Even Glad Sørhaug

The Potential for Fuel Cells to Provide Electricity and Heat Supply in Norwegian Buildings

Master's thesis in Energy and Environmental Engineering
Supervisor: Völler, Steve
June 2021

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Abstract

While Norway is often cited as the green battery of Europe due to the sheer amount of hydropower plants scattered through the mountainous landscape, there still exists a huge potential to further decarbonize multiple sectors of the economy. Norway has during the last couple of years been a net importer of electricity, and a potential solution to becoming less reliant on the European energy mix is including hydrogen technologies along with renewable energy sources within the energy sector.

Energy use in buildings account for more than a third of the energy used in Norway. During this thesis the potential for utilizing hydrogen fuel cells to provide electricity and heat in Norwegian buildings were examined. This was done by providing an overview of the state of hydrogen technologies in Norway as well as in the rest of the world, presenting a theoretical foundation for fuel cell and energy system components, and creating an optimization model to examine the economic potential for the inclusion of fuel cells in an energy system.

The results form the simulations indicate that given current trends in the development of hydrogen technologies and future estimates of cost reductions it could become profitable to include fuel cell combined heat and power units in Norwegian buildings by the year 2050. The modeled energy system used the microgrid at Campus Evenstad as a basis, and introducing a fuel cell unit into the system resulted in a decrease of the annual costs of the system by 10.7 % and reducing the indirect emissions by 67.5 %. Using economic parameters for current costs of fuel cells and hydrogen production, however, it was found that it could not currently be considered profitable to include fuel cell combined heat and power in Norwegian buildings. Introducing the fuel cell unit in 2020 ensured that the annual cost of the system increased by 4.4 %, while only covering 13 % of the electricity demand.

Through a sensitivity analysis and levelized cost of energy calculations it was revealed that the price of hydrogen would have to fall below 1.5 EUR/kgH2 to make a fuel cell combined heat and power unit profitable in Norway. This price reduction is deemed unrealistic to achieve within the next decade. With the expected cost reductions for investment in fuel cells, the critical hydrogen cost will be increased to 1.9 EUR/kgH2, which is well below the expected cost for green hydrogen in 2050. Seasonal differences will affect the optimal dispatch of fuel cell units, and based on the results from the optimization model a more strategic dispatch was proposed. By implementing a selective operational scheme for the fuel cell it was possible to reduce the number of start/stop-cycles from 219 to 39 during a year to mitigate permanent potential losses and increase the economic lifetime of the technology.

Analyzing the use of fuel cell combined heat and power units in six different building types revealed that buildings with a higher ratio of thermal-to-electricity demand were better suited for this technology. Apartment buildings, hospitals and nursing homes are facilitating people during the nights as well as the days, requiring a more stable energy demand resulting in a cost reduction of 18.9, 15.6 and 17.0 % respectively.

Among the future work regarding the potential for implementation of hydrogen technologies for energy use in buildings in Norway, is the opportunity to compare the technology directly with competing alternatives, like heat pumps, to make a more informed decision. Furthermore, it will be useful to quantify the added benefits provided by hydrogen solutions. Among these benefits are the potential for peak-shaving, energy storage and on-site fuel production.

Sammendrag

Norge blir ofte betegnet som Europas grønne batteri på grunn av den massive mengden vannkraft som finnes rundt i det fjellstrakte landskapet, likevel finnes det et stort potensiale for å kutte karbonfotavtrykket i flere sektorer av økonomien. Norge har over de siste årene hatt en netto import av den europeiske energimiksen, men en kombinasjon av hydrogenteknologier og fornybare energikilder kan være en poteniell bit av puslespillet som gjør landet mindre avhengig av å importere strøm fra Europa.

Energibruk i bygg står for over en tredjedel av energiforbruket i Norge. Denne oppgaven omhandler en undersøkelse av potensialet for bruk av hydrogenbrenselceller til produksjon av elektrisitet og varme, såkalte kraftvarmeanlegg, i norske bygg. Denne undersøkelsen ble gjennomført ved å se på den nåværende tilstanden for hydrogenteknologi i Norge, såvel som resten av verden, og bruke eksisterende tallgrunnlag til å danne et bilde av hvordan energisystemer vil påvirkes ved å introdusere et brenselcelle-kraftvarmeanlegg gjennom simuleringer.

Resultater fra simuleringene viser at den nåværende utviklingen av hydrogenteknologier og fremtidsestimater for kostnadsreduksjon antyder at det vil være lønnsomt å inkludere brenselcelle-kraftvarmeanlegg i norske bygg innen 2050. Energimodellen brukte mikronettet på Campus Evenstad som basis, og introduksjonen av kraftvarmeanlegget resulterte da i en årlig kostnadsreduksjon på 10.7 %, og en reduksjon på 67.5 % i indirekte utslipp fra det lokale energisystemet. Ved investering i brenselceller i 2020 med nåværende priser, var resulterete derimot en økning på 4.4 % for kostnader, og en dekning på kun 13 % av energibehovet.

