., 2016; Hansen et al., 2019; Jacobson et al., 2017). Nevertheless, 100% Renewable Energy (RE) in all energy sectors, including the heat and the transportation sectors, requires further research and can be achieved in the long run or at small, city-level scales. Examples already exist for several cities, including Hamburg in Germany, Copenhagen in Denmark, and Växjö in Sweden, which aimed to achieve a 100% renewable energy supply by 2050 (Hansen et al., 2019).

This study mainly considers the energy system in the Swedish context. The Swedish power supply is largely based on non-fossil fuels. In 2018, RES accounted for around 50% of total electricity generation in Sweden, of which hydropower accounted for 40% of total production (Swedish Energy Agency, 2020a). The contribution of wind power in Sweden is small, about 10% of total production in 2018. However, new projections increase the total installed capacity in the country by around 6 GW by 2030. Solar power accounted for less than 1% of the national power supply in 2018.

Another example of renewables-based energy supply in Sweden is the expansion of using biomass and waste in thermal energy plants such as Combined Heat and Power (CHP) plants. CHP plants play an important role in both heat and power generation in Sweden. According to the Swedish Energy Agency, CHP plants accounted for 9% of electricity generation in 2018, around 7% of which is produced by combusting biomass-based fuels. Biomass, including wood and bio-wastes, is the common type of fuel used in CHP plants for thermal power supply (Beiron, 2020). Electricity production in Sweden by different generation sources between 1990 and 2018 is shown in Figure 3 (adapted from IEA, 2020). The expansion of biomass utilization in the cogeneration process started in the 1990s and massively increased through 2014. After this year, biomass use has become relatively stable, with a gradual annual increase (Ericsson & Werner, 2016). Data on allocation of different fuels used in CHP plants indicates an increase of 16% in the use of solid biomass and municipal waste from 2015 to 2019 (Statistics Sweden (SCB), 2020).

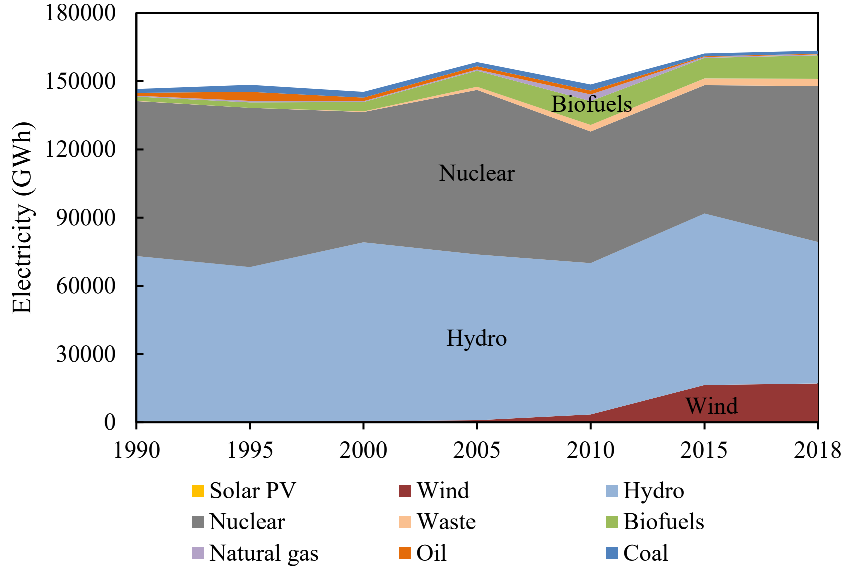

Figure 3: Electricity generation by type of source in Sweden, 1990-2018.

1.1 Motivation and challenges

The objectives of this thesis are based on the literature study and the review of the renewable energy supply technologies and system flexibility options. A literature review has been performed in Chapter 2 to highlight the knowledge gap and is briefly summarized in this section to find the challenges.

The energy supply from some of the renewable resources such as wind power and solar energy depends on weather conditions and can be intermittent. The increased penetration of renewable power in the future system can jeopardize the flexibility of the system and the reliability of supply. Therefore, to maintain flexibility is the main challenge for a power system with high RES penetration (IRENA, 2019). Lack of system flexibility can cause the curtailment of renewable energy and increase system costs, or, in contrast, make RES an unreliable generation source to meet demand. System flexibility in this thesis is based on the definition used by Milligan et al. (2015), and refers to a measure of balancing the generation and demand at system level and different time resolutions, including daily and hourly variations. In the investigation, the flexibility of the system is quantified by the share of renewables in the energy system, the amount of energy output that can supply the demand, and changes in the interaction with the power grid and the amounts of import and export.

Several flexibility technologies and configurations such as energy storage, interconnection of energy sectors, cogeneration strategy, conversion control, and demand-side management could be applied to increase the balance between energy demand and the irregular power supply from renewables (Energimyndigheten, 2019). Some are already in use at small scales. However, they can be applied on larger scales, such as at system level, using a novel integration approach. Using chemical storage technologies such as batteries and power-to-gas conversion technology, it is possible to control the variable power generation from renewables and maintain the security of supply. In case of overproduction, the energy storage can reduce power curtailments in the system while ensuring higher RES penetration (REN21, 2018). The large-scale application can lead to using the full potential of the flexibility technologies to achieve a technically and economically efficient energy system that relies on RES and a more flexible power grid (Gyalai-Korpos et al., 2020). There is still a shortage of studies on large-scale integration of RES and flexibility technologies with the existing energy system.

The increased penetration of RES and application of flexibility technologies are likely to increase the complexity of the energy system. This means that the new energy policy for supporting electricity generation from RES such as wind and solar power could affect the production planning of existing thermal plants like CHP and cause competition between these plants and RES (Beiron, 2020; Salman et al., 2019; Swedish Energy Agency, 2019). Indeed, the production of thermal power depends on the price of electricity as well as the demand. Thus, the increasing power supply from RES using wind, solar, and hydro energy may influence the price and demand and, subsequently, the optimal operation of thermal power plants. However, the large-scale interaction of RES with existing thermal plants and the resulting impacts on the production planning of the system have been less investigated.

As mentioned earlier, interconnecting the power, heating, and transport sectors can also be a potential solution for increased flexibility in the system (Göransson et al., 2019). Electrification of the transportation and heating sectors has led to the expansion of renewable energies in other sectors in addition to the power sector (REN21, 2018). However, the electrification strategy of increasing Electric Vehicles (EVs) penetration or application of Heat Pumps (HPs) in buildings could increase electricity consumption. Using variable RES to supply the increased electricity demand in such electrified systems may result in energy imbalances. In addition, the system may not meet the increased demand considering the climate change and market trends

(Alizadeh et al., 2016; Beiron et al., 2020). The limited capacity of the transmission lines and power grid can also restrict the power export and import in the renewable system and may lead to renewable energy curtailments. From a system-level perspective, CHP plants can contribute to solving some of the challenges related to the future power system. With reliable production capacity, CHP plants can meet the power deficiency when the generation from RES is low and help to solve the energy system's imbalances. Therefore, the combination of different energy sources, conversion technologies, and storage is a pathway to a more balanced system in the future. Still, there is insufficient knowledge on the integration of RES by merging different sectors. More investigations are needed to find the optimal integration pathway by considering the operational strategy of the existing energy conversion plants.

1.2 Objectives and research questions

Motivated by energy policies such as the EU Roadmap 2050 and the Paris Agreement for increased penetration of renewable energy, and given the abovementioned challenges, this thesis aims to increase the knowledge of production planning of existing CHP plants and the flexibility of the energy system with large-scale interaction with renewables.

Based on the literature study, the objectives of this thesis are:

- investigating the increased power supply from RES by adding distributed rooftop PV systems to an energy system dominated by existing CHP plants
- analysing the integration of power storage and polygeneration, and the effects on the flexibility of the studied energy system
- investigating the impacts of high-share renewable energy supply and the flexibility options on the production planning of the CHP plants and operational strategy of the studied system
- determining the impacts of possible energy developments, climate change, and market trends related to energy demand and supply on the optimal performance of the integrated energy system
- suggesting a novel integration pathway and the optimal configuration of energy technologies leading to maximized renewables share and minimized operation costs.

The objectives of this thesis have been achieved by formulating and answering the following research questions:

- **RQ1 (Increased renewable power supply and system flexibility)**
  How can integration of RES with existing cogeneration plants influence the production planning and flexibility of the system?
- **RQ2 (Integration strategy and polygeneration)**
  How can integrated biofuel production with CHP plants affect the production planning of CHP plants and support system flexibility?
- **RQ3 (Trends in demand and supply)**
  What are the impacts of possible energy developments for fossil fuel-free energy supply, climate change, and market conditions on the production planning of the existing and future energy systems?
- **RQ4 (Optimal system configuration and strategy)**
  What is the optimal integrated production pathway for a more flexible cogeneration system?

1.3 Thesis contributions

The thesis contributions corresponding to the appended papers are as follows:

- **Paper I** studies the status of a regional energy system to address the heat and power use and the potential power supply from rooftop PV systems in the region. Based on the optimization, the study provides insights and suggestions about how the production planning of CHP plants, considered as the backbone of the Swedish regional energy system, can be altered by high renewables penetration scenarios.
- **Paper II** proposes a new solution by integrating large-scale power-to-hydrogen storage to the system investigated in Paper I, in order to improve the power imbalances. The investigation provides an understanding of the optimal operational strategy of CHP plants to support system-level flexibility in the transition towards a 100% renewables-based integrated system.
- **Paper III** studies a polygeneration system, including straw-based bioethanol production integrated with thermal plants and rooftop PV systems described in Paper I. By analysing the impacts on production planning of CHP plants and system flexibility, this study provides knowledge about the quantified benefits of the polygeneration in terms of balance between demand and supply.

- **Paper IV** optimizes a polygeneration system by integrating the pyrolysis oil production to the energy system described in Paper II. This study suggests a novel solution for integrating the renewable power to transport biofuel production through onsite conversion of power to hydrogen and integration strategy. Furthermore, this study contributes to increased knowledge of production planning and flexibility of the suggested system, considering uncertainties in the energy system such as climate changes, future market trends, and fossil fuel-free energy supply.
- **Paper V** proposes an optimal configuration of the integrated system by analysing the potential of systems studied in Papers II and IV for increased flexibility. This assessment also determines the system with better performance in terms of operational strategy with respect to technical, economic, environmental, and social aspects.

1.4 Outline

The outline of the remainder of this thesis is as follows:

Chapter 2: *Literature study*
This section provides a detailed overview of the studies on renewable energy systems, systems flexibility, and production planning. The theoretical background starts with an introduction to the increased use of RES and the potential flexibility resources, and the solutions implemented in this thesis.

Chapter 3: *Research methodology*
This chapter describes the investigated cases and scenarios. The research methods, the mathematical formulation of the model, and optimization are also included in this chapter.

Chapter 4: *Results and discussion*
Modelling and optimization results are presented in this chapter, followed by detailed discussion of the research questions.

Chapter 5: *Conclusions*
This chapter presents the most important findings of the thesis.

Chapter 6: *Future work*
Suggestions and possibilities for further research are presented in this chapter.

2 Literature review

In this chapter, studies related to the scope of this thesis, including increased energy supply from renewables, techno-economic studies on the integrated biofuel production technologies, system flexibility technologies like energy storage, and optimization, are reviewed. The main purpose of this chapter is to provide the necessary context for the investigation and introduce the research gap.

2.1 Increased share of RES and flexibility in the energy system

Due to the variation of energy supply from RES over very short time intervals, a need for flexibility in the energy system may arise to accommodate more renewables-based energies and maintain system balance (Beiron, 2020; Daraei et al., 2019).

In the literature, there are several definitions for the term “flexibility”, depending on the type of research and the flexibility needed in the system. For instance, one interpretation of flexibility, by the European Commission, is optimality against any type of uncertainty that might occur in the system (González et al., 2015). In this thesis, the definition provided by National Renewable Energy Laboratory (NREL) is used (Milligan et al., 2015), which defines it as the ability to create a balance between variable energy supply and demand for an optimal system operation.

One of the possible pathways to increase system flexibility is to integrate renewable power resources with conventional power plants such as thermal power production plants. This allows for a more stable power supply and energy balance in the system by using the controllable thermal power generation alongside the variable renewables. Other flexibility alternatives include energy storage, power-to-x technology, forecasting possible variations using predictive models, and installation of new flexible generation sources, such as CHP plants (Alizadeh et al., 2016; Gils & Simon, 2017). Integration of energy technologies could improve flexibility on the supply side by offering different alternatives such as multi-fuel utilization and production of multi-products in a single energy system (Mancarella, 2014). The ability of different integration technologies including CHP plants, HPs, electric boilers, electrolyser, hydrogen fuel cell vehicles, and EVs to improve flexibility of system with high share of RES was analysed and compared by Lund & Mathiesen (2009). They found that each of these technologies could increase system flexibility by integrating different penetrations of RES and with different economic and technical potentials.

The increased penetration of RES could jeopardize the operation pattern and profitability of existing plants in different energy systems, e.g., CHP plants in the Swedish energy system (Beiron et al., 2020; Salman, Dahlquist, et al., 2019). Moreover, interaction between RES and existing conventional energy systems could increase system complexity in terms of overall coordinated operation, economic results, and optimal production without compromising system performance. Thus, it is necessary to optimize the system considering different criteria that influence the production planning of the existing plants (Shao et al., 2016).

Other flexibility improvement measures are demand response models like price-responsive programs and peak shaving, upgraded transmission technologies with high-temperature wires and control systems, and new market regulations for increasing integration possibilities (Alizadeh et al., 2016). This thesis focuses on two flexibility pathways for the regional energy system in high-share renewables scenarios: integrations through polygeneration of power, heat, and biofuels; and long-term power storage by using power-to-hydrogen conversion technology.

2.2 Polygeneration

A polygeneration system refers to an energy system in which multiple energy products such as heat, power, chemicals, and transport fuel can simultaneously be supplied from a single unit (Jana et al., 2017). In other words, a single type of input fuel is utilized to produce different energy products. A commonly used example of a polygeneration system is the CHP plant. With the polygeneration approach, the waste energy and by-products could be used in other energy processes for additional energy supply. Therefore, polygeneration design of an energy system can increase system efficiency and optimal energy use compared with standalone systems (Jana et al., 2017). Moreover, system flexibility in terms of balance between demand and supply could be increased with polygeneration, as the system can switch between multiple energy products depending on demand and system operation.

Given a high potential for biomass utilizations, Baltic countries have a high biofuel production potential (Leduc et al., 2012). However, the conversion of biomass to biofuel is less efficient than fossil fuel, given its low energy content. Moreover, the production yield of some biofuel production process is relatively low. For example, the production yield of bioethanol through fermentation of biomass is up to 35% (Eriksson & Kjellström, 2010). By integrating biofuel production with CHP plants in a polygeneration system, the combustible residues and by-products of the system can be used to provide additional energy and increase system efficiency. This strategy could also influence the production planning of energy conversion plants and improve system flexibility.

Polygeneration through integration of bio-refineries with CHP plants has been the focus of several studies that investigate such systems from various aspects, including the economic, technical, and environmental (Holmgren et al., 2016; Kohl et al., 2013; Lythcke-Jørgensen et al., 2014; Lythcke-Jørgensen & Haglind, 2015; Salman et al., 2018). These investigations proved the technical feasibility of integration of energy technologies, and the potential effects on improved system efficiency that can lead to reduced system costs and positive environmental impacts. Gustavsson and Hulteberg (2016) reported the potential of integrated biomass gasification with the existing CHP plants to increase energy efficiency by up to 15%. In a similar study, Galvagno et al. (2017) reported an improved gasification-CHP system using fruit waste as the feedstock. Jana and De (2017) studied the polygeneration of heat, power, and ethanol from rice straw and reported improved life-cycle emissions compared with standalone units.

As part of the investigation in this thesis, production planning of CHP plants in a polygeneration system, by integrating fermentation for bioethanol production and pyrolysis, were analysed. Bioethanol is one of the major examples of transportation sector biofuel and can be produced from a variety of biomasses (Hattori & Morita, 2010). Based on the type of biomass, bioethanol is classified into three categories: bioethanol from sugar-based biomass; starch-based bioethanol; and bioethanol from cellulosic materials, known as second-generation bioethanol (Hammond & Mansell, 2018). The thermochemical process of bioethanol production is the same for all three classes of fuel, and includes saccharification, sugar fermentation, and distillation. However, depending on the type of the feed used, pre-treatment and hydrolysis may be necessary to access fermentable sugars (Larsen et al., 2009).

Pyrolysis is a thermochemical process by which biomass is converted at an elevated temperature to solid, gaseous, or liquid high value products (Ringer et al., 2006; Y. Yang et al., 2018). The purpose of the decomposition of biomass in pyrolysis is to produce one main product. The primary product from pyrolysis is usually bio-oil, while syngas and biochar are the by-products (Y. Yang et al., 2018). The ratio of pyrolysis products can be changed depending on parameters such as biomass pre-treatment, heating rate, and process temperature. For instance, pyrolysis at low heating rate, so-called slow pyrolysis, is used when formation of biochar is desired, whereas a high heating rate is needed for fast pyrolysis, where bio-oil production is favoured (Görling et al., 2013). The intermediate liquid bio-oil from pyrolysis can be further upgraded by hydro processing into biofuels that are more suitable for direct use in the current transportation sector (Salman et al., 2017a; Shemfe et al., 2015).

The main technical findings of the abovementioned studies on polygeneration systems using bio-refineries were used as the basis for this thesis that focuses on impacts on production planning and system flexibility.

2.3 Power-to-hydrogen technology

The electricity storage is the process of converting electricity to an easily storable form of energy. The stored energy can be converted to different forms of energy such as electricity, synthetic fuels, and other energy carriers (Chen et al., 2009; Dti report, 2004). The main advantage of using power storage is load balancing to meet the peak demand and supply required energy when production is variable. This can increase the use of renewables in the energy system and reduce electricity imports.

The methods of storing electrical energy can be classified into various categories, depending on storing period, functions, the response time, and, most commonly, the form of the stored energy (Chen et al., 2009; International Electrotechnical Commission (IEC), 2011; Molina, 2010). Based on the latter factor, the power storage technologies can be divided into four main classes, including mechanical, electrical, chemical, and electrochemical. Pumped hydro is the main type of mechanical energy storage and batteries are the most used electrochemical storage method. Power-to-hydrogen storage, as one of the promising technologies for long-term power storage, is categorized in the chemical class. This technology is used for power storage in this thesis.

The essential process in power-to-hydrogen storage systems is water electrolysis, through which excess power is converted to hydrogen. In the electrolytic cells, the molecules of water are split into oxygen and hydrogen by consuming power. The hydrogen, as a valuable energy carrier, can be stored in a high-pressure storage tank. It can later be used in the gas grid or further transformed into electricity using fuel cells or used for production of synthetic fuels, such as methane, in the presence of enough carbon sources (Andrijanovits et al., 2012; Götz et al., 2016; Heinisch, 2014). Based on the efficiency, lifetime, and type of the electrolyte materials, the most-used electrolysis technologies are Alkaline Electrolysis (AEL), Polymer Electrolyte Membranes (PEM), and Solid Oxide Electrolysis (SOEC) (Lewandowska-Bernat & Desideri, 2018).

Alkaline electrolysis is the most mature technology, and it is mostly used for large-scale applications. This type of electrolyser has an efficiency that ranges between 66% and 74% (Lewandowska-Bernat & Desideri, 2018). The major problem with AEL is the elevated risk of corrosion and thus high maintenance cost. PEM is a relatively new electrolysis technology, compared with AEL which is commercially available since 1978. The investment cost of these electrolysers is greater than the AEL type. However, high operation flexibility, short shutdown/start up time, and higher purity of the hydrogen produced are some of the advantages of using a PEM electrolyser, making this technology popular. PEM is considered for the electrolysis in this study. The SOEC electrolysis is a developing technology that is not yet widely available at commercial scale. The main advantage of SOEC electrolysers is the reduced electricity demand for hydrogen production, compared with other available technologies. However, operation at high temperature would cause degradation of materials and negatively affect the stability of the technology in the long term (Götz et al., 2016; Lewandowska-Bernat & Desideri, 2018).

The second stage in the power-to-hydrogen conversion is hydrogen storage. There are various methods of storing hydrogen after production, including underground storage, compressed gas storage, and compressed liquid tanks. However, according to Götz et al. (2016), high-pressure storage in the gas cylinders after hydrogen compression using an electric-based compressor is the most used method. It should be noted that it is challenging to handle and store hydrogen as it is the lightest known molecule, with a very wide range of flammable concentration. Therefore, there is a risk of asphyxiation and/or explosion due to leakages of liquefied hydrogen or high pressures (Johansson et al., 2018).

2.3.1 Possibilities for hydrogen use

The renewable hydrogen produced by electrolysis could be utilized in different energy sectors and manufacturing industries. This can also create a link between the renewable power and the other end-user sectors where the production and application of the renewable energy is challenging.

The use of hydrogen in refineries, in the production of ammonia, chemicals, and synthetic fuels are some examples of its industrial applications. The hydrogen can also be injected into the gas grid to be used for heat production or in gas turbines. The other alternative for hydrogen use is in the transportation sector as a fuel for fuel-cell electric vehicles. Replacing fossil fuels with hydrogen in the transport sector leads to a significant reduction in carbon emissions. Power and heat production by fuel cells is another pathway for optimal use of hydrogen (IRENA, 2019). Fuel cells with megawatt capacity can be connected to the electricity grid for utility-scale applications. The hydrogen production from electrolysis and potential end-use sectors are illustrated in Figure 4.

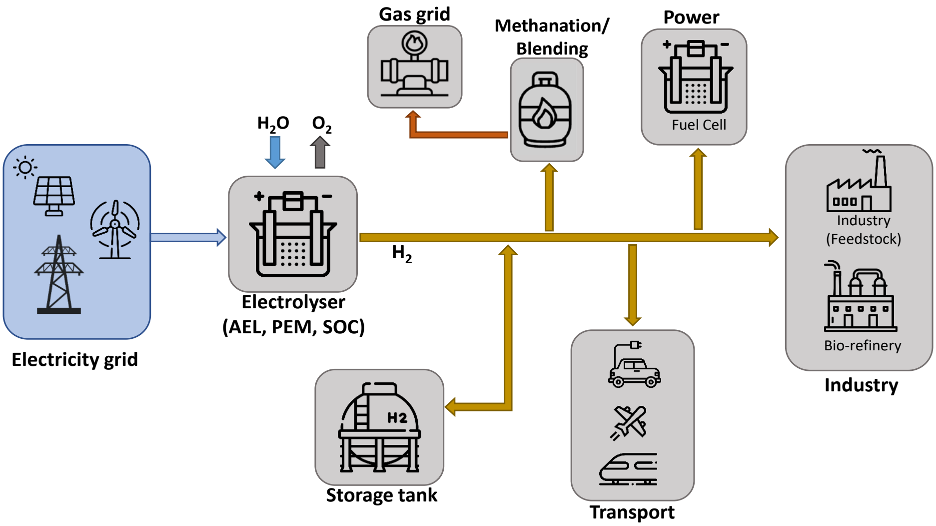

Figure 4: Power-to-hydrogen process and potential end uses (based on IRENA, 2018).

In this study, hydrogen applications for power generation using fuel cells, and for biofuel production in bio-refineries were investigated.

Fuel cell

Adding fuel cells to the power-to-gas system, known as power-to-gas-to-power installations, allows stored hydrogen to be used for heat and power production. Through the electrochemical processes in the fuel cell, the chemical energy stored in the hydrogen is converted into electric energy. Thus, the conversion process in the fuel cell is considered as reverse electrolysis (Kotowicz et al., 2018).

According to Kotowicz et al. (2018), the use of fuel cells for combined heat and power supply has undergone a significant evolution from small-scale applications to commercial installations in recent years. Like the electrolyser classifications, several types of fuel cell exist, classified according to the electrolyte used in their structure and the fuel type used. The operating electrical efficiency of PEM fuel cell varies between 40% and 60% (Larminie & Dicks, 2003; Li et al., 2009). The electric voltage of a single fuel cell is normally below 1 V (Kotowicz et al., 2018). To increase the voltage and thereby the output power of fuel cells, the cells are connected in series, technically called stacks (Kotowicz et al., 2018). More cells can also be connected in parallel to achieve the desired current and power parameters. The main output of fuel cells is electrical energy, which can be estimated by the electrical efficiency of the fuel cell. The output also includes some energy losses, including heat from unreacted hydrogen, energy from water production, and other electrochemical reactions, as well as the heat that dissipates. The waste heat generated from fuel cells can be used for heating supply such as for space heating (Gimba et al., 2016; Li et al., 2009).

Use of hydrogen in drop-in biofuel production

Drop-in biofuels are liquid biofuels with a similar structure to the conventional diesel and petroleum-derived fuels. The biomass can be converted into drop-in biofuels in two main steps. The first step takes place through different thermochemical technologies such as pyrolysis and gasification, in which the biomass is converted to an intermediate liquid fuel. Further processes and chemical reactions are needed in the second step, to upgrade the intermediate fuels to drop-in biofuels (Dyk et al., 2019; Salman et al., 2020). Different steps in the production chain of drop-in biofuels by thermochemical processes are shown in Figure 5.

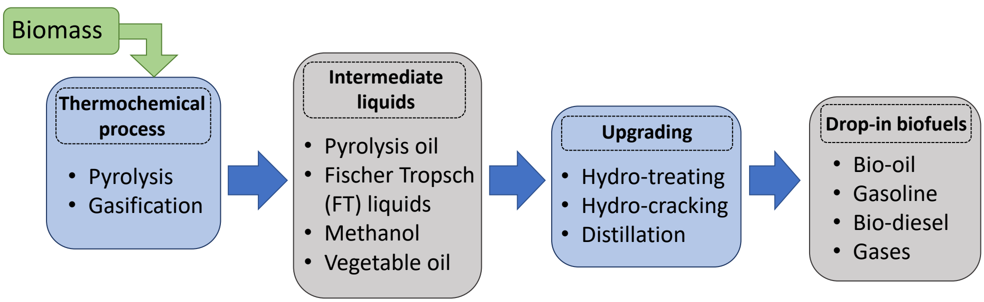

Figure 5: Conversion platform of biomass to drop-in biofuels.

The main challenge in the upgradation of the intermediate liquid fuel is the removal of the oxygen that is present in the structure of the biomass. This is normally done through a chemical reaction between the fuel and hydrogen to reject the oxygen in the form of water, known as hydro-processing (Bridgwater, 2012). Hydro-processing to upgrade the pyrolysis oil or methanol from gasification to higher-quality products requires a large amount of hydrogen. The required hydrogen can be provided from external suppliers. However, transporting hydrogen to the consumption points is challenging and expensive given current infrastructure of pipelines, delivery technologies, and dispensers. Some of the key challenges related to hydrogen dispensing are hydrogen purity, energy efficiency, hydrogen leakage through transportation, and safety issues (Office of energy efficiency & renewable energy, 2020).

An alternative supply of hydrogen for drop-in biofuels in bio-refineries is the onsite water electrolysis, using excess power from renewable resources. Despite the high capital cost of this technology, it is considered the “green” source of hydrogen (Dyk et al., 2019). This approach can also channel the renewable power to the transport sector and biofuel production. Power-to-hydrogen can contribute to lower life-cycle emissions from bio-refineries, where large amounts of fossil-based hydrogen from gas or coal has been utilized for decades (European Environmental Bureau (EEB), 2020; IRENA, 2018). Using electricity from renewable resources to produce hydrogen, the CO_2 emissions from electrolysis is zero. However, conventional hydrogen supplied from coal combustion can emit up to around 20 kg CO_2 per kilogram of produced hydrogen (Bartlett & Krupnick, 2020). Thus, replacing fossil-based hydrogen, used as feedstock in refineries, with renewable hydrogen can significantly increase the chance of decreasing system CO_2 emissions.

2.4 Energy system optimization

In this section, a summary of the research related to the optimization of integrated systems and flexibility of systems with increased renewable energy supply is presented.

Increased renewable energy supply

Design and optimization of an energy system with high-renewable shares of up to 100%, especially in the power sector, has been the focus of recent investigations. The sustainability of three different integrated systems from five local renewable resources, including biomass CHP plants, wind power, hydropower, PV systems, and biogas, was investigated for a regional energy system in Finland (Väisänen et al., 2016). The decision-making analysis in this study found the integrated wind and hydropower, and integration of the PV system and CHP plants, to be more sustainable options in terms of high energy efficiency, lower environmental impacts, good technical performance, and the increased share of renewables in the regional power supply. Levihn (2017) studied the interaction of CHP plants with large-scale HPs and renewable power supply in Stockholm, Sweden and found it a feasible approach to increase the share of renewables in the system. Given the need for increased flexibility in the renewables-based system, Brouwer et al. (2016) investigated the influence of different flexibility technologies on the electricity supply in the European energy system, with a high renewable share of up to 80%. In a similar study of the energy system in France, the demand-response model and power transmissions were found as options to increase flexibility in a fully renewable power sector in the region (Krakowski et al., 2016). Large-scale energy storage and dispatchable generation sources are the flexibility measures found by Pfenninger & Keirstead (2015) for an economically viable power sector with more than 80% renewables in the UK. These studies focus on the potential of the system to balance production surplus and deficit in a power sector based on high-share renewables. However, a greater share of energy supply from RES, interacting with conventional energy conversion plants, affects the operational strategy of the existing system. In light of these possible effects, Wang et al. (2018) investigated the cost-optimal planning of integrated energy systems consisting of CHP plants, PV systems, and batteries for maximizing the use of solar energy. They proved that the operating cost of the proposed system is significantly reduced compared to the actual system data. However, the lifetime loss of battery has a significant impact on the optimization result. The optimization in this study was performed for a power system in an industrial park with a PV power capacity of 0.4 MW_p, and the impacts of large-scale power storage were not investigated.

Integration of power-to-gas technology

There are many investigations of power-to-hydrogen conversion technology used for seasonal storage of renewable power. The potential of this technology for system flexibility and reducing energy curtailments is highlighted by several authors (Heinisch, 2014; Heinisch & Tuan, 2015; Lewandowska-Bernat & Desideri, 2018; Lyseng et al., 2018). Mesfun et al. (2017) investigated the impact of power-to-gas and power-to-liquid processes on controlling the intermittent renewable energy supply in the power grid in the Alpine region. The possibility of capturing surplus energy and its use in the transport and heating sectors; increased share of renewable power supply from 0.85 to 65 GW; reduced CO_2 emissions by using carbon in synthetic gas generation; and the reduced energy curtailment are the main findings of their study. Power-to-gas/liquid conversion technologies were also found to be key technologies in increasing system flexibility by linking the power, heating, and transport sectors. Zakeri & Syri (2015) performed a life-cycle cost analysis of different power storage technologies, including power-to-gas conversion using fuel cell and gas turbine. The study showed that the cost of storage is low for the power-to-gas technology, however, the capital cost is high, especially when using fuel cells. Therefore, more research is required to increase the competitiveness of this storage technology in terms of economics and performance.

The optimal design of adding the power-to-hydrogen storage to the renewable system was also investigated. For example, Jentsch et al. (2014) proposed an optimal capacity in the range of 6 to 12 GW for a power-to-hydrogen storage to be integrated with the power system in Germany with 85% of renewable power production. For small-scale application, Zhang et al. (2016) found a better economic performance of the power-to-gas storage compared with other conventional storage methods, like battery-based storage. Nigim et al. (2009) showed that the integration of RES, conventional heat and power cogeneration plants, and power storage could manage the short-term variations in power supply from renewables and increase the system flexibility. By this integration approach, the energy loss from the power storage, produced as waste heat, can be utilized in the District Heating (DH) network, which improves system efficiency (Lümmen et al., 2019), but affects the operation strategy of existing thermal plants. This aspect was less explored in literature and the focus was mainly on creating a balance between supply and demand in energy systems with high penetration of renewables.

Polygeneration and integration of energy technologies

Integration of various energy conversion technologies and the interconnection of energy sectors have been seen as an approach for increased system flexibility. Polygeneration of transport biofuels such as methane, methanol, bio-oil, and drop-in biofuels, together with heat and power from CHP plants, have been investigated in several studies (Daianova et al., 2012; Djuric Ilic et al., 2014; Dyk et al., 2019; Kohl et al., 2013; Salman et al., 2018; Starfelt et al., 2010). According to Karvonen et al. (2018), the integrated production of the pyrolysis bio-oil with CHP plants increases the pyrolysis efficiency by around 20% and improves the environmental impacts. In a similar work, Bridgwater (2012) highlighted the improved efficiency and economic benefits of the integration of pyrolysis with different energy technologies in a bio-refinery. As investigated by Shemfe et al. (2015), integrated gasoline and diesel production from pyrolysis with an electricity generation unit is technically feasible and increases system efficiency by 2%. However, high capital costs, due to bio-oil hydro-processing, is challenging. Salman et al. (2020) studied the integrated pyrolysis oil production with existing CHP plants and onsite hydrogen production through gasification. According to their study, the system is technically feasible and can increase the economic benefits and flexibility of the system. In another study, Salman et al. (2020) designed the same integrated system but used SOEC electrolysis technology for the onsite hydrogen production and showed a stable economic performance and improved efficiency. However, there is still a need for large-scale optimization of such systems with a focus on increasing the share of renewables and system flexibility while reducing system cost.

The studies on polygeneration mentioned above essentially assess the potential of the integrated system from the technical and economic points of view, and highlight the increased energy conversion from the polygeneration system. Nevertheless, the interaction of such systems with renewables in a more flexible system still requires more in-depth research. As Lund & Münster (2006) suggested, the integration of the power and heat sectors is a possible strategy to increase the share of renewables in the energy system. The studied integrated system consists of HPs, heat storage, CHP plants for heat and power supply, and renewable resources including photovoltaic and wind power. The proposed system showed the ability to increase the renewable power input in the system and to improve system flexibility by using excess power in HPs for heat supply. In this regard, Mathiesen et al. (2015) also reported that the design of smart energy systems integrating power, thermal, and gas grids can increase the penetration of RES and enable a 100% renewable system with high flexibility. This system enables the intermittent renewable energy sources, such as solar and wind power, to use the new flexibility options, including energy storage, HPs, and EVs. This approach also showed the technical and economic potential to design a 100% renewable system. However, the study did not analyse the possible impacts of the smart systems on existing thermal plants and traditional energy systems.

2.5 Point of departure

The conclusion of the studies on power-to-hydrogen storage with increased penetration of RES indicates the technical feasibility of utilization of this technology to increase flexibility in the system. According to Lyseng et al. (2018), around 76% of studies are focused on small-scale applications of power storage integrated with residential-level RES utilization and techno-economic investigations. However, the impacts on operational conditions of existing energy plants, like biomass-based CHP, at regional level are less investigated. Moreover, the system's optimal performance in terms of energy import and export, fuel use, the production cost under increasing share of RES, and use of seasonal power storage is less investigated.

On the integration and polygeneration side, adding drop-in biofuel production to the existing CHP plants and the parallel onsite hydrogen supply from renewables has not been extensively investigated in literature. The focus of most of the studies tends to be on the technical and economic feasibility of the renewable system, with few considerations of the role of existing energy conversion plants under uncertainties and trends in the energy system such as climate changes or the electrification of the heating sector. The impacts of such developments on production planning of the system are also less considered. Therefore, the potential of the existing CHP plants at system-level to be integrated with other renewable-based technologies, the impacts on the optimal planning of the system, and the effective flexibility solutions are yet to be widely investigated. The following key concepts derived from the literature study in this chapter were used as a basis for modelling, optimization, and analysis in this thesis:

- **Decarbonization** by shifting to renewable energy supply is one of the main pillars of the sustainable energy transition. In this thesis, enhanced power supply from distributed rooftop PV systems is proposed.
- Due to intermittency and stability problems of the renewable energy supply and the limited grid capacity, rising share of RES requires **flexibility** in the system.
- The main goal in solving the flexibility issues in the renewable system is to **maximize RES penetration while minimizing the operation costs** of the system. Using this concept, a cost-optimization model is developed in this study for the system with increased share of renewables.
- **Energy storage** is a key development technology and yet to be expanded for large scale applications. **Use of gas for long-term energy storage** and its versatile applications in the power, heat, and transport sectors increase the system flexibility. Therefore, a system-level power storage using power-to-hydrogen technology is integrated to the system in this thesis and investigated.
- **Integration of energy technologies** is an option for increased flexibility. It is important to find **cost-effective** integration.
- **Polygeneration by integration of biofuel production with CHP plants** increases the overall performance of the system. Bioethanol and pyrolysis oil production integrated with CHP

plants are examples of polygeneration approaches assessed in this study.

- **Changes and uncertainties** in the energy system influence demand and optimal planning. The impacts of climate changes, trends in energy demand and supply, and fossil fuel-free energy-supply target are evaluated in this study as examples of possible developments.

This thesis combines the above-mentioned concepts but focuses on the potential of existing CHP plants to be integrated with other energy technologies in the future renewable system. Existing thermal plants and thermal power supply play an important role in balancing demand and supply in the renewable system. Therefore, it is important to analyse the production planning of the existing CHP plants in the energy transition. In this thesis, CHP plants are the backbone of the studied energy system and their operational strategy is modelled and optimized under different scenarios of high RES share and potential flexibility options at system-level.

3 Methodology

This chapter presents the research methods that were employed in **Papers I** through **V** to address the research questions in section 1.2. The chapter describes the energy system configurations developed for modelling, the data collection and analysis, and the scenario development to investigate system flexibility and production planning.

3.1 Research approach

An optimization model to find the most cost-effective energy supply and plant operation was developed to answer the research questions presented in section 1.2. Heat and electricity are the main products of the studied energy system, mainly produced from biomass-based fuels such as wood, municipal bio-waste, and solid biofuels that are mainly forest residues. However, there is a possibility to utilize fossil fuels in the system, including oil and coal, for example during peak demand periods. Mixed Integer Linear Programming (MILP) is chosen to solve the combinatorial optimization problem in this study that contains integer, continuous, and binary variables. MILP shows fast conversion and uses well-defined methods to find a global optimum for complex problems at large-scale, such as integrated energy systems (Kantor et al., 2020).

The following configurations were modelled and optimized to investigate the role and operational planning of the CHP plants in a diverse future energy system with an increased share of renewables and greater flexibility:

- potential power supply from regional rooftop PV systems and its interaction with existing CHP plants
- integrated power-to-hydrogen with CHP plants and rooftop PV systems

- utilization of fuel cells connected to the power-to-hydrogen storage system for increased system flexibility
- integration of straw-based bioethanol production with existing CHP plants, considering availability of feedstock in the regional system
- retrofitting the investigated energy system with drop-in biofuel production by integrating the wood pyrolysis and onsite hydrogen supply to the existing CHP plants.

The overall methodology approach is depicted in Figure 6. To assess the described cases, the following research methods have been applied:

- Literature study: The existing related works on increased share of renewable power supply, energy system flexibility, and existing flexibility techniques were studied to obtain the background information and to identify the knowledge gaps. The flexibility options focused on in this study are large-scale energy storage and the integration approach (**Papers I, II, and III**).
- Data collection: The key parameters in the studied system were identified and the required data was collected. Data collection includes data for the studied energy conversion plants, available renewable resources and the energy supply estimations, and data on the demand side. Input fuels availability, system production capacity and efficiencies, and the costs for purchasing, producing, importing, and exporting fuels and energy have been collected and/or estimated. The historical data from existing energy companies and available databases such as SCB and the Swedish Energy Agency were used for data collection and estimations. The most recent production years of 2015 and 2018, for which most of the data was available, were selected as the base years for data collection and further modelling in this thesis (**Papers I, II, and III**).
- Modelling and optimization: The energy system under different configurations of the polygeneration system and integrated power storage was modelled using the MILP method in General Algebraic Modelling System (GAMS). Several optimization scenarios considering future energy developments and changes in energy demand were developed and analysed to answer the research questions (**Papers I, II, III, and IV**).

- System analysis: The modelling results from optimization were further analysed to determine the impacts of the described integrations on the performance of the CHP plants and system production planning (**Papers II, III, and IV**). The studied optimization cases were then compared to find the best energy system configuration, considering the flexibility potential. A multi-criteria analysis using Analytical Hierarchy Process (AHP) method was employed with respect to key indicators including technical, economic, environmental, and social aspects, with several qualitative and quantitative sub-criteria (**Paper V**).