Gjennom sensitivitetsanalyse og kalkulasjoner av levelized cost of energy ble det klart at prisen for hydrogen må ligge under 1.5 EUR/kgH2 for at introduksjon av kraftvarmeanlegg skal være lønnsomt i norske bygg i dag. Denne prisreduksjonen er ikke ansett som realistisk å oppnå over det kommende tiåret. Sesongbaserte forskjeller vil påvirke den optimale utløseningen av kraftvarmeanlegget, og basert på resultatene ble det foreslått en strategisk operasjonsmetode. Ved å introdusere en selektiv oppetidstaktikk ble antallet start/stopp-sykler redusert fra 219 til 39 sykler gjennom ett år. Dette kan utvide den økonomiske levetiden til anlegget ved å dempe permanente tap i potensiale.

Ved å analysere bruken av kraftvarmeanlegg i seks forskjellige typer bygninger ble det gjort klart at bygninger med høyere varme-til-elektrisk behov var bedre egnet for denne typen teknologi. Leilighetskomplekser, sykehus og sykehjem er

bygninger som huser mennesker både på dagtid og på nattetid. Dette resulterer i et mer stabilt energibehov og resulterte og en årlig kostnadsreduksjon på 18.9, 15.6 og 17.0 % respektivt nå brenselcelle-kraftvarmeanlegget ble introdusert.

Blant fremtidig arbeid innen potensialet for implemenering av hydrogenteknologier for energibruk i bygg i Norge, vil det være av interesse å sammenligne teknologier direkte med konkurrerende alternativer, som varmepumper, for å få et mer detaljert helhetsbilde. Det vil videre være interessant å også ta høyde for andre fordeler som teknologien bærer med seg. Disse fordelene inkluderer blant annet potensiale for kutting av effekt-topper, enerilagring og lokal hydrogen-produksjon.

Preface

This master thesis was written during the spring term of 2021 for the Department of Electrical Power Engineering at the Norwegian University of Science and Technology in Trondheim. This work is the final paper written to complete a five year degree as master of technology, specializing in 'Energy and Environmental engineering' and amounts 30 credits.

First of all, I would like to extend great appreciation to my supervisor Steve Võller at NTNU. Without his commitment to green energy and persistent encouragement I would not have been able to produce this thesis. In addition I would like to extend gratitude to Frederico Zenith and Igor Sartori at Sintef for lending me assistance and sharing their considerable knowledge regarding fuel cell technology and smart energy systems respectively.

During the process of writing this assignment I have learned a lot about the scientific process, in addition to all the knowledge I have gained about hydrogen as the basis of an energy solution. It has been a meaningful semester teaching me the value of structured planing setting goals for each coming week. As with most of the world during this last year, my final semester was affected by the COVID-19 situation and ensured that I would have to write most of this assignment from my room in Trondheim.

Contents

Nomenclature

General Constants

$\dot{m}_{H_2}$	Mass Flow of Hydrogen
$\dot{n}_{H_2}$	Molar Flow of Hydrogen
ΔG	Gibbs Free Energy
ΔH	Change in Enthalpy
ΔS	Change in Entropy
η	Efficiency
$\lambda_{renewable}$	Fraction of Energy Production from Renewable Sources
μ_f	Fraction of Utilized Hydrogen in Cell
A	Area
C_F, t	Cost of Fuel for Period, t
C_I, t	Cost of Investment for Period, t
C_M, t	Cost of Maintenance for Period, t
c_p	Specific Heat of Water
E_t	Energy Delivered during Period, t
E_{rev}	Maximum Reversible Cell Voltage
F	Faraday's Constant
I_{Cell}	Current Through Cell
I_{solar}	Hourly Solar Irrandiance
M_{H_2}	Molar Mass of Hydrogen
N_{nc}	Number of Cells
P_{FC}	Power of Fuel Cell Stack
Q_{CHP}	Heat Available from CHP unit
r	Dicount Rate
T_{In}	Indoor Ambient Temperature
T_{Op}	Operational Temperature for Fuel Cell
T_{Out}	Outdoor Ambient Temperature
V_{Cell}	Cell Voltage of Fuel Cell

Indices

i	Technology type
t	Time step

Parameters

η_i	Efficiency
E_{bat}^{min}	Minimum energy stored in TES
E_{tes}^{min}	Minimum energy stored in battery
$P_i^{min/max}$	Minimum or maximum power output [kWh/h]
$Q_i^{min/max}$	Minimum or maximum heat output [kWh/h]

Sets

$\mathcal{G}$	All generator units

$\mathcal{H}$ All heating units

$\mathcal{I}$ All technology units

$\mathcal{T}$ Time steps

Variables

$\mathrm{e}_t^{bat/tes}$ Energy stored in battery or TES [kWh/h]

$\mathrm{p}_{i,t}, q_{i,t}$ Power or heat production [kWh/h]

$\mathrm{p}_t^{bat_{dis/ch}}$ Power charged or discharged to/from battery [kWh/h]

p_t^{boiler} Power to electric boiler [kWh/h]

$\mathrm{p}_t^{imp/exp}$ Power imported or exported [kWh/h]

q_t^{dh} Heat imported from DH [kWh/h]

$\mathrm{q}_t^{tes_{dis/ch}}$ Heat charged or discharged to/from TES [kWh/h]

List of Abbreviations

AFC	Alkaline Fuel Cell
ALM	Active Load Management
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicles
BOP	Balance of Plant
CDE	Carbon Dioxide Emissions
CHP	Combined Heat and Power
COP	Coefficient of Power
CCS	Carbon Capture and Strorage
DH	District Heating
DHW	Domestic Hot Water
DMFC	Direct Methanol Fuel Cells
DSO	Distribution System Operator
ESS	Energy Storage Systems
EU	European Union
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicles
FES	Flywheel Energy Storage
GC	Green Certificates
GED	Gravimetric Energy Density
GHG	Greenhouse Gas
GWP	Global Warming Potential
HESS	Hydrogen Energy Storage System
HHV	Higher Heating Value
HP	Heat pump
HT	High-Temperature
ICEV	Internal Combustion Engine Vehicles
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
LNG	Liquid Natural Gas
LP	Linear Programming
LT	Low-Temperature
MCFC	Molten Carbonate Fuel Cells
MEA	Membrane Electrolyte Assembly
MILP	Mixed Integer Linear Programming
MOF	Metal Organic Framework
NB	Net Benefit
NG	Natural Gas
NPC	Net Present Cost
NPV	Net Present Value
OCV	Open-Circuit Voltage
P2G	Power-to-Gas
P2P	Power-to-Power

PAFC	Phosphoric Acid Fuel Cells
PEM	Polymer Electrolyte Membrane
PEMFC	Polymer Electrolyte Membrane Fuel Cells
PHES	Pumped Hydro Energy Storage
PV	Photo Voltaic
R&D	Research and Development
REC	Renewable Energy Certificates
SG	Self-Generation
SOFC	Solide-Oxide Fuel Cells
SMR	Steam Methane Reforming
ST	Solar Thermal
STES	Solar Thermal Energy System
TEr	Thermal-to-Electricity ratio
TES	Therma Energy Storage
UPS	Uninterrupted Power Supply
UV	Ultra Violet
VED	Volumetric Energy Density
VRE	Variable Renewable Energy
WTW	Well-to-Wheel
ZEN	Zero-Emission Neighborhood

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Motivation

The world will have to adapt considerable changes to stay below the 2-degree scenario goal of The Paris Climate Accord. Key among these changes will be the shift away from fossil fuels to more sustainable energy sources. To achieve this, hydrogen is often proposed as a central piece of the solution. Hydrogen is today used in many industrial processes, and can itself be produced by reforming fossil fuels, through gasification of combustibles, or by using electricity with water electrolysis. Hydrogen technologies like polymer electrolyte membrane electrolyzers, waste gasification units and fuel cells are emerging in the market today and could lay the foundation for a hydrogen based economy spanning across multiple market segments and sectors from transportation through industry and energy.

Hydrogen utilized as fuel for fuel cells provide zero-emission electrical power and thus has the potential to help mitigate greenhouse gas emissions from the energy sector. Fuel cells have a relatively high electrical efficiencies and can be combined with both long-term hydrogen storage and local hydrogen production technologies. As such they pose as an effective tool to combine with the emerging sector of variable renewable energy sources like wind turbines and solar PV to form decentralized energy systems. Some fuel cell and electrolyzer types also have rapid dynamic response and modular scalability, making them suitable to both decarbonize local energy production and provide much needed flexibility for the grid operators.

One of the restricting factors for mass implementation of fuel cells are the costs of both investment and operation. By taking advantage of the temperature inherent in fuel cells during operation, some of the economic losses associated with the technology can be negated due to the increase in net energy output per unit of consumed hydrogen. Delivering both heat and electricity could decrease the reliance on standalone heating technologies in the energy system and make fuel cells more profitable. Norway already has a rich history of both producing and utilizing hydrogen in mainly industrial processes for production of ammonia and methanol, and multiple companies specializing in hydrogen technologies have emerged over the last decades. These factors indicates that there could exist a unique opportunity for Norway to combine renewable energy sources with developing hydrogen technologies to decarbonize the energy sector. Few pilot projects, surveys or research papers have been written about the prospect of implementing fuel cell combined heat and power technologies within the Norwegian energy systems, so this is what was attempted during the course of this thesis.