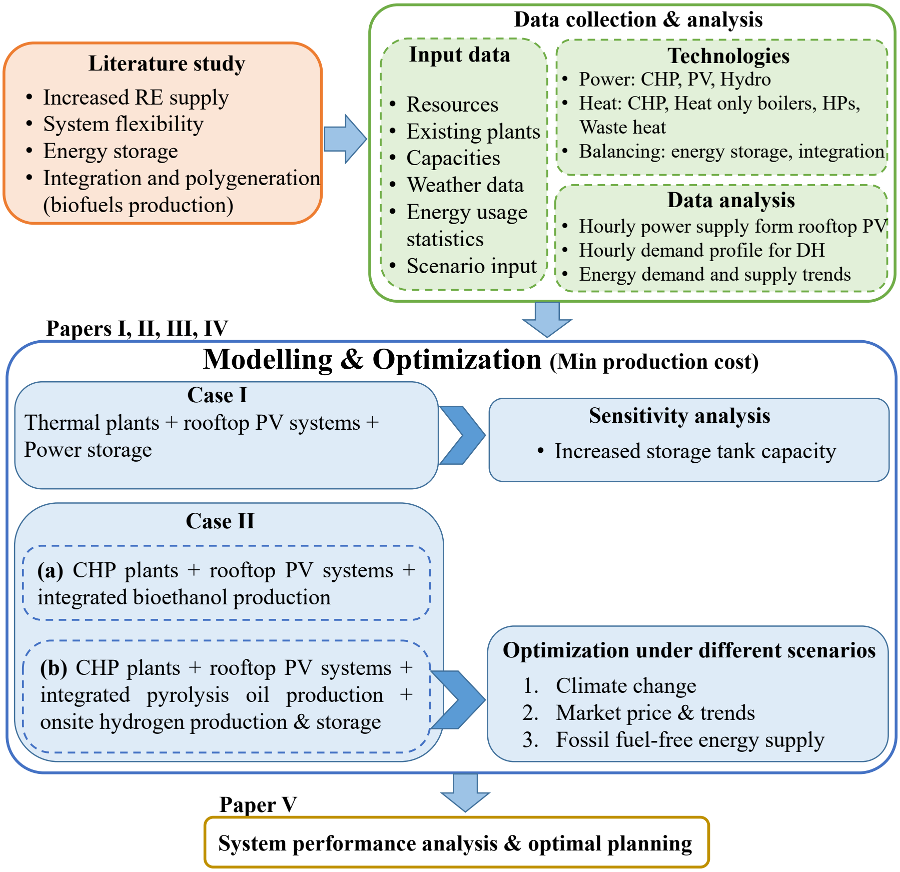

Figure 6: Methodology approach.

3.2 Description of the reference system and investigated cases

To investigate the system flexibility and the optimal production planning, two different cases for integration of energy storage and biofuel production to the thermal plants and PV systems were modelled and optimized.

In **Papers I** to **IV** in this thesis, a mathematical optimization model of different energy systems has been developed. The model was applied for potential evaluation and long-term production planning considering the system costs and future scenario analysis. Depending on the purpose of modelling, the temporal and spatial scales vary for different models. In **Papers I** and **III**, the optimization model was developed to find the potential of the existing CHP plants to be integrated with other energy technologies in align with the increased renewable energy supply. Daily variations in energy supply and demand for a large-scale energy system at county level were considered in the analysis. However, **Papers II** and **IV** aim to model the interactions between different components of the system considering a time resolution with one-hour time step. These papers also investigate the detailed operational strategy and flexibility of the overall system with power storage. For better understanding of sector interconnections and the impacts on system flexibility and energy output, a smaller spatial scale, that is city level, was used to model the polygeneration system in **Paper IV**. The information about the resolution, scale, and application of the optimization model in different cases is listed in Table 1.

Table 1: Information of the optimization model developed for different system configurations in studied cases.

System configuration	Purpose/Application	Spatial scale	Time resolution	Objective	Analysis indicators
Base configuration: Thermal plants + Rooftop PV systems (Paper I)	Optimization, Potential evaluation, Operational strategy	Regional scale (county level)	Daily variations over one-year period	Cost optimization	Energy imports, Emissions, Overall performance
Case I: Base configuration + Energy storage (Paper II)	Optimization, Flexibility in power system, Impacts on production planning	Regional scale (county level)	Hourly variations over one-year period	Cost optimization	Energy imports, Emissions, Overall performance, System flexibility
Case II (a): Base configuration + Integrated bioethanol production from cereal straw (Paper III)	Optimization, Potential evaluation of polygeneration, Impacts on production planning Sectors interconnections	Regional scale (county level)	Daily variations over one-year period	Cost optimization	Energy outputs, Emissions, Overall performance
Case II (b): Base configuration + Integrated pyrolysis oil production + Onsite hydrogen supply from renewable power (Paper IV)	Optimization, System flexibility, Impacts on production planning, Sectors interconnections	Regional scale (city level)	Hourly variations over one-year period	Cost optimization	Energy imports, Emissions, Overall performance, System flexibility

The following sections in this chapter describe the reference energy system, investigated cases, and the modelling details.

3.2.1 Reference energy system

Reference system at county level

The regional energy system of Västmanland County, central Sweden, was used as the case study in Case I and Case II(a). Västmanland, with a land area of 5,118 km^2 and 275,800 inhabitants, consists of 10 municipalities (Regionfakta, 2020; SCB, 2019). The County is considered an industrial region in Sweden. Mälarenergi, one of the largest Swedish energy companies that cogenerates heat and power, supplies the County's heating demands, together with several regional thermal plants. Due to Västmanland's location and its moderate weather, and considering the existing energy companies, data availability, and computation time, Västmanland was chosen as a representative regional system for this study. The energy system in the region comprises five CHP plants and 28 heat-only boilers (HOB). Biomass-based fuels, including wood, bio-waste, wood pellet, and solid biofuels are predominantly used at the thermal plants for energy conversion processes. However, it is also possible to use fossil oil and coal in the system, mostly at HOBs. The installed capacity of each plant and the used input fuels are described in **Paper I**. There are 30 hydropower stations in the region with a total capacity of 51 MW and a 1 MWp solar park with 92 solar trackers. In 2018, the energy supply from the regional system could meet around 528 GWh of the electricity demand and provided around 2,253 GWh of DH (Mälarenergi AB, 2018b; Swedish Energy Agency, 2020b; Västra Mälardalens Energi och Miljö AB, 2017). The location of the studied energy system, including the type of energy conversion plants, is depicted in the map in Figure 7.

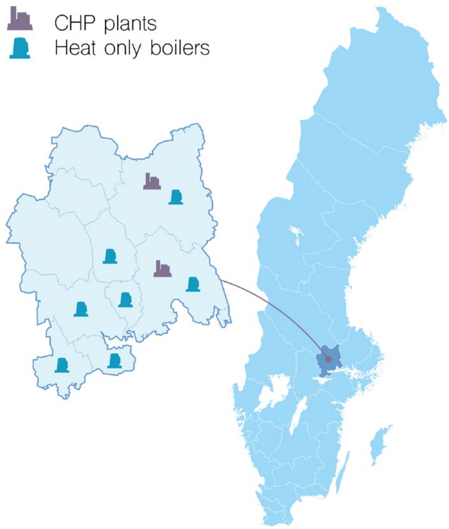

Figure 7: Map of the studied energy system at county level.

Reference system at city level

To perform a detailed analysis in polygeneration case (Case II(b)), only the CHP plants in Västerås, the capital of Västmanland, were used as the reference energy system. Västerås is Sweden's fifth largest city. A map view of the location of Västerås is depicted in Figure 8. There are four CHP plants in Västerås with 90% thermal efficiency. The system can convert the energy of both biomass-based and fossil fuels, including wood, bio-waste, solid biofuels, peat, oil, and coal, into heat and electricity. However, bio-waste is the predominant fuel type used for energy conversion processes with an annual utilization of up to 400 kton (Mälarenergi AB, 2018a). The specifications of CHP plants in the region are summarized in Table 2. There are two HPs at the CHP plant with a total heat capacity of 27 MW and an average Coefficient of Performance (COP) of 3.5. These HPs contribute to the DH supply and are included in the optimization model. The CHP plants are also equipped with a water tank for heat storage with the total capacity of 2,100 MWh, which was used in the optimization model for this case.

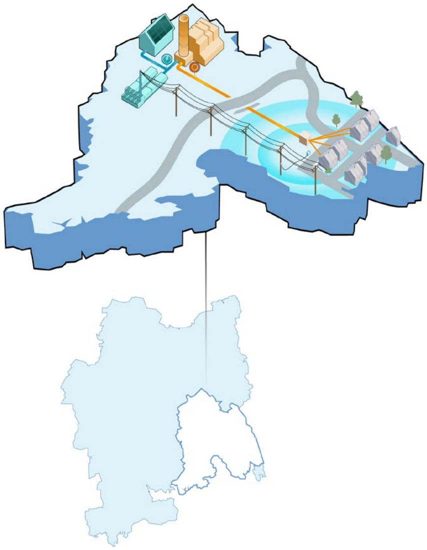

Figure 8: Map of the studied energy system at city level.

Table 2: Specification of the reference CHP plants in Case II (b) (Mälarenergi AB, 2018a).

CHP plant	Installed capacity (MW)	Input fuels	Max heat generation (MWh)	Max power generation (MWh)
Plant 1	165	Fossil oil, coal	116	49
Plant 2	165	Fossil oil, coal	116	49
Plant 3	220	Coal, peat, wood, solid biofuels	155	65
Plant 4	220	Tall oil, solid biofuel, bio-waste	155	65

The total capacity of hydropower plants in Västerås is 2.5 MW (Mälarenergi Vattenkraft AB, 2020; Svenska kraftnät (SVK), 2020) and its contribution to the power supply was also added to the optimization model.

3.2.2 Case I: integration of thermal plants with rooftop PV systems and power-to-hydrogen-to-power installations (**Papers I** and **II**)

Case I was developed to answer **RQ1** regarding increased share of RES in the energy supply and increased flexibility. This case considers an energy system dominated by CHP plants, which are interacting with rooftop PV systems (**Paper I**) and power-to-hydrogen-to-power installations (**Paper II**). The excess power in the system is stored in the form of hydrogen, through PEM electrolysers, and in the event of power deficiency, the hydrogen can be used in the PEM fuel cells to produce electricity. A large-scale storage system with an input power capacity for the electrolyser that matches the capacity of the regional energy system is considered in order to investigate the potential of the hydrogen storage and the fuel cell contribution to supply the power shortfalls in the system. Case I is described and investigated in **Paper I** and **Paper II**.

Rooftop PV systems and hydrogen storage

The rooftop PV systems were considered as the variable renewable source in this study. The potential daily and hourly power supply from the PV panels installed on the rooftop of buildings in Västmanland region was estimated using the available rooftop area for panel installations. The roof area was calculated using data on the number of buildings of different types, such as single-family and multi-family houses, and public buildings, and the average floor area (Swedish Energy Agency, 2020b). The statistics on the number of buildings were processed in QGIS, a graphical information platform for analysing geographical data. Given an average rooftop area of 120, 160, and 100 m^2 for single-family houses, multi-family houses, and public buildings, respectively, the total roof area was estimated to be around 8.2 km^2 (**Paper I**). The estimated roof area together with the solar radiation on the panel surface and the panel efficiency and performance ratio are used in equation (1) to calculate the potential power supply from the proposed PV systems.

$$\mathrm{q}_{\mathrm{t}}^{\mathrm{PV}} = A \cdot H_t \cdot r \cdot PR \tag{1}$$

q_t^{PV} is the estimated solar power output at each time step t, A is the available area for panel installation in m^2, H_t is the solar radiation on tilted surface per time step in W/m^2 estimated based on the historical weather data and using the open-source package OptiCE (OptiCE, 2020; SVEBY, 2018), r is the efficiency of the panel, and PR is the panel performance ratio. A solar panel with a peak power of 270 W_p and performance efficiency of 16%, assuming a tilt angle of 42°, was considered to perform the calculations (Carlgren et al., 2019). The estimated power output was then used in the optimization model as the contribution of the distributed PV systems to the regional power supply.

To increase system flexibility, a large-scale power-to-hydrogen storage was integrated to the thermal plants and PV systems (**Paper II**). The main components in the power-to-hydrogen installations are the electrolyser, compressor, and the storage tank. A PEM electrolyser with a maximum energy input capacity of 900 MW and efficiency of 74% is included in the system to store the surplus power in the form of hydrogen. To meet the power shortage in the system, a PEM fuel cell with a production capacity of 350 MW and efficiency of 47% is also integrated to the system. The size of the storage installations was selected based on the size of the regional system, potential excess power in the system, and the amount of electricity imports.

During the electrolysis processes, there will be some waste heat generation, which can be utilized in the DH network and contribute to the heat supply. The overview of the studied system in Case I, including different components and energy conversion units, is illustrated in Figure 9. In the figure, the fuel import means importing feedstock used in the CHP plants and HOBs. Imported and exported products in the figure stand for heat and power that need to be imported to the studied region or can be exported to other regions.

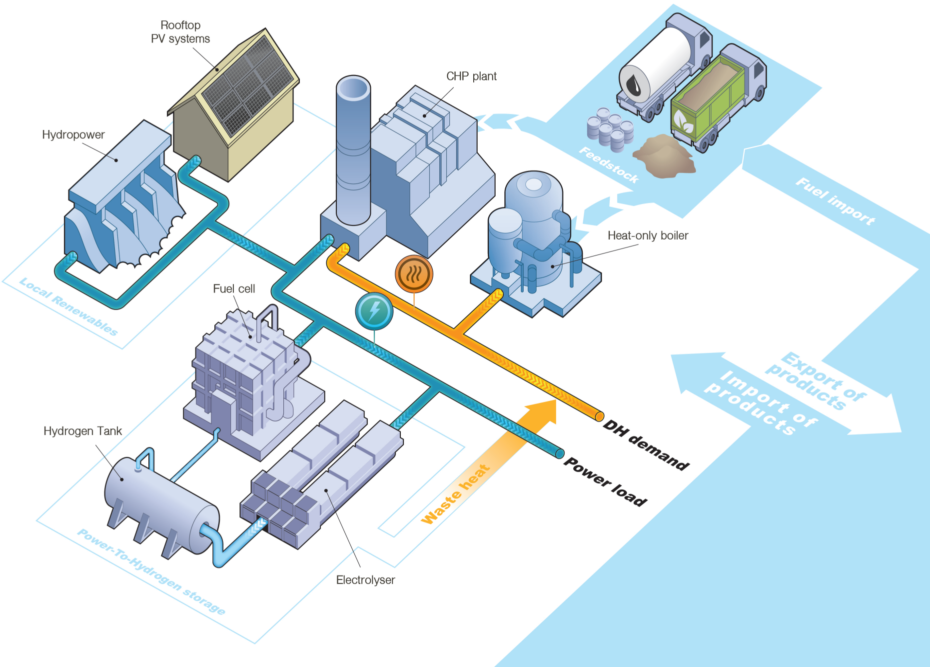

Figure 9: Schematic view of the studied system in Case I.

3.2.3 Case II: integrated biofuel production with CHP plants and rooftop PV systems (**Papers III** and **IV**)

Case II was developed to answer **RQ2** that aims to study the effect of polygeneration and the integration of energy technologies on system performance. The effects of interconnecting the power, heating, and transport sectors on the production planning of energy plants and flexibility were evaluated by developing two different system configurations. One considers the integrated bioethanol production with CHP plants and rooftop PV system (**Paper III**), and the other adds pyrolysis oil production to the system consisting of CHP plants, rooftop PV systems, and onsite hydrogen production via power-to-hydrogen conversion (**Paper IV**).

(a) Integrated bioethanol production with CHP plants and rooftop PV systems (**Paper III**)

Being a renewables-based biofuel, bioethanol is one of the alternative fuels in the transportation system that can potentially reduce the CO_2 emissions. This biofuel can be produced from a wide range of biomass. However, using biomass wastes such as straw can make the bioethanol more advantageous concerning emissions and production cost. In this polygeneration case, a straw-based bioethanol plant with a production capacity of 87 MW was integrated with each existing CHP plant and rooftop PV systems described in Case I. The separate hydrolysis and fermentation (SHF) process was considered as the bioethanol production method in the polygeneration system. The optimization model was then developed considering daily production of bioethanol from available cereal straw in the region. Straw production from cereals cultivated in the region, including wheat, oat, and barley was estimated and used in the model. The ratio of ethanol production to the input straw is around 0.25. In the investigated polygeneration system, by-products from biofuel plants, mostly lignin, can be used as additional feed in the CHP plants for further heat and power supply. In addition, the surplus heat from hydrolysis processes can be used in the DH network. The schematic view of the studied system is shown in Figure 10.

The system has interrelations with regional renewables. Moreover, a share of the DH demand could also be satisfied by using available industrial waste heat in the region. It is possible to import feedstock used in CHP plants and HOBs. Moreover, the lack of heat and power supply in the system can be satisfied by importing, while excess heat and power will be exported. To develop the optimization model, the results were employed from techno-economic investigations of a similar polygeneration system, including integrated bioethanol production with CHP plants, by Starfelt et al. (2010)

and Daianova et al. (2012). The potential effects of the proposed system on energy supply and production planning of the CHP plants were analysed.

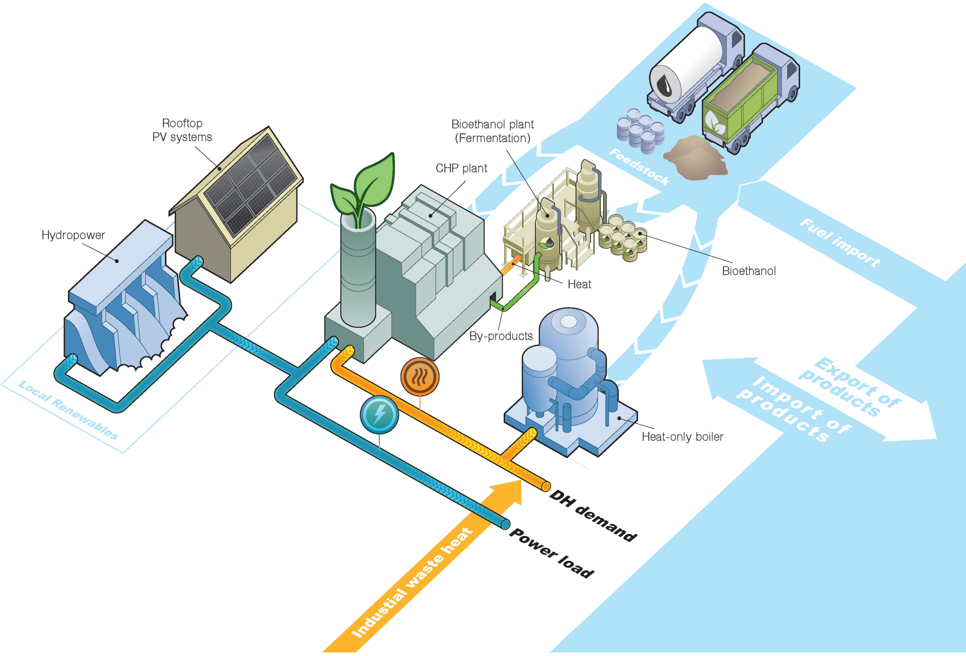

Figure 10: Schematic view of the integrated system in Case II (a) (bioethanol production).

(b) Integrated drop-in pyrolysis oil production with CHP plants, rooftop PV systems and onsite hydrogen production (**Paper IV**)

This case focuses on polygeneration with increased interaction with renewable power compared to Case II (a). Drop-in bio-oil production from integrated wood pyrolysis was included in this studied system, and flexibility and production planning of the system were analysed. Results of the previous studies on pyrolysis in a polygeneration system (Karvonen et al., 2018; Salman, Dahlquist, et al., 2019; Salman, Schwede, Naqvi, Thorin, & Yan, 2019; Salman et al., 2020) were applied to find input data, including production efficiency and energy required for the pyrolysis. The input fuel is wood with a moisture content of 50% that needs to be treated and dried prior to utilization in pyrolysis. A pyrolysis reactor with a bio-oil production capacity of 90 MW was considered in the integrated system. Biochar and syngas are the by-products of pyrolysis with respective production ratios of 0.22 and 0.12 compared to dry-based feed wood. The chemical energy of the by-products can be converted to heat in the integrated CHP boiler. The renewable power supply from rooftop PV systems is integrated to biofuel production through onsite hydrogen storage that can be used for bio-oil upgradation. The power-to-hydrogen installation similar to the system in the Case I was also used in this system.