1 Introduction

In this thesis the potential for including fuel cell combined heat and power technologies for buildings in existing or future microgrid systems located in Norway is investigated.

1.1 Problem statement

Despite the large amount of carbon-neutral hydropower produced in Norway, the country has during the last couple of years been a net importer of European electricity. Part of the solution to the problem, and path towards becoming less reliant on the European energy mix might be to include hydrogen technologies along with renewable energy sources within the energy sector.

The investigation into the problem as stated above is accomplished by reviewing the current status of FC and hydrogen technologies, as well as relevant research and projects being performed in Norway and the rest of the world. In addition, an optimization model is developed to investigate the techno-economic potential of such units today and towards 2050.

The model utilizes the programming language Python, using the linear programming tool Pyomo. The objective is to investigate the steady state performance of a microgrid on an hourly basis and assess the economic values related to investment, maintenance and operation of the system. The main system being analyzed is based on the FME ZEN[1] pilot project of Campus Evenstad. This grid-connected microgrid is located at Inland Norway University of Applied Sciences (Høyskolen i Innlandet) in Stor-Elvdal, and note worthily includes a solar PV array, bio-CHP unit, bio-boiler, a Li-ion battery and EV charging station. The site of Campus Evenstad was chosen as a case study for this thesis due to available data from the energy system and the cooperation between NTNU and FME ZEN . By examining the economic impact and performance of a microgrid energy system when including an FC-CHP unit the aim is to quantify the potential for using this technology to provide both heat and electricity to buildings in Norwegian conditions.

[1]Research Center on Zero Emission Neighbourhoods in Smart Cities (Forskningssenter for Miljøvennlig Energi) - https://fmezen.no/

1.2 Scope of work

The thesis consists of three main contributions to the subject at hand. Each of these contributions have their own set of objectives. For simplicity the contributions will be referred as C1, C2 and C3.

C1 - Literature review of hydrogen technology
Present an overview of the current economic and technical status, as well as estimated future developments for hydrogen technologies within Norway and the rest of the world. This is separated into two objectives.

> **O1.1** - Present an overview of the history of hydrogen technologies in Norway, as well as the current status and future estimates for the hydrogen economy
>
> **O1.2** - Present an overview of hydrogen technologies in the energy sector

C2 - Techno-economic analysis of FC-CHP energy systems
Examine the potential for FC-CHP units in a microgrid by developing an optimization model. This is separated into two objectives.

> **O2.1** - Investigate the economic potential for including FC-CHP units in a commercial sized energy system within Norway
>
> **O2.2** - Examine which economic factors influence the profitability of an FC-CHP energy system

C3 - Practical aspects of implementing fuel cells in Norway
Discuss some benefits, challenges and driving forces of implementing FC and FC-CHP units in Norway. This separated into three objectives.

> **O3.1** - Present an overview of geographical considerations for the FC energy system and infrastructure regarding hydrogen delivery
>
> **O3.2** - Discuss which role the FC-CHP units could fill in the energy system
>
> **O3.3** - Present an overview of potential benefits that comes from including FC-CHP units in the energy system

1.3 Approach

By using a theoretical foundation, available data and the Pyomo tool, an Mixed Integer Linear Programming (MILP) optimization model was developed. Throughout the thesis, different configurations of microgrid systems was optimized to analyze how an FC-CHP unit would affect the performance of an energy system.

1.4 Limitations

To evaluate the actual potential for FC-CHP systems, as described in the problem statement, it would be helpful to utilize and incorporate real measured data for both consumption and production of energy at Campus Evenstad. The same holds true for the performance of a real life FC system, and thus achieve a more realistic response.

The economic costs related to the components in the system are similarly gathered from data sheets, technical reports and direct communication with the relevant companies. Due to the relatively rapid rate of change in production costs of emerging technologies, there are however uncertainties associated with most of the economic foundation used in the model. word

1.5 Structure and contents

- **Chapter 1: Introduction**
  This chapter aims to provide context by presenting background information, as well as motivation and scope of the specialization project at hand.
- **Chapter 2: Literature Review**
  This chapter presents a summary of relevant research efforts that are related to the subject of this project. The chapter provides information on existing hydrogen energy systems, additional segments of the hydrogen economy as well as modelling strategies used for modelling FC-CHP systems.
- **Chapter 3: Background Theory**
  This chapter presents theoretical concepts related to FC and CHP systems.
- **Chapter 4: FME ZEN**
  This chapter presents a general description of the work done by the FME ZEN initiative, as well as the case of Campus Evenstad.
- **Chapter 5: Method** This chapter describes the method used to examine the potential for FC-CHP systems in Norway. In short, a description of the proof of concept model, modelling of energy demand for non-residential buildings and simulation strategy is presented.

- **Chapter 6: Results from initial simulations**
  This chapter presents and discusses the relevant results retrieved during the simulations carried through the specialization project. At the end of the chapter a selection of questions regarding the practical aspects of implementing fuel cell combined heat and power in Norway will be posed. These will be answered in Chapter 7.

- **Chapter 7: Answers to research questions**
  This chapter attempts to answer the research questions posed at the end of Chapter 6

- **Chapter 8: Discussion**
  This chapter discusses further the results found during Chapter 6. The limitations of the method and the data used during the thesis will be addressed and debated.

- **Chapter 9: Conclusion**
  This chapter will present a summary of the contributions laid forth during the course of the thesis and end with concluding remarks regarding the significance of the findings. The thesis is rounded off by recommending some measures for further researching the subject of FC-CHP in Norwegian buildings.

2 Literature Review

Chapter 2 presents a summary of related work that has been done in the field of hydrogen fuel cells. The aim is to establish a scientific context for this thesis, by investigating four main categories: hydrogen technologies and their roles in Norway through history, presently and future prospects; hydrogen technologies outside of Norway, and which goals have been set by external companies governmental bodies; economic development analysis of hydrogen technologies; the environmental impacts associated with hydrogen technologies. All cost estimates will be given in the currency presented in the respective source material.

2.1 Energy use in Norway

NVE monitors the energy use within Norway. The latest available data regarding energy use comes from 2019 and puts the total amount at a combined 236 TWh, of which 136 TWh was in the form of electricity [1]. Approximately one third of this energy was used in buildings. Residential buildings used a combined 48 TWh of energy where two thirds were used for space heating. Non-residential buildings used 36 TWh with a combined 50 % being used for heating and cooling purposes.

2.2 Hydrogen in Norway

Norway has a long history of water electrolysis all the way back to Norsk Hydros Vemork facility near Rjukan, utilized for production of hydrogen, ammonia and heavy water from the 1940s. Hydrogen has however mainly been utilized in industry until around the 2000s, where fuel cells gained some interest in the automotive and energy sector. One example is the pilot wind/hydrogen-system installed at the Island of Utsira in 2004 [2], and a laboratory PV/hydrogen-system at IFE Kjeller [3] in 2005.

By the year 2030 DNV[2] estimates that Norway could experience a combined domestic hydrogen demand of approximately 255 ktons per year, 82 % of which will go to industrial processes like ammonia and methanol [4]. This leaves 18 % of the demand for the transport sector, as the potential within the energy sector was not discussed. The report highlights the potential for local production of hydrogen through water electrolysis, particularly for energy intensive purposes like maritime transport, where the production can be connected directly to wind farms.

[2]Det Norske Veritas (formerly DNV GL) - http://dnv.no

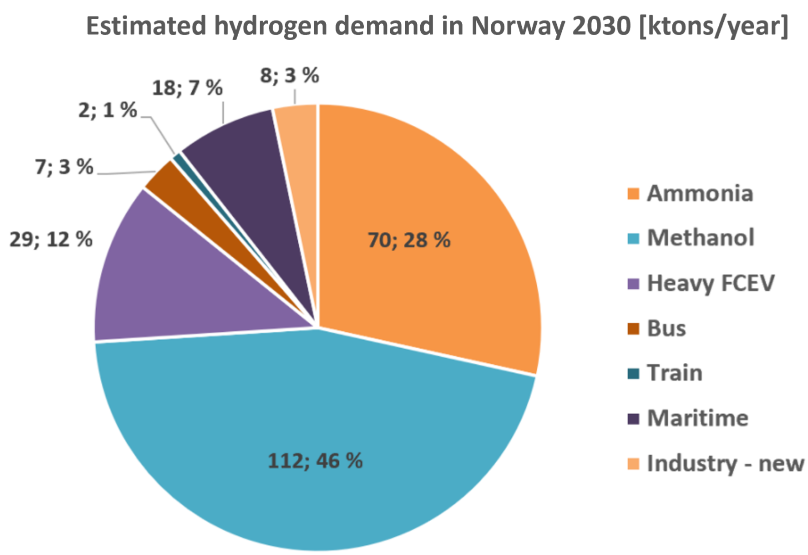


Figure 2.1: Estimated hydrogen demand in Norway by 2030 (Based on Figure 1-2 [4])

Implementing hydrogen technology in the transportation sector alone could contribute to reducing about 1% of the national Carbon Dioxide Emissions (CDE). This highlights one of the added potential benefits of the hydrogen economy, in addition to jobs creation.