Rooftop PV systems in the region

The potential PV power supply in Västerås was estimated using an approach similar to that described for Västmanland in Case I. However, the estimation for Västerås was found based on the maximum available roof area in the region calculated by Yang et al. (2020). They estimated the potential area for panel installation using the number of buildings of various types, the optimal orientation of roofs with different classifications, and the tilt angle of the panels. Given the maximum area and the solar radiation in the region, the hourly solar power output was calculated in OptiCE (Carlgren et al., 2019; Kraftpojkarna, 2018; OptiCE, 2020) and used in the model. The system configuration in Case II (b) is shown in Figure 11.

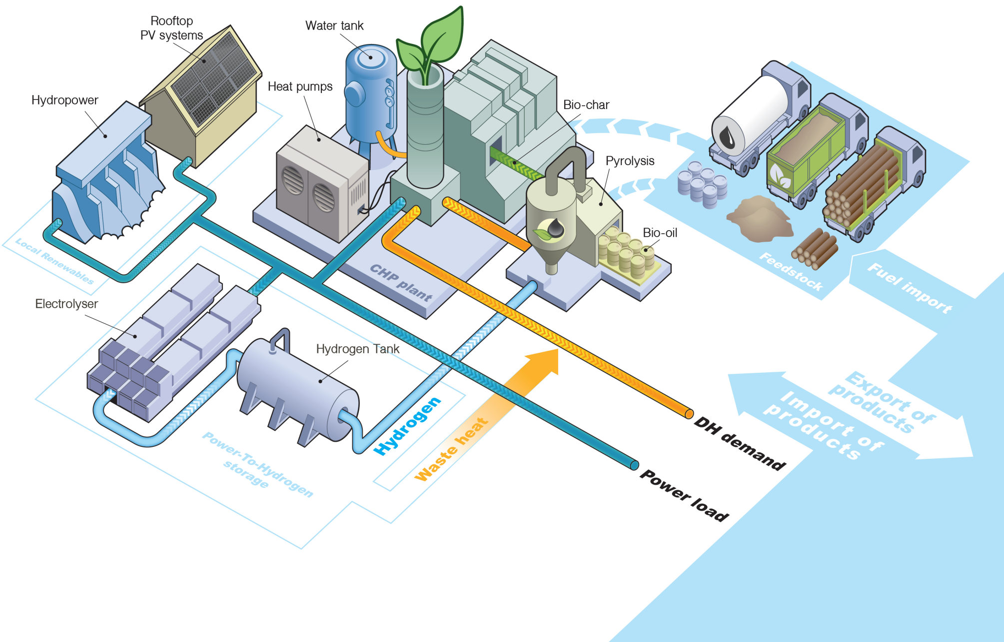

Figure 11: Schematic view of the integrated system in Case II (b) (pyrolysis oil production).

3.3 Mathematical formulation and modelling

A MILP-based optimization model was developed for the studied systems. The entire chain of the energy system, from feedstock availability to the final energy products, was considered in the optimization model. The number of input fuels to the system, number of the energy products, number of plants, and time steps over the year were defined in different datasets as $\tilde{F} = \{1, \dots, F\}$, $\tilde{N} = \{1, \dots, N\}$, $\tilde{P} = \{1, \dots, P\}$ and $\tilde{T} = \{1, \dots, T\}$, respectively. The objective of the optimization is to minimize the total production cost of the system that includes the cost of purchasing and/or importing fuels, expenses related to energy conversion processes at plants, costs for importing energy products, and cost of purchasing industrial waste heat when available. The profits from exporting or selling excess energy are subtracted from total system expenses. The mathematical formulation of the objective function is expressed in equation (2).

$$\begin{aligned}
Min: \quad & System\ Cost \\
& = Fuel\ purchase\ cost\ +\ fuel\ import\ cost\ +\ process\ cost \\
& +\ product\ import\ cost\ +\ industrial\ waste\ heat - export\ benefits \\
& = \sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{f=1}^{F} c_{f,t}^{F} \times F_{f,p,t} + \sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{f=1}^{F} c_{f,t}^{F,imp} \times F_{f,p,t}^{imp} \\
& + \sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{f=1}^{F} pc_{f,p,t} \times \left(F_{f,p,t}^{imp} + F_{f,p,t}\right) + \sum_{t=1}^{T}\sum_{n=1}^{N} c_{n,t}^{q,imp} \times q_{n,t}^{imp} \\
& + \sum_{t=1}^{T} q_{t}^{WasteHeat} \times c^{Waste} - \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{p=1}^{P} c_{n,t}^{q,exp} \times q_{n,p,t}^{exp}
\end{aligned} \tag{2}$$

The parameters and variables used in equation (2) are described in Table 3. To model the thermal energy plants, the historic data provided by the regional energy companies were used.

Table 3: Parameters and variables used in the objective function of the MILP model.

Parameters/Variables	Unit	Description
$F_{f,p,t}$	ton	Amount of available fuel *f* used in plant *p* in time step *t*
$F_{f,p,t}^{imp}$	ton	Imported fuel *f* to plant *p* in time step *t*
$c_{f,t}^{F}$	SEK/ton	Cost of purchasing fuel *f* in time step *t*
$c_{f,t}^{F,imp}$	SEK/ton	Importing cost of fuel *f* in time step *t*
$pc_{f,p,t}$	SEK/ton	Process cost of fuel *f* in plant *p* in time step *t*
$q_{n,t}^{imp}$	MWh	Imported product *n* in time step *t*
$q_{n,p,t}^{exp}$	MWh	Product *n* from plant *p* exported to the external market in time step *t*
$c_{n,t}^{q,imp/exp}$	SEK/MWh of product	Price of product *n* (imported or exported) in time step *t*
$q_t^{WasteHeat}$	MWh	Recovered industrial waste heat in time step *t*
c^{waste}	SEK/MWh	Purchasing cost of industrial waste heat

3.3.1 Thermal energy plants + PV systems (Base model)

The constraint equations for the optimization model can be defined by the energy balance in the system, limitation related to the system capacity, fuel availability, and the restrictions for importing and exporting.
The energy balance in the thermal plants is shown in equation (3).

$$q_{n,p,t} = \sum_{f=1}^{F} \left(F_{f,p,t} + F_{f,p,t}^{imp}\right) \times Conv._{f,p,n} \tag{3}$$

$q_{n,p,t}$ is product *n* delivered from production plant *p* in time step *t*. $Conv._{f,p,n}$ shows the conversion rate of fuel to energy product at the respective plant. The quantitative relation between heat and power supply from the thermal plants, known as the power-to-heat ratio or Alpha value (∝), is used to find the conversion rate at each CHP plant. Using the Alpha value, the energy content of the fuel and the efficiency of the CHP plant, the conversion rates for heat and power supply in the CHP plant can be estimated:

$$\propto = Power\ generation/Heat\ supply$$

$$Conv._{f,p,Heat} = \eta_{CHP} \times HV_f \times \frac{1}{1+\propto} \quad (4)$$

$$Conv._{f,p,Power} = \propto \times\ Conv._{f,p,Heat}$$

HV_f is the energy content of the respective input fuel in MWh/ton and η_{CHP} is the plant efficiency. According to the real-time data from the energy companies in the studied region, an average Alpha value of 0.42 is assumed for the CHP plants (Mälarenergi AB, 2018a).

As formulated in equation (5), the energy output from each plant is limited by the capacity of that plant and the minimum production limit.

$$\sum_{f=1}^{F} \left(F_{f,p,t} + F_{f,p,t}^{imp} \right) \times Conv._{f,p,n} \leq Q_{n,p,t}^{max} \times U_{p,t}$$

$$\sum_{f=1}^{F} \left(F_{f,p,t} + F_{f,p,t}^{imp} \right) \times Conv._{f,p,n} \geq Q_{n,p,t}^{min} \times U_{p,t} \quad (5)$$

$Q_{n,p,t}^{max/min}$ stand for the maximum and minimum production limits of the plant and $U_{p,t}$ is a binary variable showing the operation of the plant. U equals one means that the plant is in operation, whereas a U of zero shows that the plant is offline.

The amount of fuels that can be used at the plant in the model is restricted by the maximum quantity of fuels used in the reference energy system ($F_{f,p}^{Available}$) and the limitations on importing ($F_f^{imp\text{-}limit}$), as shown in equation (6).

$$\sum_{t=1}^{T} F_{f,p,t} \leq\ F_{f,p}^{Available}$$

$$\sum_{p=1}^{P} \sum_{t=1}^{T} F_{f,p,t}^{imp} \leq\ F_f^{imp-Limit} \quad (6)$$

The CO_2 emissions from the energy conversion processes in plants and the marginal emissions by power importing to the system are calculated using the respective emission factors (Swedish Environmental Protection Agency, 2018) in equation (7). The emission factors for different types of fuels can be found in Table 4. Some of the values in the table were provided by the energy companies in the region. The emission factor for power to estimate the marginal emissions is 0.78 ton_{CO2}/MWh_{power} (Profu, 2018).

$$Emissions_t^{Plants} = \sum_{p=1}^{P}\sum_{f=1}^{F}\left(F_{f,p,t} + F_{f,p,t}^{imp}\right) \times EmissionFactor_{f,p}$$
$$Emissions_t^{Marginal} = q_{Power,t}^{imp} \times EmissionFactor^{Power} \quad (7)$$

Table 4: Emission factors from different fuels at thermal plants (Mälarenergi AB, 2018a; Swedish Environmental Protection Agency, 2018).

Fuel type	Emission factor (ton $_{CO_2}$/ton $_{fuel}$)
Oil	3.2
Coal	2.7
Peat	1.2
Wastes	0.2 - 0.48
Woody biomass	0.35 - 0.8
Biofuels	0.3 - 0.8

The heat and power demand of the region have to be met at each time step in the model, as formulated in equation (8). In other words, the total energy supply from thermal plants ($q_{n,p,t}$), local renewables ($q^{PV/Hydro}$) and the energy import (q^{imp}), minus the extra production that can be stored/sold (q^{extra}) will fulfil the demand.

Power demand: $$\sum_{p=1}^{P} q_{Power,p,t} + q_{Power,t}^{imp} - q_{Power,t}^{extra} + \mathrm{q}_\mathrm{t}^{\mathrm{PV}} + \mathrm{q}_\mathrm{t}^{\mathrm{Hydro}} \geq Demand_{Power,t} \quad (8)$$

Heat demand: $$\sum_{p=1}^{P} q_{Heat,p,t} + q_{Heat,t}^{imp} - q_{Heat,t}^{extra} + q_t^{WasteHeat} \geq Demand_{Heat,t}$$

$q_t^{WasteHeat}$ is the amount of waste heat from other industries, as a potential supplier to the DH network. The potential capacity of the industrial waste heat is estimated to be 35 MW. Based on the data provided by the energy companies in the region, around 65% of this capacity is recovered in DH network (Västra Mälardalens Energi och Miljö AB, 2017).

To estimate the modelling data for heat demand, statistics on the total heat demand in the region collected from Statistics Sweden (SCB) (Swedish Energy Agency, 2020b), and the hourly delivered DH to consumption areas provided by the local energy companies (Mälarenergi AB, 2018a) were used. The power demand is also found using reports from the Swedish Transmission System Operator (TSO) for the electricity consumption within the regional network (SVK, 2020). Due to confidentiality issues, the grid capacity for power import and export was assumed based on historical data from the Swedish TSO, and the maximum power transmitted in the network in the reference years was used as the grid limitation in the studied system.

To analyse system performance, the overall energy efficiency is determined using a general definition given in equation (9). The energy input and output can be changed in the equation according to the configuration in each studied case.

$$Overall\ system\ efficiency = \frac{Total\ energy\ output}{Energy\ input\ from\ fuels + Energy\ from\ renewables + Energy\ imports} \quad (9)$$

3.3.2 Power-to-hydrogen-to-power system (Case I)

By integrating power storage to the system, the base model needs to be modified. The excess power in the system can be utilized in an electrolyser to produce hydrogen. This conversion can be described by equation (10), using the efficiency of the electrolyser and energy content of hydrogen (HV_{H2}) in MWh/Nm^3 (Heinisch & Tuan, 2015). It should be noted that the possibility of using imported power for hydrogen production was not considered in the model and only the excess power can be converted to hydrogen.

$$Hydrogen_t^{prod.} = PtG_t \cdot \left(\frac{\eta_{electrolyser}}{HV_{H_2}}\right) \quad (10)$$

PtG_t shows the excess electricity (MWh) at different time steps used in the electrolysis for hydrogen production ($Hydrogen_t^{prod.}$) in Nm^3. Considering the same parameters for the fuel cell, equation (11) calculates the quantity of the hydrogen used for power generation ($Hydrogen_t^{used.}$) in Nm^3.

$$Hydrogen_t^{used} = GtP_t \cdot \left(\frac{1}{\eta_{FC} \cdot HV_{H2}}\right) \quad (11)$$

The electricity use of the compressor was estimated using the compressor efficiency and the assumed inlet pressure and temperature in the equations used by Li et al. (2009) and Zhang et al. (2016). The estimated compressor electricity was then included in the electricity consumed by the electrolyser. Table 5 summarizes key parameters used for modelling the hydrogen production and storage.

Using the equations (10) and (11), the level of storage in the hydrogen tank at the pressure of 10.7 MPa (Tschiggerl et al., 2018) can be described by adding the amount of production to the stored hydrogen at the previous time step, minus the consumed hydrogen for power supply (equation 12).

$$Hydrogen_t^{stored} = Hydrogen_{t-1}^{stored} + Hydrogen_t^{prod.} - Hydrogen_t^{used} \quad (12)$$

The amount of hydrogen stored could not exceed the capacity of the storage tank (*Stored*^{Max}):

$$Hydrogen_t^{stored} \leq Stored^{Max} \quad (13)$$

As shown in equations (14) and (15), the amount of power used in the electrolysis and the power supply from the fuel cell are also limited by the electrolyser and fuel cell capacities (PtG^{max}, GtP^{max}).

$$PtG_t \leq PtG^{max} \quad (14)$$

$$GtP_t \leq GtP^{max} \quad (15)$$

Table 5: Specifications of the power-to-hydrogen-to-power system in the optimization model.

Parameter	Value	Unit	Reference
LHV of hydrogen	120	MJ/kg	(Engineering Toolbox, 2003)
HHV of hydrogen	142	MJ/kg	(Engineering Toolbox, 2003)
Electrolyser (PEM)			
Efficiency	74	%	(Li et al., 2009)
Total power input	900	MW	Estimated based on the system size
Waste heat production	0.35	MJ/MJ of H_2	
Fuel cell (PEM)			
Efficiency	47	%	(Li et al., 2009)
Production capacity	350	MW	Estimated based on the system size
Waste heat-to-power ratio	1.13	-	
Compressor			
Efficiency	70	%	(Li et al., 2009; Zhang et al., 2016)
Total power input	43	MW	Estimated based on (Li et al., 2009; Zhang et al., 2016)
Assumed inlet pressure	0.6	MPa	(Li et al., 2009; Zhang et al., 2016)
Assumed inlet temperature	20	˚C	(Li et al., 2009; Zhang et al., 2016)
Hydrogen tank			
Capacity	$6×10^6$	Nm^3	(Tschiggerl et al., 2018)
Inlet pressure of H_2	10.7	MPa	(Tschiggerl et al., 2018)

Given the constraints for the hydrogen storage, the equation (8) for demand can be updated as follows:

Power demand:

$$\sum_{p=1}^{P} q_{Power,p,t} + q_{Power,t}^{imp} - q_{Power,t}^{extra} + \mathrm{q_t^{PV}} + \mathrm{q_t^{Hydro}} + \mathrm{PtG_t} - \mathrm{GtP_t} \geq Demand_{Power,t} \quad (16)$$

Heat demand:

$$\sum_{p=1}^{P} q_{Heat,p,t} + q_{Heat,t}^{imp} - q_{Heat,t}^{extra} + q_t^{WasteHeat} \geq Demand_{Heat,t}$$

The waste heat production from the electrolysis is also included in $q_t^{WasteHeat}$. Equation (9) is updated and used to estimate the overall efficiency of the system in Case I.

$$Overall\ efficiency = \frac{DH_{Thermal\ plants} + Waste\ heat + El_{Total} + El_{Export}}{Energy_{input\ fuels} + Energy_{Hydrogen} + El_{RES} + Energy_{Imports}} \quad (17)$$

El_{Total} is the total electricity generated by the thermal energy plants and fuel cells, and the renewable power that is directly used to meet the demand. El_{RES} includes the total electricity from the regional renewables, including PV systems and hydropower, and $Energy_{Hydrogen}$ is the energy of hydrogen used by the fuel cell.

The total annualized cost of the power-to-hydrogen-to-power system was also estimated using the Net Present Cost (NPC) and the Capital Recovery Factor (CRF) (Homer, 2020). The economic data and assumptions for annualized cost calculation are summarized in Table 6.

Table 6: Parameters and assumptions for the cost estimation of the power storage system (Li et al., 2009; Zhang et al., 2016).

	Electrolyser	Fuel cell	Compressor	H_2 tank*
Capital cost, SEK/W	10	25	25	4900
Operation & Maintenance, % of capital cost	1	1	2	1
Lifetime, years	15	5	10	20
Replacement cost, SEK/W	10	30	25	4900
Discount rate, %	2	2	2	2
Salvage value, % of capital cost	10	10	10	10
Project lifetime, years	20	20	20	20

* The unit of capital cost and replacement cost for hydrogen tank is SEK/kg.

A sensitivity analysis was performed on the system described in Case I. The analysis investigates the influence of hydrogen storage capacity on the power export and the system cost. The excess power in the system can be either stored or exported. Therefore, the possibility of power export in the system with different hydrogen tank capacities was analysed. The minimum capacity limit was set to be the same as the tank capacity in Case I (6×10^6 Nm^3) and the upper limit was selected based on the maximum capacity needed to store the entire excess power from the renewables.

3.3.3 Integrated biofuel production (Case II)

(a) Integration bioethanol production

The objective function and constraint equations formulated in the base model can be applied to the integrated bioethanol production after some modifications.

To determine the conversion rates at ethanol plants, the following equations suggested by Daianova et al. (2012) are used:

$$Conv._{f,p}^{Heat,Eth} = \propto_p^{Heat} \times \eta_p^{Eth}$$
$$Conv._{f,p}^{El,Eth} = \propto_p^{El} \times \eta_p^{Eth} \qquad (18)$$

α^{Heat} and α_p^{El} are the ratio of excess heat and power production to ethanol production, and η_p^{Eth} is the ethanol-to-input fuel ratio (Daianova et al., 2012; Starfelt et al., 2010, 2012).

The studies by Starfelt et al. (2010, 2012), in which an integrated bioethanol plant was designed and analysed, were used as the reference to estimate the maximum bioethanol production, considering the capacity of plant and conversion ratio of inlet fuels to bioethanol (equation (19)). The same references and the study by Hamelinck et al. (2005) were used to find the costs for input straw and bioethanol production.

$$Max\ bioethanol\ production = \dot{m}_f^{Eth} \times \eta_p^{Eth} \qquad (19)$$

$\dot{m}_f^{Eth}$ in equation (19) shows the maximum inlet energy flow in MWh to the ethanol plant, estimated to be 350 MWh.

The available harvesting area, production yield and the ratio between residues and crop were used to estimate the potential straw production in Västmanland as described in **Paper III**. The estimation is based on the data for year 2015 and the results are presented in Table 7. Total available straw for bioethanol production was estimated to be around 237 kton.

Table 7: Cultivated cereal straw in the studied region (Daianova et al., 2011; Swedish Board of Agriculture, 2015b).

	Available area (ha)	Yield (ton/ha)	Crop-residue ratio	Availability of straw (%)	Straw production (kton)
Winter wheat	19 999	7.1	1.3	0.57	105
Spring wheat	6 454	5.4	1.3	0.57	26
Winter barley	0	-	1.2	0.57	-
Spring barley	15 733	5.1	1.2	0.57	55
Oat	14 467	4.8	1.3	0.57	51

The overall efficiency of the polygeneration system (η_{system}) is given in equation (20).

$$\text{Overall efficiency} = (Bioethanol + DH + Power)/Total\ energy\ input \qquad (20)$$

The excess energy using by-products and power supply from renewables are included in *DH* and *Power* in the equation.

Table 8 shows the key input parameters used for modelling the integrated bioethanol production.

Table 8: Input data for modelling the integrated bioethanol production.