2.2.1 Hydrogen strategy

The Norwegian country is in theory well suited for becoming a hydrogen society, having abundant hydro electric power and petroleum for production of hydrogen, as well as being a country reliant on heavy duty transportation like trucks and ferries. In addition, there are multiple industrial pathways for hydrogen including production of ammonia, methanol, or titanium oxide at Equinor, Yara or Eramet facilities respectively, which are all highlighted in a report from 2019, by at that time DNV GL, concerning the potential for hydrogen on the behalf of The Norwegian Government [4]. Hydrogen could also potentially be used as fuel in combustion processes to reduce CDE emissions associated with industry, however this will require a cost reduction for hydrogen or added penalties for Greenhouse Gas (GHG) emissions. These factors highlights both the supply and demand prospects of hydrogen in Norway today.

2.2.2 Hydrogen in the transportation sector

Norway has been at the forefront of the worldwide push towards decarbonizing the transportation sector, in large part due to governmental subsidies for buying Battery Electric Vehicles (BEV)s or Fuel Cell Electric Vehicles (FCEV)s in addition to the right to utilize lanes dedicated to public transportation and free parking. BEVs have however been the by far most popular alternative with more than 300,000 [5] registered vehicles by the year 2020, compared to a mere 160 FCEVs [5]. Although the economic incentives from the government are the same, the lack of hydrogen refueling infrastructure and generally higher costs of operation has lead to the massive discrepancy.

For long distance transport of passengers or freight, one of the main hurdles limiting electrification is the weight of vehicles themselves. Larger vehicles require more power and thus more stored energy to reach their destination, and batteries, while scalable become very heavy with increased storage capacity. Hydrogen on the other hand has a very high gravimetric energy density, and storage of hydrogen only require an additional 0.030 kg/kWh for the fuel, compared to $\approx$5.25 kg/kWh for a Li-ion battery. The fleet of heavy duty vehicles like trucks are thus a focus point for the Norwegian FCEV strategy. The same holds true for both maritime transportation and air traffic as well.

2.2.3 Fuel cell projects in Norway

There have been a few FC related pilot projects in Norway over the previous two decades. Two projects utilizing FCs in micro grid energy systems are the cases of the island of Utsira and Rye Farm at Byneset in Trondheim. The micro grid at Utsira was a Wind/Hydrogen system in operation between 2004 and 2010. It utilized excess power from the Variable Renewable Energy (VRE) sources to produce hydrogen through electrolysis, which could be stored and used when needed. Haugaland Kraft has plans to perform another test project at Utsira during the upcoming years. They were, among other subsidies, given a grant of $\approx$7 MNOK by Enova in 2020. The goal of the second iteration of the microgrid at Utsira is to examine the potential for locally produced energy and storage solutions as an alternative to investing in a new sub-sea cable, as the current one is starting to become obsolete due to its age, and the increased power demand on the island.

The microgrid at Byneset is a PV/Wind/Hydrogen system located at Rye Farm, and it is a part of the European Union (EU) REMOTE project. The goal of REMOTE project is to demonstrate the techno-economic potential for hydrogen storage solutions to provide power to remote or off-grid areas. Rye Farm has a 100 kWe Low-Temperature (LT)-Polymer Electrolyte Membrane Fuel Cells (PEMFC) and a 50 kW electrolyzer. The process of utilizing excess energy to produce a gaseous fuel, like pure hydrogen is known as P2G (Power to gas), and the reverese is known as G2P (Gas to power). The gas can then be stored, so the produced energy can be shifted in time or geographical location in such a P2P (Power to power) system.

Norway has approximately 130 ferry routes and are currently working on multiple projects to substitute old diesel driven ferries with modern alternatives that are hydrogen driven. The route between Hjelmeland and Nesvik in Rogaland, and the route across Vestfjorden in Lofoten are both set to incorporate FC ferries by the end of 2021, becoming the first commercial hydrogen ferries in the world. The ferry MF Hydra in Hjemlandssambandet is equipped with two 200 kWe FC stacks from Ballard, along with a 1,360 kWh battery storage to power an electrical motor [6]. The ship also has a diesel motor as a backup system. It was decided by Norled, the shipping company in charge of the project to utilize cryogenically liquefied hydrogen for the ship. This is mainly due to the increased volumetric energy density compared to compresssed hydrogen, allowing for longer distances and longer durations between filling sessions. This liquefied hydrogen will be imported from Germany through vehicle transport and will be provided by the company Linde Gas, who are also responsible for providing the hydrogen storage solution on-board the ship. Linde Gas is one of the worlds largest providers of green hydrogen production. The Norwegian companies Westcon Yards and LMG Marin were also central in realising the ferry project, which is scheduled to be in operation during the summer of 2021.

Cruise lines like Havila are also looking into retrofitting some of their cruise ships with hydrogen systems [7], to mitigate the GHG emissions from the recreational maritime transportation sector. Some of their giant cruise ships are scheduled to install a 3.2 MW FC system along with battery storage for additional flexibility. The FC stack will be a PEM unit, and provided by PowerCell Sweden.

2.2.4 Hydrogen infrastructure

There are three common means of delivering hydrogen at the desired location: vehicle transportation, gas pipelines and on-site production. The costs associated with each of these alternatives will vary on a case by case basis, dependant on which storage solution is used for the hydrogen, the transported distance and the quantity of hydrogen delivered to the destination. Over longer distances and in smaller quantities vehicle transportation, either liquefied in tankers or compressed in tube trailers is a suitable alternative at a cost of ≈1.50 USD/kg for quantities of 500 kg/day [8]. In larger quantities, pipeline transportation could be a more viable solution at ≈1.00 USD/kg, although the transportation cost for hydrogen through pipelines increase more rapidly with the distance travelled.

2.3 Hydrogen outside of Norway

Although Norway was a pioneer in the early days of hydrogen technology utilization, fuel cells have never been prioritized in any section of the Norwegian economy. On the other hand, most of the G7 countries have during the last decade developed strategies for implementing fuel cells in both the energy and transportation sectors. This section will look at which goals and upcoming or current projects the EU, USA and Japanese governments have with regards to FC technology in the energy sector. Projects focusing on cogeneration solutions will be highlighted.

2.3.1 Existing fuel cell projects

In this subsection a few existing FC projects in the energy sector will be presented. These come in a variety of sizes from smaller micro CHP (μCHP) units, most often used for smaller residential single family buildings to medium and large scale commercial and industrial units providing more than 1 MWe. The size classifications for FC systems are as follows:

- Micro CHP (residential): $<$ 5 kWe
- Medium CHP (commercial): 5 kWe $-$ 400 kWe
- Large CHP (industrial): $>$ 400 kWe

Some existing projects are shown in Table 2.1.

Japans Ene-Farm project, as seen in Table 2.1 has allowed for a massive push towards implementing FC-CHP in their residential segment. Notable achievements include a 300’000 installed units by 2019 [19] and a cumulative power of more than 35 MW [20]. Figure 2.2 shows the growth in in the number of installed residential FC-CHP units in Japan from 2009 to 2014.

Table 2.1: Examples of existing fuel cell systems [Based on Tab. 2.1 [9]].

Company	FC Type	Rating	Summary
Panasonic	PEMFC	1kWe	Part of Japans residential FC-CHP program ENE-farm. Market ready [10]
SOFT-PACK	SOFC	1-2 kWe	Primary power and hot water supply. Early-market solution [11]
Plug Power	PEMFC	5 kWe	μCHP for residential buildings. Field test stage [12]
Nestack	PEMFC	100 kWe	Commercially available PEM-CHP units from 100-1000 kWe [13]
Toshiba	PEMFC	100 kWe	PEM-CHP test system in Shunan, Japan [14]
Ballard	PEMFC	100 kWe	Stationary ESS for backup power. Test system for the REMOTE Project at Rye Location in Trondheim [15]
Bloom Energy	SOFC	200 kWe	Stationary backup power solutions for commercial use [16]
UTC Fuel Cells	PAFC	200 kWe	Primary power and CHP of public area in Working Park [17]
Fuel Cell Energy	MCFC	250 kWe	Test system with 1500h of use during test period. Emphasises the added efficiency-benefits of potentially introducing heat recovery to the system [18]

2.3.2 Future FC CHP prospects

As a part of the EU Horizon 2020 initiative, there are a handful of projects specifically aimed towards furthering the fuel cell technologies. PACE, AUTO-RE, SO-FREE, EMPOWER, GREEN HYSLAND are some of the projects that specifically investigates the potential of using both electricity and heat[3]. In the latest Hydrogen Roadmap for Europe, it is estimated that at least 7 % of heat demand in buildings

[3]Information about fuel cell projects related to the EU initiative Horizon 2020 can be found on the web-page of Fuel Cell And hydrogen Joint Undertaking (FCH) - https://www.fch.europa.eu/page/energy