Parameter	Value	Unit	Reference
Maximum inlet flow	350	MW	Estimated based on Starfelt et al. (2010)
Heating value of cereal straw	4	MWh/ton	(Starfelt et al., 2012)
Production capacity	87	MW	(Starfelt et al., 2010)
Bioethanol production yield	25	%	(Starfelt et al., 2010)
Heating value of bioethanol	7.5	MWh/ton	(Daianova et al., 2012)
Heat demand for bioethanol production	1.2	MJ/kg of feed	(Starfelt et al., 2010, 2012)
Fuel cost (cereal straw)	288	SEK/ton	(Daianova et al., 2012)
Bioethanol production cost (incl. capital charge)	800	SEK/MWh	Estimated based on Hamelinck et al. (2005) and Starfelt et al. (2012)

(b) Integrated pyrolysis oil production

The equations and constraints developed for the base model can also be applied in this case. However, the conversion rate of wood to pyrolysis products in the integrated system needs to be added to the model. Moreover, the possibility of using the stored hydrogen for bio-oil upgradation, the water tank in the system for heat storage, and the contribution of available centralized HPs to the DH supply were modelled in this case. The production cost of upgraded pyrolysis oil based on the amount of fuel consumed and the revenue from selling the pyrolysis oil were also considered in the objective function (equation 2) for this case.

According to Karvonen et al. (2018), the production efficiency of pyrolysis oil from dry wood is 0.66. The same value was used as the conversion ratio for bio-oil production from pyrolysis in the model. The relation between the by-products and the feed wood was estimated based on the simulation results from previous studies (Karvonen et al., 2018; Salman et al., 2020). Equation (21) estimates the potential energy supply from pyrolysis biochar and syngas ($E^{byproducts}$). The ratio of by-products to dry input feed ($R_{byproduct\text{-}fuel}$), the energy content of by-products ($HV_{byproduct}$), and the efficiency of integrated CHP boilers (η_{CHP}) were used in the equation. $E^{byproducts}$ can be utilized in the pyrolysis process and for additional DH and power supply from CHP plants. The energy balance of the CHP plant integrated with pyrolysis process is given in equation (22).

$$E^{byproducts} = HV_{byproduct} \times R_{byproduct-fuel} \times \eta_{CHP} \quad (21)$$

$$\sum_{f=1}^{F}\sum_{n=1}^{N}\left(\left(F_{f,p,t} + F_{f,p,t}^{imp}\right) \times Conv_{f,p,n}\right) + E_{p,t}^{byproducts} - Energy_{p,t}^{ToPyrolysis} = \sum_{n=1}^{N} q_{n,p,t} \quad (22)$$

$E_{p,t}^{byproducts}$ is the total energy of by-products ($E^{byproducts}$) used in CHP plant p at time step t, and $Energy_{p,t}^{ToPyrolysis}$ is the energy from CHP plant p used by the integrated pyrolysis process at time t.

The hydrogen required for the upgradation is around 4–5 wt% of the total produced bio-oil that can be provided by the stored hydrogen, as described in the model for Case I. There is no fuel cell in this case, while the hydrogen is used in drop-in bio-oil production. The lack of hydrogen for the process can be satisfied by importing hydrogen to the system.

Similar to the mathematical model developed for the hydrogen tank, the excess heat supply in the system can be stored in a water tank up to the maximum tank capacity ($Tank^{Max}$) and further be used to meet the DH deficiency in the system (equations (23) and (24)). The heat loss is not considered in the calculations for the heat storage.

$$Tank\ Level_t = Tank\ Level_{t-1} + q_t^{Ch-tank} - q_t^{DisCh-tank} \quad (23)$$

$$Tank\ Level_t \leq Tank^{Max} \quad (24)$$

Considering also the heat supply (q_t^{HP}) and the power consumed by HPs ($PtHP_t$), the demand equation in Case II can be formulated as in equation

(25). Biofuel demand was not considered in the model and it is assumed to be sold as a valuable energy product.

Power demand:
$$\sum_{p=1}^{P} q_{Power,p,t} + q_{Power,t}^{imp} - q_{Power,t}^{extra} + \mathrm{q}_{\mathrm{t}}^{\mathrm{PV}} + \mathrm{q}_{\mathrm{t}}^{\mathrm{Hydro}} + \mathrm{PtG}_{\mathrm{t}} - \mathrm{PtHP}_{\mathrm{t}} \geq Demand_{Power,t} \quad (25)$$

Heat demand:
$$\sum_{p=1}^{P} q_{Heat,p,t} + q_{Heat,t}^{imp} - q_{Heat,t}^{extra} + q_t^{WasteHeat} + \mathrm{q}_{\mathrm{t}}^{\mathrm{HP}} + q_t^{DisCh-tank} \geq Demand_{Heat,t}$$

The amount of $q_t^{Ch-tank}$ is included in $q_{Heat,t}^{extra}$. The possibility to import heat is still considered in the system. Table 9 summarizes the input data used for the developed integrated system in Case II.

The overall efficiency of the system is estimated using equation (26).

$$Overall\ efficiency = \frac{DH_{Thermal\ plants} + Waste\ heat + Heat_{HPs} + El_{Total} + El_{Export} + Bio\ oil}{Energy_{input\ fuels} + El_{RES} + Energy_{Imports}} \quad (26)$$

The parameters for the energy output in the equation are similar to those described in the efficiency calculation for Case I. The heat supply from HPs and energy of the bio-oil are also considered. The input power to the electrolyser and HPs is included in $Energy_{input\ fuels}$ and $Energy_{RES}$.

Table 9: Summary of the input data for modelling the integrated pyrolysis oil production.

Parameter	Value	Unit	Reference
Pyrolysis			
Production capacity	90	MW	(Salman et al., 2020)
Water content in feed wood	50	%	(Karvonen et al., 2018)
Heat demand for pyrolysis	1.8	MJ/kg of feed	(Karvonen et al., 2018; Salman et al., 2017b)
Heat demand for feed drying	2.6	MJ/kg of water evaporated	(Karvonen et al., 2018; Salman et al., 2017b)
Hydrogen use for upgradation	4	Wt% of bio-oil	(Salman, Dahlquist, et al., 2019)
Heating value of bio-oil	4.2	MWh/ton	Estimated based on (Karvonen et al., 2018)
Fuel cost (feed wood)	420	SEK/ton	(Salman et al., 2020)
Bio-oil production cost (incl. capital charge)	1200	SEK/MWh	(Dutta et al., 2015)
Bio-oil selling price	8900	SEK/m^3	(Preem, 2020)
Hydrogen production			
Electrolyser efficiency, incl. compressor efficiency	71	%	(Li et al., 2009)
Total power input	350	MWh	Estimated based on the system size
Hydrogen tank capacity	$6x10^6$	Nm^3	(Tschiggerl et al., 2018)
Hydrogen production cost	60	SEK/kg	(Ainscough et al., 2014; Christensen, 2020)
Hydrogen importing cost	90	SEK/kg	(Björkman, 2020)

3.4 Scenario development

Motivated by the expected changes of the future energy system, three scenarios were developed to analyse the impacts on the production planning of system, as addressed in **RQ3**. The integrated system described in Case II(b) was used for this analysis. The scenarios consider potential future energy developments, climate change, market price, and trends in energy demand and supply. In other words, how the energy demand and supply might differ in the future and affect the performance of the proposed integrated system were evaluated in these scenarios to answer RQ3.

Scenario 1: climate changes

GHG emissions in a long-term can cause variations in the climate and thus in solar radiation, air temperature, and wind speed patterns. Climate change can subsequently result in variations in energy conversion and consumption patterns (Parkpoom et al., 2004). Therefore, it is important to investigate the influences of the climate changes on energy demand and thereby on the energy system's operational conditions.

In this scenario, hypothetical future heat and power demand was calculated using climatological data and their impacts on the performance of the studied system were assessed. To estimate demand profiles, the data on air temperature, surface solar radiation and wind speed patterns for year 2050 were retrieved from the Copernicus portal for climate projections (Copernicus Climate Change Service, 2020; EURO-CORDEX, 2017). An ensemble of the available global and regional climate models for the Representative Concentration Pathways (RCP) 4.5, considered an intermediate radiation scenario (SMHI, 2021), were used to find the climate data. A climate period of 10 years between 2045 and 2055 and the grid points around the studied region of Västmanland County were considered for data collection. The hourly mean of data from the climate models over the considered period was then calculated for temperature, wind speed, and solar radiation.

To determine heat and power demands, the climate data were used in an Artificial Neural Network (ANN)-based model. The model was first trained using the previous years' meteorological data and the respective hourly heat demand for Västerås. The model was then used to estimate the heat demand profile in 2050 using the average climatological data retrieved from climate models. It should be noted that the categorical data, including month, day of the week, and hour of the day were considered in the model for demand estimations (detailed description of the model is presented in **Paper IV**). Due to the interconnection between regional heat and power demand, the results of the predicted heat demand were used to find the changes in demand profile for electricity. The changes in the electricity use pattern by population growth or zero-energy buildings were not considered for predicting the demand profile. The estimated DH and power demand in this scenario compared with demand in the base year are shown in Figure 12.

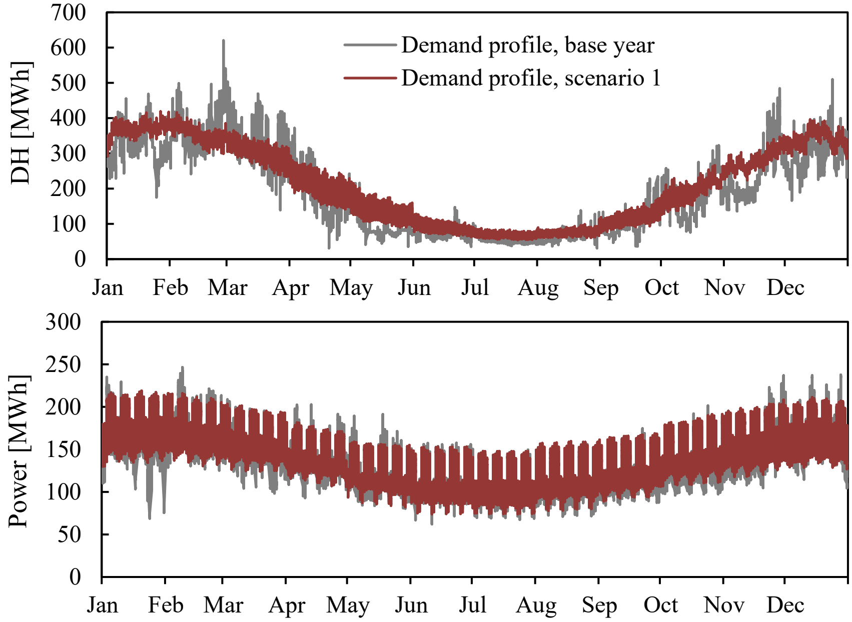

Figure 12: Estimated DH and power demand in Scenario 1 compared with demand in base year.

Scenario 2: Market trends

This scenario considers some of the potential developments in the energy system that also affect energy demand and price. According to Sköldberg & Rydén (2014), competition among different heat supply technologies in the heating market in Sweden is increasing and there is a continuous growth in use of HPs as a direct heat supplier. The increased application of HP in the region can affect both DH and power demand. Based on previous studies (Göransson et al., 2019; Sköldberg & Rydén, 2014), it was assumed that 50% of the heat demand in the studied region by 2050 is satisfied by direct use of HPs. Pumps and compressors in the HP systems consume electricity as input energy. Therefore, increased application of HPs as the replacement in DH-based buildings increases regional electricity use. Considering the electricity use for space heating in different sectors such as industries and residential buildings and the increased share of the HPs with an average COP of 3.5 (Damm et al., 2017; SCB, 2020), the electricity use by HPs was estimated and added to the demand profile for 2050.

Electrification of the transport system due to increased penetration of EVs is another potential driver for the market change, which is also considered in this scenario. Given the average driving pattern of vehicles in the studied region (*D*), the mean energy use by the vehicle in kWh/km (*E*) (Göransson et al., 2019), the population growth, and number of EVs in the region (*N*), the approximate electricity use for 100% penetration of EVs was calculated (equation (27)). It should be noted that the peak hours of driving during weekdays and weekends, and the average driving distance at various time of the day were considered in the driving pattern of vehicles (Liu et al., 2015). The estimated electricity use by EVs (*Y*) was then included in the electricity demand profile, which also includes power use by HPs.

$$Y = \sum_{n=1}^{N} E \times D \qquad (27)$$

These developments can subsequently affect the future electricity price. A cost-effective power system model, developed by Göransson et al. (2019), was used in this scenario to determine the future variations in the electricity price that may occur after the described energy developments. The model considers the influence of the interactions and electrifications of different energy sectors, including the transport system and heat supply, on the power system of northern Europe. The 2050 price profile calculated by the model for southern Sweden, including the case study region in this thesis, was also used in the current scenario (Beiron et al., 2020; Göransson et al., 2019). It should be noted that there might be other energy improvements in the future system not considered in this scenario, such as increased penetration of wind power, which could affect the electricity price. Figure 13 shows the demand profiles for DH and power in Scenario 2 compared with demand in the base year.

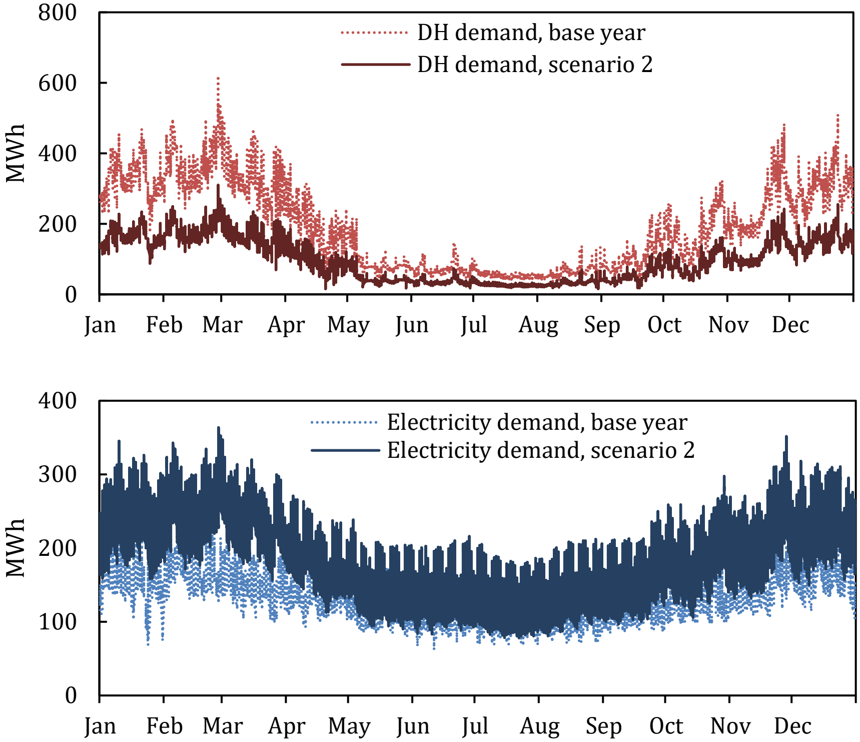

Figure 13: Estimated DH and power demand in Scenario 2 compared with demand in the base year.

Scenario 3: Fossil fuel-free energy supply

One of the primary factors in the energy transition is the increased renewable-based energy supply and reduced utilization of fossil fuels. New policies for carbon pricing and increased taxes for GHG emissions act as a driving force for the reduced use of fossil fuels at energy conversion plants (Schiebe, 2019). Based on the environmental reports from the energy company in Västerås, the share of fossil fuels, including fossil oil and coal, decreased by around 60% between 2014 and 2018 as a result of building a new biomass-based CHP (Mälarenergi AB, 2020). As described in section 3.2.1, the regional system can use both biomass and fossil fuels for energy supply. Motivated by the potential increase in renewable power in the future system, this scenario suggests the elimination of fossil-based boilers, while increasing bio-power supply from a new implemented biomass-CHP. A recently built wood-based CHP boiler in the CHP plant in Västerås was considered for modelling in this scenario with the specifications summarized in Table 10.

Table 10: Specifications of the new biomass-CHP plant.

Parameter	Value
Installed capacity (MW)	220
Input fuels	Wood
Max heat generation (MWh)	150

3.5 Multi-criteria analysis (**Paper V**)

In this study, an AHP-based MCDA was used to find the optimal integrated system configuration. The modelled system with high share of PV power and energy storage in Case I and integrated pyrolysis oil production in Case II (b) were selected for the analysis.

AHP is one of the multi-criteria decision-making methods that allows a pairwise comparison between both qualitative and quantitative criteria for several alternatives. Different steps and estimations in AHP described by Cabala (2010) were used to do the analysis in this thesis. The first step in AHP is to create a hierarchical structure of the considered criteria for different alternatives, considering the goal of the analysis. In this thesis, different criteria of technical, economic, environmental, and social nature, including several sub-criteria, were considered. The hierarchical structure of the system is shown in Figure 14.

The second step is to identify the relative importance of each considered factor by developing pairwise comparisons between criteria. Pairwise matrices were created for the studied optimization cases considering main/sub-criteria, and different factors were given a weight. To ensure the reliability of the weight of each criterion, the consistency of the pairwise assessment is examined using the consistency ratio (CR). According to Cabala (2010), for CR values above 10%, the pairwise evaluation and the criteria weighting need to be revised.

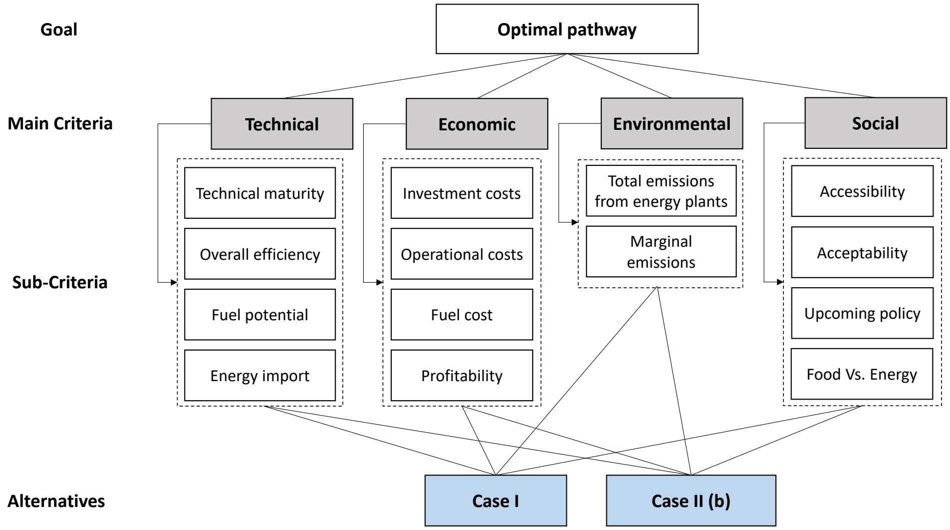

Figure 14: Hierarchy tree of the included main criteria and sub-criteria for selecting the alternative system.

In this study, experts from energy companies as well as researchers from an academic organization were asked to do a subjective assessment. Two researchers and four energy experts participated in the assessment and evaluated the criteria and sub-criteria through a pairwise comparison. The average of the given values was then estimated and used in the decision analysis. The estimated CR for each comparison matrix was below 10%. Therefore, experts' subjective assessments were considered acceptable. The estimated weights of each criterion and the respective sub-criteria are shown in Figure 15.

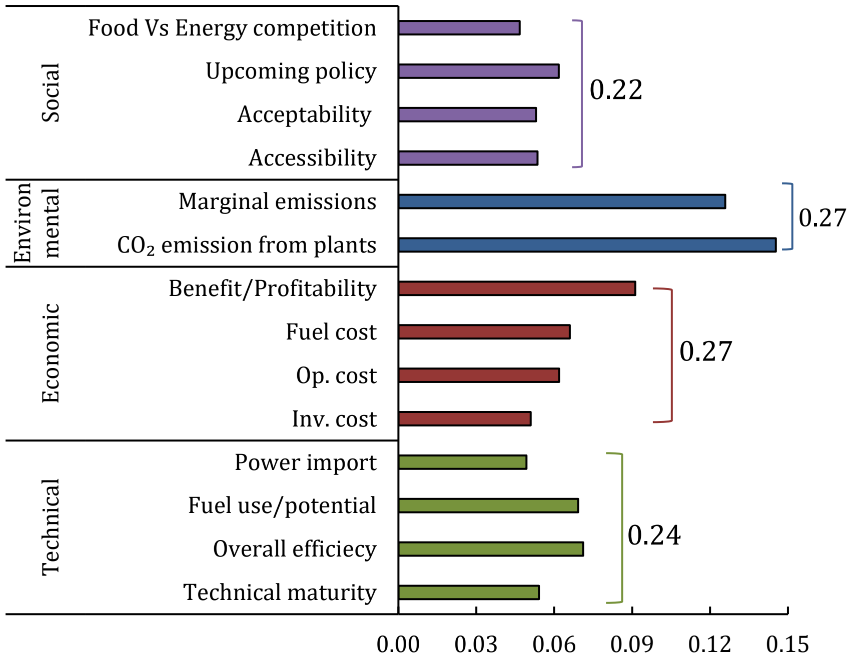

Figure 15: Weightage of main criteria and sub-criteria.

The optimization results of the systems investigated in Case I and Case II (b), such as the overall efficiency, system costs, energy imports, and CO_2 emissions, were employed to perform the comparison between alternatives, considering quantitative technical, economic, and environmental aspects. For the qualitative criteria under social aspects, optimization cases were evaluated and ranked by researchers and energy experts. The rank of each case is between 0 and 1, depending on how well they match with considered criteria. Thus, a value close to 1 indicates the better performance of the respective case. To keep the consistency in evaluation, the data for cases under the quantitative criteria were also normalized in the range between 0 and 1. Equation (28) was used to estimate the cumulative ranking of each alternative/case (j) according to the main criterion (k).

$$Y_{jk} = \sum_{i=1}^{N} W_{ik} \times R_{ji} \tag{28}$$

W_{ik} is the weight of the sub-criterion i under the relevant main criterion k, R_{ji} shows the rank of the alternative j with respect to sub-criterion i, and N is the number of sub-criteria considered for the respective main criterion.

4 Results and Analysis

This chapter presents the key results from the appended papers with additional findings on the potential of integrating energy technologies. The analysis is divided into five sections to answer the research questions regarding enhanced energy supply from renewables; impacts of power storage, polygeneration, and energy developments on the system production planning and flexibility; and the optimal system configuration. The chapter concludes with a general discussion of the results.

4.1 Potential power supply from rooftop PV systems (**Papers I, II,** and **III**)

RQ1 considers the production planning of the existing thermal plants in the system, which interacts with increased renewable power supply. The potential solar power production from the regional rooftop PV systems was investigated in **Papers I, II,** and **III**. Integration of the proposed PV systems with the regional thermal plants in Västmanland County could significantly increase the power supply, which could subsequently reduce electricity imports to the region by around 40%. The average daily production from the rooftop PVs in Västmanland and the regional demand in the reference year are depicted in Figure 16. The potential PV power supply can meet around 39% of the total annual power demand in the region. However, the production profile shows variations over the year. High solar radiation during summer leads to the increased power supply from the PV systems. The surplus power could also be exported to the grid. The production, however, decreases in winter and there is no power supply for several days due to weather conditions and solar radiation pattern. Therefore, other energy sources for power generation, such as CHP plants, power import, or power storage, are required to improve imbalances in production and meet night-time and winter power demands. According to the optimization results, the CHP plants can provide around 20% of the regional power demand, which shows an increase compared to its 13% share in the reference system. The investigation shows that the primary product in CHP plants is heat and the performance of the system in the optimization model is based on supplying the heat demand in the region. Therefore, increasing renewable power supply in the system from rooftop PVs does not affect the operational strategy of the thermal plants.

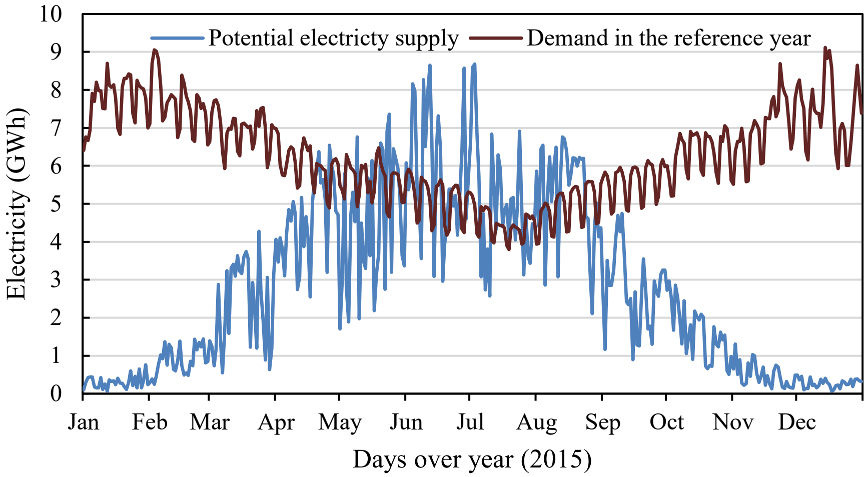

Figure 16: Potential power supply from rooftop PV systems in Västmanland.

Overall, the daily production profile and the impacts on the power imports indicate the potential of using such PV systems in the region. However, to be able to evaluate the contribution of the variable renewable power supply to the regional system, hourly simulations, including energy storage possibilities, were investigated in **Papers II** and **IV** and the results presented in the following section.

4.2 Integrated power-to-hydrogen technology with PV systems and CHP plants in Case I (**Paper II**)

One aim of **RQ1** was to analyse the impacts of high renewable share on the system flexibility. Therefore, the influence of power storage on system flexibility, by adding power-to-hydrogen conversion, was investigated in Case I in this study and the results were presented in **Paper II**. A summary of the key findings from the optimization of the base system and the system in Case I is provided in Table 11. Around 44% of the power demand in the studied region is met by the power import. The hourly import is high during winter and it reaches a maximum of 325 MWh. The power supply from thermal plants in the system provide 27% of the regional power demand in 2018. The maximum production capacity of the rooftop PV systems in Västmanland is estimated at 1 GWP. The power generation from the distributed PV systems in this case can provide around 25% of demand.

Table 11: The optimization results of the energy system with and without power-to-hydrogen technology (base year 2018).

	CHP + PV systems	Case I (with power storage)
Electricity demand (GWh)	2398	2398
Electricity supply (GWh)		
PV systems	1115	1115
Hydropower	83	83
CHP plants	645	648
Electricity import (GWh)	1102	1055
Max electricity import (MW)	325	325
Power to hydrogen	NA	130
Hydrogen to power	NA	43
Electricity export (GWh)	477	409
DH demand (GWh)	2293	2293
DH supply (GWh)		
From thermal plants	1869	1862
Industrial waste heat	202	202
Waste heat from electrolysis	NA	87
System cost (MSEK)		
Production cost (energy plants)	859	821
Annualized cost for storage	NA	3120
CO_2 emissions (kton)		
From energy plants (total)	575	572
From energy plants (fossil-based)	269	269
Marginal emissions	860	823

The integration of power-to-hydrogen-to-power conversion technology into the system further decreases the total power imports by 4%. The hourly energy balance between power demand and supply indicates that the power import is reduced to zero in 54 hours of the studied year. According to the modelling results, around 7% of the total power production in the optimized system is stored in the form of hydrogen. The working load of the electrolyser is higher during summer due to increased power supply from renewables. The power flow from different generation sources including grid imports is shown in Figure 17.

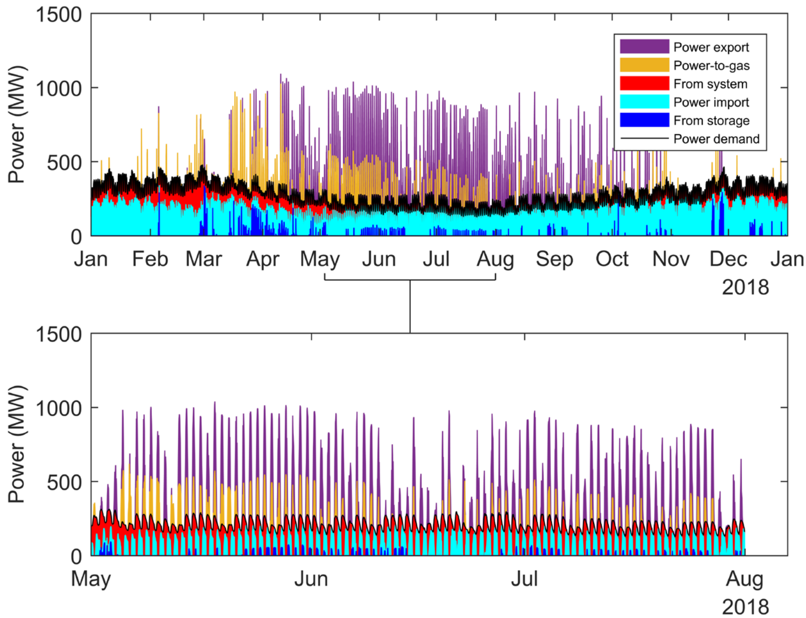

Figure 17: Hourly power flow by source in the system with power-to-hydrogen-to-power storage (Case I).

During hours when the hydrogen tank reaches full capacity, the surplus power can be exported to the regional grid. Furthermore, based on the optimal system performance, the electricity is exported, even if it is possible to store energy in the form of hydrogen. This could make the system more profitable and reduce production costs, but at the same time, reduces the amount of stored hydrogen in the system that can be used in the fuel cell. Based on the optimization results, 409 GWh of surplus electricity in the system is exported to the grid, accounting for 22% of total production. The contribution of the fuel cell to the power supply accounts for around 2% of demand in the studied year. Despite the insignificant contribution of fuel cells to meet power shortages, integrating this technology to the system leads to a slight reduction in the power imports. Moreover, conversion of renewables-based hydrogen to power using fuel cells potentially increases the penetration of renewable power generation in the system. Large-scale fuel cell utilization for renewable power supply is not yet a commercially mature technology; thus, the annualized cost for power-to-hydrogen-to-power is high, estimated to be round 3,120 million SEK.

Considering the limited grid capacity in the region, around 1% of the excess power generated from the distributed PV systems during summer is curtailed. Therefore, increasing the capacity of the storage system and the transmission lines are some possible solutions to reduce renewable energy curtailments and improve system profitability. The results for the grid power flow and the operation of the hydrogen storage tank are shown in Figure 18. Negative values in the figure show the amount of electricity that is imported into the system from the grid, whereas the positive power flow indicates the surplus energy that is exported into the grid. The results depicted in the figure show fluctuations in charging and discharging pattern of the hydrogen tank. From May to June, most of the excess power in the system is converted into hydrogen and the storage tank is charged. During this period, lower amount of power is exported to the grid compared with other periods, such as during June and July, when the capacity of the tank is full. Thus, a great share of the electricity is injected to the grid. Between June and October, hydrogen storage occasionally reduces export of surplus power. By contrast, utilization of stored hydrogen in the fuel cell for power generation results in reduced power imports to the system during December and occasionally from January to May. The highest amount of hydrogen used from the tank was in March, which resulted in zero power imports to the system.

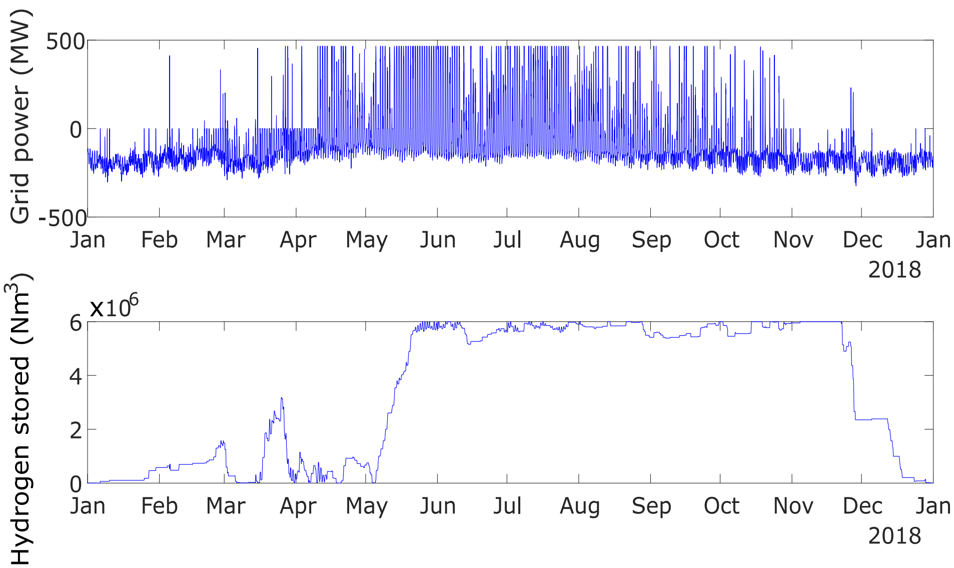

Figure 18: Grid power flow and the hydrogen tank level in the studied system in Case I.

The performance of the thermal energy plants from the results shows that the CHP plants account for 83% of total production and provide a large proportion of the regional DH demand. HOBs account for the remaining 17% of production. Of the five existing CHP plants in the system, the bio-waste plant has the highest working load, operating on its full load for about 215 days. The operating time of the fossil-based CHP plants using coal is very low and they account for only 7% of the total heat supply from CHP plants.

The produced waste heat from the conversion processes in fuel cells and electrolysers can be used in the DH network and contributes to the heat supply. The total waste heat produced from the electrolyser and fuel cell is around 87 GWh, providing around 5% of DH demand. The contribution of the total waste heat from power-to-hydrogen is shown in Figure 19. Based on the modelling results, the electrolysers are mostly in operation during summer when the solar power production is high. The heat demand is, however, low during this period. Hence, the waste heat from the electrolyser is mostly produced during the low-DH-demand period.

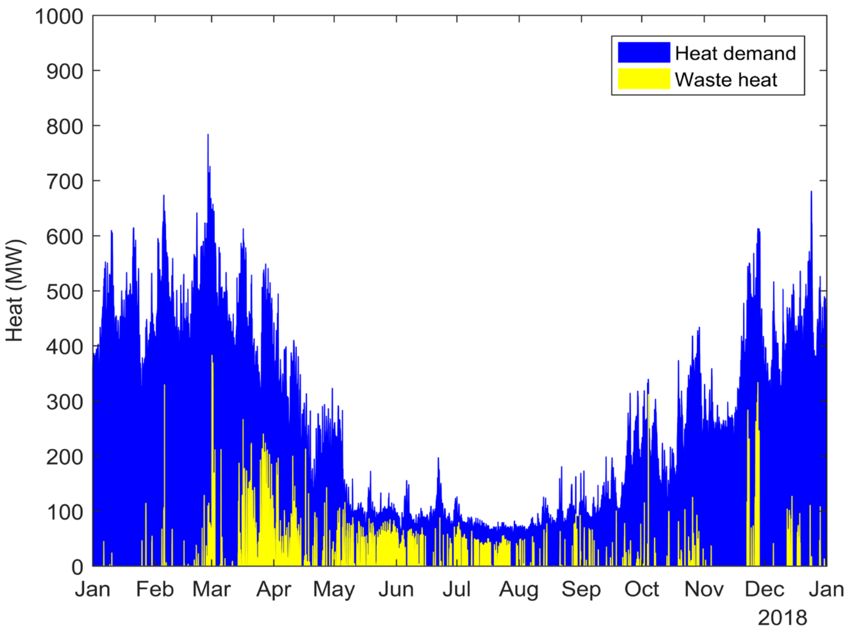

Figure 19: The contribution of the waste heat from power-to-hydrogen system to the regional heat demand.

Utilization of waste heat in the DH network could increase the overall efficiency of the system. However, the high waste heat production in the system influences the production planning of the thermal plants by reducing the operation hours. Therefore, the production of electricity from CHP plants decreases. The lower energy supply from CHP plants leads to a reduction in the fuel use and thereby in the cost related to fuel production. Evaluating the optimization results indicates that the amount of wood consumed in the system is reduced by 15 kton compared to the amount used in the base system in 2018. Moreover, the amount of CO_2 emitted by the combustion of fuel at plants can be decreased. The total amount of the CO_2 emissions from the energy conversion plants, including the fossil-based and biomass-based emission, is 572 kton in the optimized system. Fossil-based CO_2 accounts for 47% of total emissions. Importing electricity to the system will also lead to 823 kton marginal CO_2 emissions.

Increased hydrogen storage capacity (**Paper II**)

According to the results shown in Figure 17, about 76% of surplus power from the PV system is exported to the grid and yields profit in the system. The remainder is stored in the form of hydrogen in the storage tank. Increasing the capacity of the hydrogen tank could increase the storage potential of the system. Therefore, a sensitivity analysis with respect to different capacities of the hydrogen tank is conducted to evaluate the maximum potential for power storage in the optimal scenario. The capacity of the tank proposed in Case I is used as the minimum value and the maximum capacity is estimated using the maximum required size of the tank, that is around 120×10^6 Nm^3.

The results of the analysis in Figure 20 show that the power export decreases by increasing the capacity of the hydrogen tank. However, for a tank capacity greater than 50×10^6 Nm^3, electricity exports remain constant with minor variations. Based on the optimized system, even given large capacities of the storage tank, there will still be some share of power exported and the amount remains relatively unchanged beyond a threshold of 50×10^6 Nm^3. The system exports electricity to the grid during the off-peak hours and when the electricity price is high, in order to increase system revenues. According to the results, 50×10^6 Nm^3 is considered the optimal capacity of the hydrogen tank, since beyond this capacity the benefits of exporting power are relatively constant, whereas the investment costs increase.

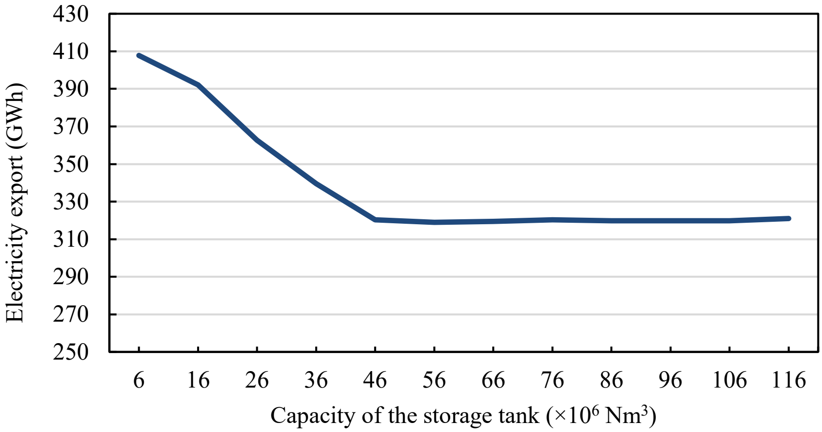

Figure 20: The effect of the hydrogen tank capacity on the electricity export.

Investigating an extreme case scenario, considering no capacity limit for the hydrogen tank, indicates that the entire amount of surplus power can potentially be stored in the form of hydrogen in the tank with a capacity of 105×10^6 Nm^3. The working load of the electrolyser and fuel cell, and subsequently the contribution of the waste heat to the DH network will increase in this extreme case scenario. The increased performance of the fuel cell can also reduce power imports to the system by 14% compared with Case I. By contrast, no power exports to the grid and the lack of exporting incomes increase system costs in the extreme case scenario by 4%. Moreover, the storage tank capacity required for large-scale storage significantly increases the annualized costs of the power-to-hydrogen system by around 90%. Thus, from an economic viewpoint, storing the entire excess power in the system without export possibility is not beneficial.

4.3 Integrated biofuel production with CHP plants (Papers III and IV)

To answer **RQ2**, the impacts of polygeneration in Case II on the production planning of the system are presented in this section and compared with the optimization results of the base system, including existing CHP plants and the rooftop PV power supply.

Integrated bioethanol production (Case II (a))

According to the modelling results, the integration of bioethanol production with existing CHP plants increases the energy output from the thermal plants by 2%. By-products from bioethanol plants are used in the CHP plants, which increase the operating hours of thermal plants and thus increase the heat and power production. The excess heat is used in bioethanol production processes. It can also contribute to DH networks. The cereal straw that can be cultivated in Västmanland County is used for bioethanol production. The energy content of available feed shows that around 950 GWh bioethanol can potentially be produced in the region. However, due to the low production efficiency of the bioethanol plant (SHF method), that is around 28% in the integrated system, the bioethanol supply is reduced to 265 GWh. The rest of the energy of input straw appears as energy loss and by-product in the system.

The energy output from different generation sources in the system are shown in Figure 21. For 43% of the year, mainly during winter, the bioethanol plants are in operation. CHP plants and HOBs, including the energy use of by-products from bioethanol plants, provide about 91% of the total DH demand of the region. Industrial waste heat can contribute 9% of the demand. Based on the optimization results, three CHP plants and ten HOBs are in operation. Energy supply is mainly based on biomass fuels and there is no use of oil and a negligible share of coal use in the system. CHP plants are the main heat generation sources in the system, operating at 80% of their full load and accounting for 89% of total heat production in the system. The remaining 11% is generated by HOBs. One of the HOBs based on bio-waste operates with almost constant heat load throughout the year, and other boilers operate below capacity to meet demand unmet by CHP plants.

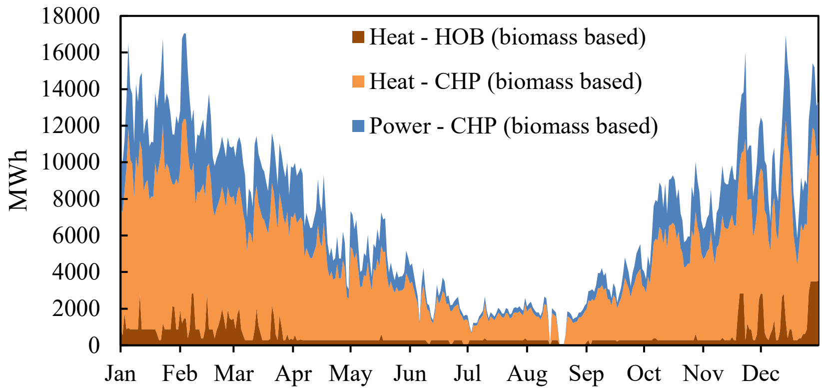

Figure 21: Energy supply from different generation sources over the studied year in Case II (a).

Thermal power supply, including the power production using bioethanol by-products, increased by about 6% in this case compared to the base system and can meet around 28% of regional demand. The optimization results show that the integration strategy can reduce total power imports by around 40 GWh, compared to the system with standalone thermal plants. However, 27% of power demand in the region is still met by power imports.

The results for CO_2 emissions reveal that the increased use of straw for bioethanol production and high electricity imports increase total emissions. By contrast, the integrated straw-based bioethanol production and use of by-products could reduce fuel consumption in CHP plants. Therefore, the fossil-based emissions decrease compared to the base system. The total emissions are 610 kton, with a 27% fossil-based share. The marginal emission in this system is around 484 kton.

With integration, the heat and power supplies from the system increase. However, the interaction of the system with PV power remains relatively unchanged, compared to the base system without integration. Due to the low efficiency of the bioethanol production plant, the overall efficiency of the system reduces to 74% in Case II (a) from around 89% in the base system. Moreover, due to the production costs of bioethanol, the cost of the integrated system is high, about 678 million SEK, 39% higher than the cost of the base system without integration.

Integrated pyrolysis oil production (Case II (b))

Similar to the integrated system with bioethanol production, optimization of the system in Case II (b) (**Paper IV)** shows that integration of wood pyrolysis to the existing CHP plants increases the total energy output from the system. The by-products from pyrolysis are used as an input fuel in CHP plants for additional energy supply, which can be applied in the pyrolysis process and/or contribute to the demand.

According to the investigation, CHP plants, including the contribution of the heat storage by water tank, provide 87% of the DH demand in the region. The total heat supply from CHP plants in this case study is 1,480 GWh, of which around 16% is stored as hot water in the water tank and further contributes to supply the DH network. The by-products from the integrated pyrolysis process provide 8% of the total heat supply from CHP plants. Therefore, there is a reduction in fuel use in the integrated system compared to the amount used in the base system without integration.

Figure 22 shows the load profiles of the CHP plants in the optimized system with and without pyrolysis and onsite hydrogen production. Comparing the results indicates that integrating pyrolysis process increases the operation time of the CHP plants as a result of using by-products from pyrolysis. However, the plants' full-load operation decreases due to the possibility of using waste heat from the electrolyser to meet part of the DH demand. The waste-based CHP plant has the highest production share among the existing plants because of its low production cost. It produces around 845 GWh DH by operating for 71% of the year, mostly above 70% of its maximum load. When heat demand is low, the by-products from pyrolysis provide heat to the region and the produced bio-oil can be sold as a valuable product and yield profit in the system.

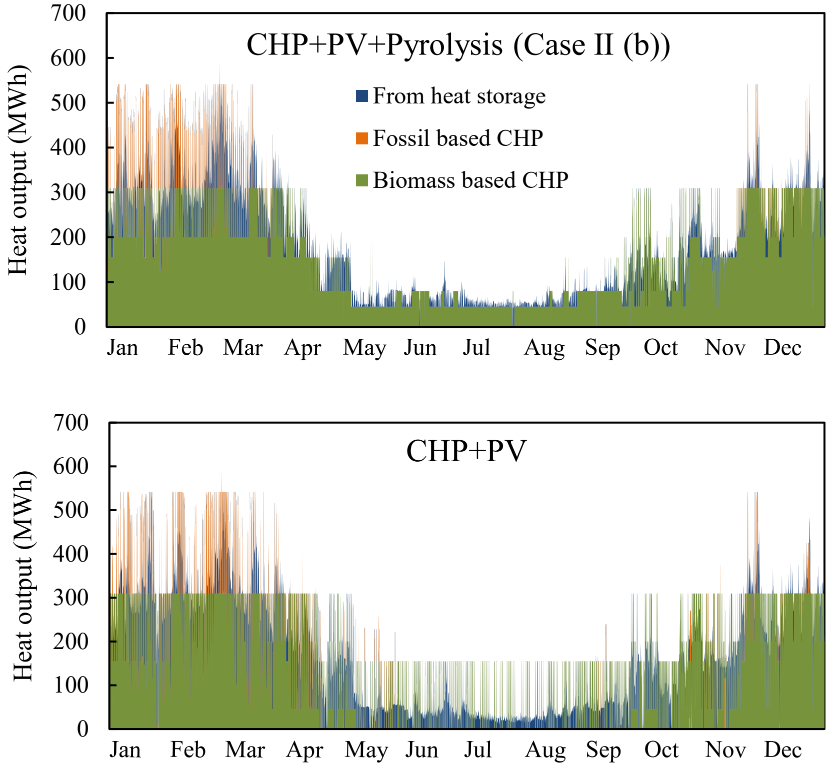

Figure 22: DH supply from different CHP plants and the heat storage in Case II (b) and the base system.

The CHP plant using wood and peat is the second unit with high operating time in the system, accounting for 35% (or 525 GWh) of total heat production. The energy supply from the fossil-based CHP plants using coal accounted for 7% of total heat production. There is no use of oil in the system. The HPs in the studied system produce 140 GWh of heat, which could satisfy 8% of the DH demand. This is 6% lower than the HPs' contribution to meet DH demand in the base system without integration. In addition, the waste heat from the electrolysis can contribute to supply the DH network, providing about 4% of DH demand in the region, leading to a reduction in fuel use compared to the base system.

Around 257 GWh of the excess power is used in the electrolyser and 5,533 tons of hydrogen are produced, which can provide 76% of the required hydrogen for upgradation of the bio-oil. The rest of the hydrogen demand is met by hydrogen imports, especially when the capacity of the storage tank is not enough to meet demand. Figure 23 shows the hourly hydrogen volume stored in the hydrogen tank. During the hours when there is excessive power generation in the system, especially in summer, hydrogen is produced and stored in the tank, supplying the hydrogen used in the pyrolysis process. When the tank capacity is at its maximum, the surplus power is exported to make revenue in the system. Moreover, when the electricity price is high, the system exports electricity instead of converting it to hydrogen through electrolysers. By contrast, when the electricity price is low, the system stores the excess power. It is also possible to produce hydrogen from the available power and use the generated waste heat if DH is needed. This is more cost-effective than importing heat and hydrogen and exporting the available excess power. Based on the modelling results of the polygeneration system in Case II (b), it can be concluded that the onsite production of the renewables-based hydrogen can lead to a reduction in the purchasing costs in the system. At the same time, the penetration of renewables is increased in the system. Moreover, it could decrease the emissions and the risks of hydrogen transport.

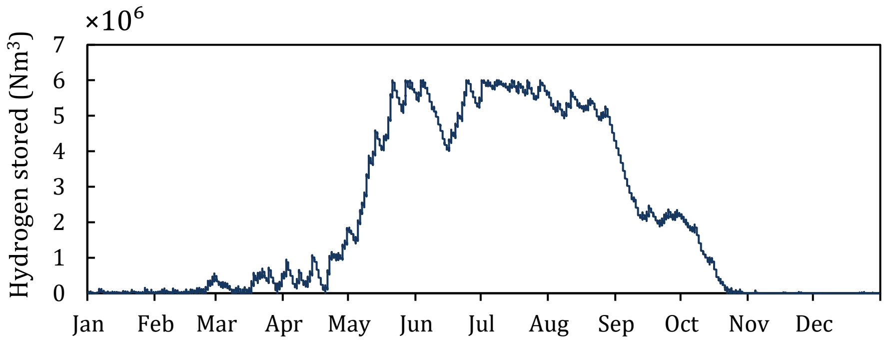

Figure 23: Hourly hydrogen storage in Case II (b).

The results of the power supply show that CHP plants account for 45% of total electricity production in the system, including the power from renewables, and can supply 50% of the total electricity demand in the system. The rooftop PV power and the local hydropower directly meet 18% of the power demand and the remaining 32% of demand is supplied by electricity imports into the system. Around 230 GWh of the total power in the system is exported. The power export is reduced compared to the export in the base system, where the possibility to store the renewable power in the form of hydrogen was not considered. The overall efficiency of the system in Case II (b) is 79%, around 10% lower than the reference system with only CHP plants. The reason for the efficiency reduction is the higher energy input for importing hydrogen and the low production efficiency of pyrolysis.

4.4 Impacts of future developments on the energy system operation strategy (**Paper IV**)

This section presents and analyses the optimization results of the developed scenarios to answer **RQ3**, considering the potential developments and/or changes in the future energy system. The scenarios investigate the influence of climate change, market trends, and fossil fuel-free energy supply on the heat and power demand as well as the operational strategy of the polygeneration system in Case II (b). The energy output from CHP plants, contributions from the electrolyser and pyrolysis, and other outcomes of different scenarios are summarized in Table 12 and compared with the base system without integration.

The optimization results for Scenario 1, which investigates climate change, show that the operation of the system in this scenario is almost similar to the system in Case II (b), with some minor differences. The heat load for fossil-based CHP plants is the same as their load in Case II (b), operating for 7% of the year. The bio-waste plants operate for 68% of the year with more than 80% of full load. In this scenario, the biomass plant (plant 3 in Table 2) has the highest total working load among plants in the system. The higher operation load of plant 3 is due to increased DH demand in Scenario 1, as it is shown in Figure 12 in section 3.4, and due to the availability of the solid biofuel in the system to be used in this plant. Despite the greater operation hours of plant 3, the bio-waste CHP plant meets a larger share of the DH demand, accounting for 53% of total heat supply from thermal plants. The thermal power in this scenario provides about 52% of the total demand. There is an increase of about 2% in the total electricity demand in Scenario 1. Therefore, the total power import to the system has increased by 11 GWh in this scenario. With climate change, the power production profile from PV systems is also changed and the total production is increased by 2%. Moreover, looking at the hourly demand profile, less electricity is required in the system for around 40% of the year compared to the base integrated system. Thus, the result for the peak power import per hour is decreased from

172 MWh in Case II (b) to 160 MWh in Scenario 1. Higher total power imports, the increased load of one of the CHP plants, and thereby increased biofuel use in this scenario resulted in a 30% increase of the total cost of the system. The higher import and fuel use also cause a reduction in the overall efficiency of the system to 72%, from 79% in Case II (b).

Table 12: Optimization results of the base system and the integrated cases in different scenarios (base year 2018).

	CHP + PV systems	Case II (b)-integrated pyrolysis	Scenario 1 (Climate changes)	Scenario 2 (Market trends)	Scenario 3 (Fossil fuel-free system)
Electricity demand (GWh)	1248	1248	1270	1718	1248
Electricity supply (GWh)					
RES (PV systems + Hydropower)	754	754	767	754	754
CHP plants using available fuels	612	573	616	286	593
CHP plants using pyrolysis by-products	NA	49	50	41	49
Electricity import	400	397	408	949	362
Max electricity import (MW)	176	172	160	297	161
Electricity export	456	230	252	188	230
Power to hydrogen	NA	257	265	112	253
Power to HPs at CHP	62	38	55	11	26
Hydrogen supply (GWh)					
Onsite hydrogen	NA	184	190	80	182
Hydrogen import	NA	60	55	120	61
DH demand (GWh)	1695	1695	1863	852	1695
DH supply (GWh)					
CHP plants using available fuels (incl. heat storage)	1457	1364	1468	681	1411
CHP plants using pyrolysis by-products (incl. heat storage)	NA	116	117	96	116
HPs (at CHP plant)	229	140	201	42	96
Waste heat from electrolysis	NA	74	76	32	73
CO_2 emissions (kton)					
From energy plants (total)	477	877	930	535	845
From energy plants (fossil-based)	264	263	263	118	207
Marginal emissions	312	310	318	740	282
Bio-oil supply (GWh)	NA	762	765	627	757
System cost (MSEK)	288	95	124	417	80
Overall efficiency (%)	88	79	72	58	71

The modelling results of Scenario 2, in which the effects of market trends are evaluated, show that the load of CHP plants decreases, since 50% of the total heat demand in the region is directly met using HPs in buildings. Similar to the system in Case II (b), the bio-waste CHP plant is the most-operated plant.

The plant works for 50% of the year in this scenario and accounts for 74% of total heat supply from all CHP plants. The other biomass-based CHP plant in the system operates mostly below capacity for 4,076 hours or 47% of the year. The fossil-based CHP boilers account for a small share of total production, operating less than 2% of the year. The low heat demand in the system is met by HPs, heat storage, and waste heat from power-to-hydrogen system, depending on the availability. With reduced heat supply, the input energy to the system is decreased. Bio-waste has the highest share among input fuels, providing 78% of total fuel used in thermal plants. There is no use of peat, oil, or biofuel in this scenario and the share of coal as the fossil-based fuel is decreased, accounting for 1% of the total fuels used in CHP plants. The fuel reduction can subsequently decrease the fossil-based CO_2 emitted from CHP plants by around 55% compared to Case II (b). The reduced energy supply from thermal plants also decreases the power supply in the system. Based on the optimization results, the thermal electricity production is 327 GWh, which meets around 20% of total demand in Scenario 2. Rooftop PV power and hydropower contribute 26% of the power supply in the system. Lack of power production is met by power imports. The total power import in Scenario 2 is 949 GWh, an increase of 551 GWh compared to power imports in Case II (b), which subsequently increases system costs and reduces overall system efficiency down to 58%. Due to the high imports of power in the system, the amount of marginal emissions is high, 740 kton. The total CO_2 emission from energy conversion processes at CHP plants in Scenario 2 is 535 kton.

As seen in Table 12, the optimization results of the fossil fuel-free system in Scenario 3 are similar to the base integrated system in Case II (b). The results show the potential of replacing fossil-based CHP plants with wood-based CHPs in the regional energy system. The total heat output from thermal plants in this scenario has the highest contribution among other studied scenarios, providing about 90% of the total heat demand of the region. The bio-waste CHP plant, with 70% operation of its full load, provides 50% of total heat demand. The new wood-based plant is the second high-load CHP plant in the system, providing 22% of heat demand. Unlike the integrated system in Case II (b) and Scenario 1, the operation hours of plant 3 in this scenario are decreased and the plant mostly operates at part load. The contribution of HPs to meet heat demand is reduced by 2% compared to the system in Case II (b). With the increased heat output from CHP plants, the total thermal power supply also increases by 46 GWh in this scenario, accounting for 51% of total power demand. The energy output from the new wood-based CHP can contribute to the reduced power imports. Moreover, the slight reduction in HPs utilization can further decrease the power import. Total power import in this scenario is 362 GWh, 9% less than the base integrated system. However, there is no change in the amount of extra power in the system. The reduced fossil fuel use and decreased power import to the system cause a reduction in the total system cost from 94 million SEK in Case II (b) to around 80 million SEK in Scenario 3. Decreased fossil fuel use in the system also results in a 21% reduction in fossil-based CO_2, from 263 kton in Case II (b) to 206 kton in Scenario 3. With lower power imports in the system, the marginal emissions are also reduced. Due to the high carbon tax in Sweden (~1,200 SEK/ton of fossil-based CO_2), which is the highest within Europe (Swedish Ministry of Finance, 2021), and possible increases in future carbon prices, lower CO_2 emissions is a positive result for Scenario 3.

A summary of the energy balance in different scenarios is provided in Figure 24.

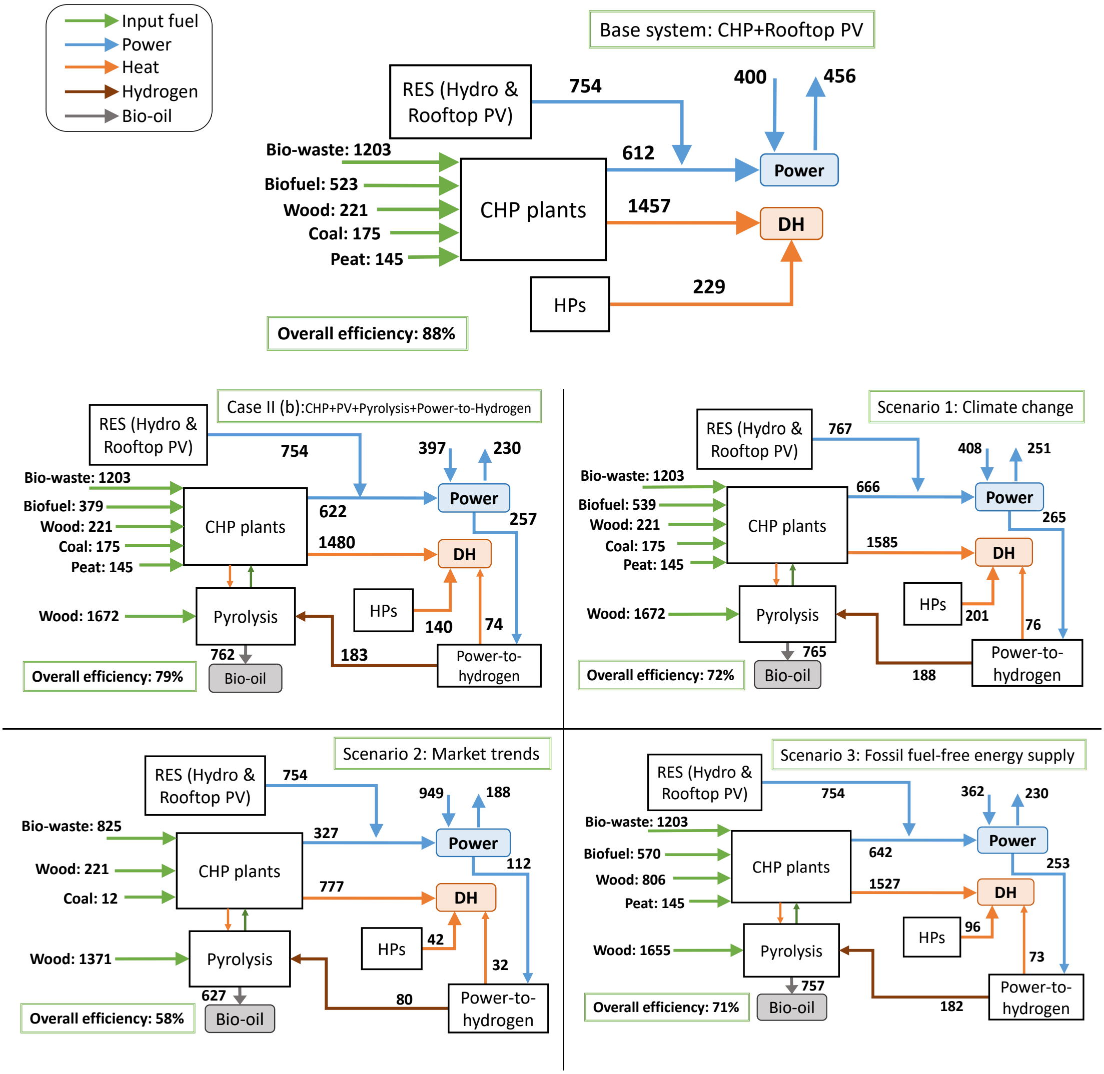

Figure 24: Energy flow results in Case II (b) under different scenarios. All values are presented in GWh.

The performance of the hydrogen storage tank in Case II (b) and in different scenarios is also compared in Figure 25. The total power export and power storage in the form of hydrogen are increased by 9% and 3% respectively in Scenario 1, compared with Case II (b). Around 7.4 kton of hydrogen is used for the bio-oil upgradation, mainly provided by onsite hydrogen production. Still, 22% of hydrogen demand is met by import.

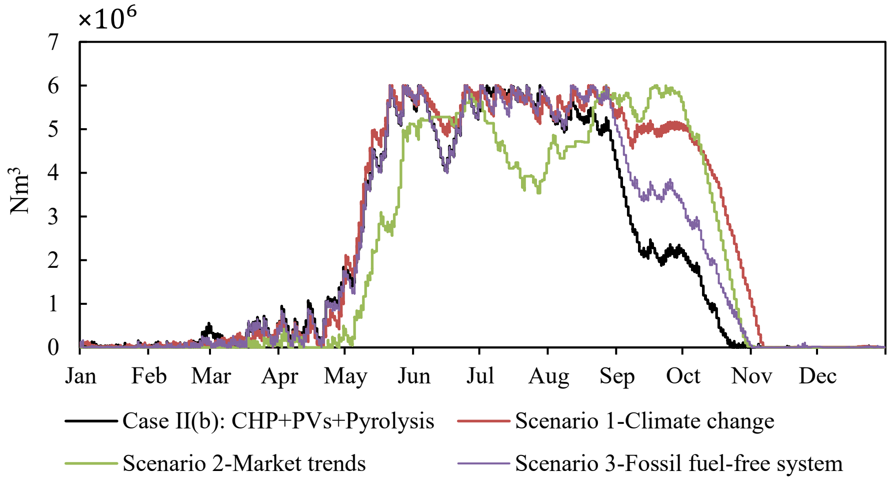

Figure 25: Status of the hydrogen storage tank in Case II (b) and under different scenarios.

With the lower electricity generation from CHP plants and the increased power demand in Scenario 2, the quantity of excess power that can be either exported or stored is decreased by 39%. Therefore, lower amounts of hydrogen can be produced in the system. Due to variations in the electricity price and an hourly price less than 200 SEK/MWh for about 60% of the year, the benefit of exports in the system is low, around 45 million SEK. This is 63% less than the benefit yielded by power exports in the base integrated case. The results indicate that onsite hydrogen production from renewable power can meet 40% of hydrogen needs for bio-oil upgradation. The yearlong status of the hydrogen tank in Figure 25 indicates that due to the low possibility to produce onsite hydrogen, the storage tank is below full capacity for almost the entire year.

According to the modelling results in Scenario 3, there is a total of 488 GWh of surplus power generation, of which 230 GWh is exported, and the rest is stored in the form of hydrogen in the system. Similar to the system in Case II (b), the available renewables-based hydrogen in the system provides 75% of the required hydrogen for the pyrolysis process.

4.5 Optimal system configuration (**Paper V**)

RQ4 aims to identify the optimal pathway for integration of energy technologies to have a cogeneration system, among those investigated, with high flexibility. To answer RQ4**,** the flexibility potential of the investigated systems in Case I for power storage and Case II (b) for polygeneration was analysed and compared in **Paper V**.

The analysis is based on the optimization results of Case I and Case II (b). The performance of the developed systems with respect to each of the main criteria as well as the cumulative performance are shown in Figure 26. The performance of the system is normalized and displayed in a rank between 0 and 1, meaning that the higher value indicates the better performance. The results of the analysis show that the integration strategy in Case II has a higher overall rank compared to the power-to-hydrogen-to-power system in Case I.

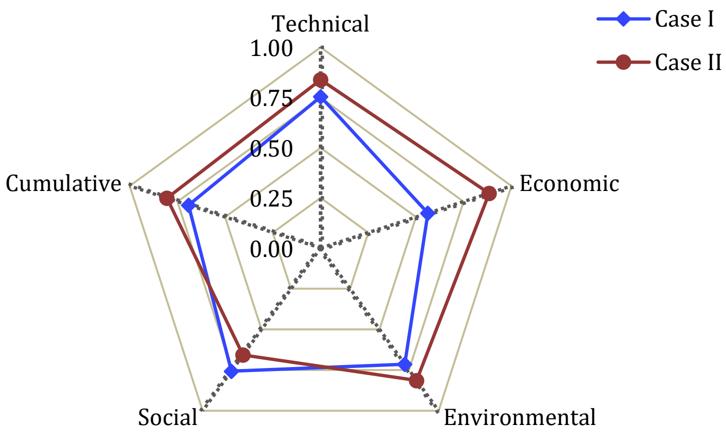

Figure 26: Rank of the studied cases according to the main criteria and the cumulative performance.

Considering the technical aspects, the application of large-scale electrolysers and fuel cells is not yet a mature technology. The production efficiency of the fuel cell is below 50% and it is not high enough to supply the lack of power. Therefore, the technical performance of the system in Case I is decreased. According to the optimization results for this system, a large share of the power demand needs to be met by power import, which is a negative point considering the limitations of inter-regional grid power transmission. The pyrolysis process in Case II needs a large amount of woody biomass for bio-oil supply. This makes Case II less desirable than Case I in terms of the fuel use/potential, which is the sub-criterion under the technical aspects. The performance of the case studies with respect to each of the sub-criteria is shown in Figure 27.

The economic performance of the studied systems shows that power-to-hydrogen-to-power technology is not cost-effective since the investment cost of this technology is still high. The future cost scenarios suggested by the Department of Energy (DOE) (2020) and Walker et al. (2016) can potentially improve the economic performance of this technology, especially for large-scale applications, and increase its commercial competitiveness. The production cost of the pyrolysis process is also high. However, the economic performance of the integrated bio-oil production with CHP plants can be improved when hydrogen is produced through onsite electrolysis. Moreover, the produced bio-oil in this system can be sold as a valuable product, for instance in the transport sector or for chemical industries and yield significant revenue in the system.

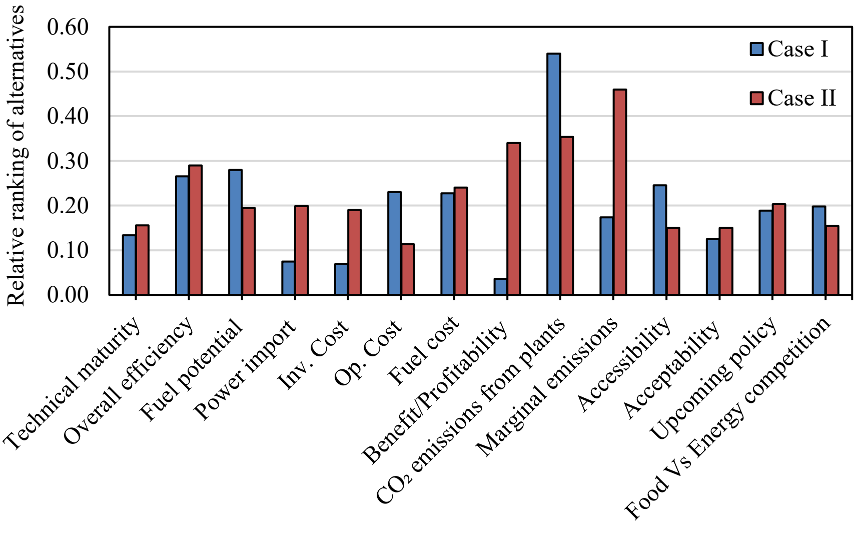

Figure 27: Relative rank of the studied cases according to the considered criteria.

The performance of cases with respect to each environmental sub-criterion is different. Based on the optimization results, integrating wood pyrolysis to the system increases the CO_2 emissions from energy conversion plants as the quantity of the wood fuel in the system increases. By contrast, the application of the electrolyser and fuel cell in Case I has insignificant impacts on the plants' emissions. However, the excessive power import to the system in this case results in high marginal emissions. Based on the importance of each sub-criterion, the integrated pyrolysis in Case II performs slightly better compared to Case I.

Both studied cases indicate almost similar performance in terms of social aspects concerning the acceptability of the technology and compatibility with upcoming energy policies. Regarding accessibility, the power-to-hydrogen system performs better than the integrated pyrolysis system. Production of pyrolysis oil using wood biomass can also jeopardize land-use competition for food and energy supply. Therefore, Case I, with higher ranks for accessibility and food versus energy competition, performs better under the social criteria.

Based on the analysis, the economic and environmental criteria have shown more impacts on the optimal flexibility solution. Considering the overall results, the cases developed in this study have similar performance according to most of the criteria, especially, technical and social. However, the integrated pyrolysis proposed in Case II is more profitable and this technology with onsite hydrogen supply is overall considered the optimal integration case in this analysis. The power-to-hydrogen-to-power system in Case I can technically perform better for small-scale implementations. However, due to high capital costs, the economic performance even on small scales would not be much improved.

4.6 Discussion on the results

This thesis studies existing CHP plants integrated with distributed rooftop PV systems and investigates the impacts on production planning and system flexibility. The investigation results provide increased knowledge about the impacts of some possible future developments on the operational strategy of the current and future energy system with a high share of RES. This section describes the assumptions and limitations related to the modelling and discusses the application of the developed optimization model. Moreover, a discussion of the key findings of this thesis in comparison with the reference literatures is presented.

Section 4.1 in this thesis highlights that the integration of PV power supply to the energy system leads to increased power supply and reduced electricity imports, without having significant effects on the operational strategy of the CHP plants. Nonetheless, to handle variations in power supply from rooftop PV systems, system flexibility is needed, in terms of balance between demand and supply. The impact of energy storage and polygeneration on the energy imbalances and the flexibility in the power system was the focus of this study, with no in-depth techno-economic investigations. Therefore, these flexibility options were assumed as ‘black box’ models in the investigation, without focusing on detailed chemical reactions inside the installations.

The power-to-hydrogen technology was investigated for power storage in this study. The amount of water consumed in the conversion of power to hydrogen was calculated using the capacity of the electrolyser. It is assumed that the surplus water recycled at the CHP plants supplies the required water for the hydrogen. However, for practical implementation of the power-to-hydrogen technology, more in-depth sustainability analyses for water use might be needed. The electricity use for the water treatment was also included in the regional demand profile in this study. The energy required to pump water in the power-to-hydrogen installations was estimated to be low and it was omitted from the calculations. As reported in different studies (Grueger et al., 2017; Jentsch et al., 2014; Lyseng et al., 2018; Mesfun et al., 2017; Zhang et al., 2017), energy storage using small- and large-scale power-to-hydrogen technologies can play an important role in integration of RES and increased flexibility. According to the investigation, using large-scale power-to-hydrogen technology for long-term power storage could increase the penetration of renewables in the power supply of the system. However, due to the high capital costs and low efficiency, the use of this technology at system-level is not yet cost-effective. In the current study, the power-to-hydrogen with fuel cell for power generation was investigated. However, using gas turbines, with lower capital costs (Zakeri & Syri, 2015), can be an alternative to fuel cells for large-scale power storage, requiring comprehensive studies from technical and economic perspectives.

Although hydrogen storage is not a mature technology, the technical and economic performance of this technology can be improved by integration with other existing energy technologies. This is investigated in Case II of this thesis. The potential of polygeneration to increase the total energy supply reported in previous investigations (Jana et al., 2017; Karvonen et al., 2018; Moncada B et al., 2016; Salman et al., 2020; Shemfe et al., 2015; Starfelt et al., 2012) has been used as a reference concept for further analysis of an integrated system consisting of thermal plants, rooftop PV system, biofuel production, and onsite hydrogen production. However, the focus of this study is on the flexibility and production planning of the system. The results for the energy output and overall efficiency of the studied polygeneration system are in alignment with the above-mentioned studies. However, the system in this thesis also shows that adding the pyrolysis process to the existing CHP plant increases the total operation time of the CHP plants by around 22%. Moreover, the investigation reveals that the integration of energy sources and energy technologies enables an increased share of renewables in different energy sectors and improves the system flexibility by reducing energy curtailments.

Energy developments could further change the operation of existing and future energy systems. Variation in electricity prices following trends in energy demand and supply (for example, increased use of HPs and EVs (Göransson et al., 2019)), climate change (Damm et al., 2017; van Ruijven et al., 2019), and more biomass-based cogenerations for fossil fuel-free energy supply (IEA, 2018) are some possible developments investigated in this thesis under different scenarios. However, the optimization of technology coupling to cover more energy technologies is not considered here. According to the study, the market trends scenario was found to significantly affect system performance, as it could increase the penetration of RES in the system but reduce the working load of the CHP plants and negatively affect the overall efficiency. The scenario for the integrated system without fossil fuel use indicates the potential of a future fossil fuel-free energy systems. However, the construction and commissioning of new biomass-based thermal plants is a main challenge from an economic perspective in the energy transition (Beiron, 2020), which needs further investigations. It should be noted that conservative assumptions were used for estimation of the demand profiles in different scenarios. Many advancements and developments might affect production and consumption patterns. Therefore, the model in this study can be improved by using real-time data. Furthermore, thorough economic analyses considering possible financial risks and future energy system regulations are needed. The optimization model of the reference case study system was validated by comparing the modelling results with historical energy data provided by energy companies in the studied regions. In this thesis, application of the optimization model at city and county levels were investigated. However, it is also feasible to extend and use the model at national scale.

The studied integrated system, including renewable resources, CHP plants, drop-in biofuel production, and onsite hydrogen supply, can be a novel solution to increase the operation and profitability of the existing CHP plants, and the system flexibility in energy transition. The study can provide useful knowledge on the potential of CHP plants to be integrated with future renewables-based technologies. The investigation results help policy makers to recognize the potential effects on production planning of existing energy plants in transition towards a renewable system, and to find the optimal operational strategy of a more reliable and cost-effective renewable energy system.

5 Conclusions

This thesis studied the production planning of a CHP-dominated energy system with increased interaction with renewable power supply. The system performance was investigated with a focus on increasing flexibility in terms of balance between demand and supply. The potential of different flexibility pathways, including energy storage and polygeneration design of the system, were evaluated, with consideration of future energy developments and market trends. The optimization model and results in this study can be used to investigate the potential performance of existing CHP plants in integration with other energy technologies in a future renewable system. The main conclusions of this study with respect to the research questions are summarized as follows:

Increased renewable power supply and system flexibility (RQ1)

Increased power supply from renewables in the energy system does not significantly affect the operational strategy of CHP plants. However, the high penetration of renewable power supply reduces the overall electricity imports to the system. Nevertheless, due to production profile variations of renewables, the hourly power imports at night and/or during peak hours, when there is lack of production from renewables, are still high. Adding power storage to such a system contributes to the increased system flexibility and renewables penetration. However, the high annualized cost of the storage system can significantly increase the system costs.

The modelling results of integrating rooftop PV systems with existing CHP plants in this thesis show a 40% reduction in total power imports to the system. Using power-to-hydrogen technology for power storage can further reduce the power imports by 4%, while increasing the contribution of renewables in the power supply by 3%. The potential waste heat production from power storage can also be used in the DH network, reducing the operation of the thermal plants in the system.

Integration strategy and polygeneration (RQ2)

Production of multi-products from a single energy system can potentially improve system flexibility. Through integration of a thermochemical process for biofuel production with existing CHP plants, the by-products from biofuel production are used as additional input fuels in the CHP plants. Thus, the operation of CHP plants increases. The excess energy supply from by-products contributes to providing the required heat for thermochemical processes and partly supply DH demand. Therefore, the input feed to the CHP plants is reduced and the overall performance and efficiency of the system are improved.

Of the polygeneration systems studied in this thesis, integrating the straw-based bioethanol production to the CHP plants increases the total energy output from CHP plants by 2%. There is 6% increase in thermal power supply in the system, which can subsequently reduce the total electricity import. Due to the low conversion rate of feed straw to bioethanol through fermentation, the potential energy in the feedstock is not totally converted to bioethanol. Therefore, the overall efficiency of the system decreases. The penetration of renewable power in this polygeneration system also remains unchanged. Integrating pyrolysis oil production and upgradation to the CHP plants as an alternative polygeneration system increases the interrelation of biofuel production with renewable power and improves system flexibility. The investigations show that the parallel onsite hydrogen production using renewable power increases the penetration of renewables in the energy supply by around 6%. Based on the modelling results, the by-products of the pyrolysis process are used as a valuable extra fuel in CHP plants, which increase their total operation time by around 2,460 hours (22%) and result in an additional 33 GWh energy supply. This can lead to a reduction in the share of solid biofuels in the input fuels to the CHP plants by 28%, which consequently reduces the system cost. Moreover, selling the biofuels can increase revenues in the polygeneration system.

Trends in demand and supply (RQ3)

The integrated system, including CHP plants, rooftop PV systems, the pyrolysis process, and the power storage (Case II (b)), was optimized and evaluated considering changes in both energy demand and supply. The investigations show that the future market trends (Scenario 2 in this thesis) could significantly influence the operational strategy of the energy system in terms of fuel use, operating hours, energy supply, power imports, and overall efficiency.

According to the investigation, high penetration of HPs to meet 50% of heat demand proportionally reduces the DH and subsequently power production from CHP plants. Therefore, the penetration of PV systems to supply power in the system increases by 8%. However, a lower quantity of excess power will be available in the system to be stored in the form of hydrogen. Thus, onsite hydrogen production decreases by 56%. This can negatively affect the upgraded bio-oil production and increase the total system cost due to high imports to the system. The 50% share of HPs use and 100% penetration of EVs, by contrast, increase total power use in the system. However, the impact of using HPs on increasing electricity demand is greater, as a 50% increase in HPs application results in a larger increase in the electricity demand, compared to 100% penetration of EVs. Given the reduced thermal power supply in the system, 55% (949 GWh) of the required electricity needs to be imported to meet the thermal power shortcomings. Overall, reduced fuel use, lower CO_2 emissions from thermal plants, and increased penetration of renewables in the power supply are the main advantages of the studied market changes in this thesis. However, high power and hydrogen imports increase system costs and reduce overall system efficiency to 58% from 79% in the base integrated system. The fluctuations in electricity prices also reduce the profitability from power export.

Climate change (Scenario 1) and the fossil fuel-free energy supply (Scenario 3) can also influence the system operation. However, overall system performance after these developments is relatively similar to the base integrated system. Based on climate data, the total heat and power demands in the region are estimated to increase in 2050. Therefore, operation of thermal plants, and thereby the amount of fuel used in the system increase by 7% and 8%, respectively. The PV power potential is estimated to also increase by 13 GWh in 2050, considering the predicted climate data. Therefore, the possibility to store renewable power and export it increases at certain specific hours.

Investigations show that a fossil fuel-free integrated system at regional scale is potentially feasible from the energy balance perspective. Using biomass instead of fossil fuels in the studied system will not significantly affect system performance. According to the optimization results, the overall efficiency of the system is 71%, with an 8% efficiency reduction compared to Case II (b). Reduction in fossil-based emissions is the main advantage of the system in Scenario 3. However, for practical application of such fossil fuel-free integrated systems, parameters such as hydrogen transportation, optimal capacity of the power-to-hydrogen system, and all the economic indicators need to be investigated.

Optimal system configuration (RQ4)

The system with high share of renewables and power storage in Case I and the polygeneration system including pyrolysis in Case II (b) were investigated from different perspectives to determine the optimal integration pathway. The two systems show similar performance under different criteria, including technical and environmental aspects. However, from an economic viewpoint, the integrated pyrolysis with CHP plants and the parallel hydrogen production has the higher rank. By contrast, the power storage system in Case I has a better performance concerning social aspects. In general, the proposed polygeneration strategy has the higher overall rank in this evaluation. Therefore, this approach can be suggested as the potential optimal configuration for increased operation and profitability of CHP plants and system flexibility.

6 Future work

The main results of this thesis suggest extension of the study in the following future directions:

- Integrated pyrolysis oil production with CHP plants using hydrogen produced via electrolysers has been investigated as one of the flexibility pathways in this thesis. However, production of chemicals such as hydrogen and oxygen using power electrolysis and converting them to methanol and ammonia by gasification integrated with CHP plants can be an alternative polygeneration system that could also affect system flexibility.
- This thesis has essentially investigated the impacts of polygeneration and flexibility solutions on the operational strategy of CHP plants. However, the CHP plants can play an important role in managing variations to balance power demand and supply. Therefore, CHP plants' production flexibility can be investigated and optimized from a large-scale power generation perspective to secure the electricity supply in renewable energy systems.

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