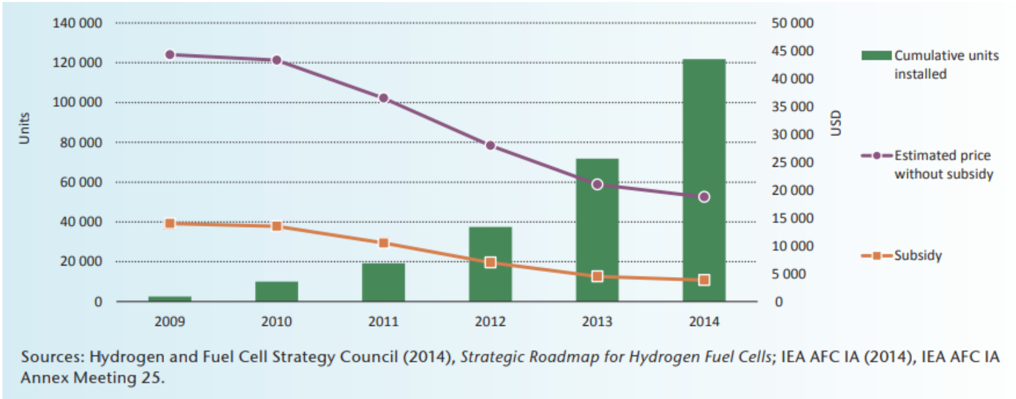


Figure 2.2: Installed residential FC-CHP units under the Japanese Ene-Farm program from year 2009 until 2014 with learning curves with and without subsidies provided by the Japanese government [21].

could be covered μFC-CHP solutions [22].

In an effort to stimulate the manufacturing of residential μFC-CHP both Germany and UK have made policies providing subsidies for potential buyers. Germany provides public investment grants [23] while The UK provided feed-in tariffs for residential energy generation, including μFC-CHP, although the initial run of the program ended in 2019 [24].

Japan has over the next decade set even more ambitious goals, aiming at 5.3 million installed μFC-CHP units by the end of 2030 [25]. Similarly, South Korea has set goals of installing 2.1 GW of cumulative power in domestic μFC-CHP systems, or approximately 2.5 million units, as well as 15 GW of stationary power production from standalone FC power plants [26].

2.4 Economic development of hydrogen technology

The economic development of fuel cell technology is in large part driven forward by the transportation sector. Much of the Research and Development (R&D), particularly on PEM, is done to improve the drivetrains for FCEV. Optimistic prognosis from Deloitte expect that cost of an FCEV bus per 100,000 km could drop below the cost of a similar Internal Combustion Engine Vehicles (ICEV) alternative by the year 2026 and BEV by 2027 [27]. Figure 2.3 shows a graph presented in the report, depicting the price estimates for a ICEV, BEV and FCEV bus.

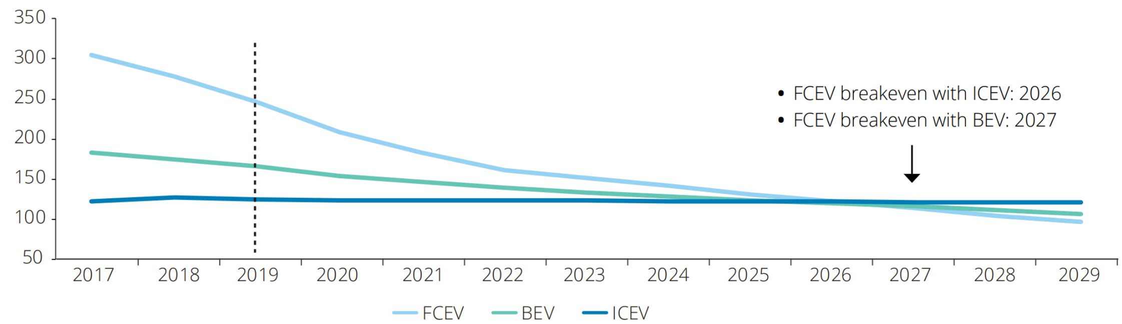


Figure 2.3: Estimate for cost reduction in total cost of operation [USD per 100 km] for BEV, FCEV and ICEV buses in the US over the coming years. The breakeven point for FCEV depends on the continued reduction of hydrogen and manufacturing costs of the FC system (Figure 27 from [27]).

Regarding FC-CHP it has been stipulated that the cost of a system will have to be lower than 1500 US$/kWe to be financially viable [28]. The profitability of such a system will depend on factors ranging from energy profile of the building, base load demand and cost ratio of electricity to fuel utilized in the fuel cell module[29].

2.4.1 Hydrogen economy

The economic feasibility of hydrogen technologies is dependent on the development of a 'Hydrogen Economy'. Some studies have been performed to find economically and environmentally friendly solutions for hydrogen production, like using excess power from offshore wind [30, 31] and wave energy [32]. The results from these studies indicate that the demand for clean hydrogen would have to increase, and the cost electrolyzer technology would have to decrease for these solutions to be profitable. Many countries have over the last five years commissioned consultant firms to create 'Hydrogen Roadmaps', and the key findings from these will be presented in the following paragraph.

The US DOE[4] expects that the export of hydrogen and hydrogen related technology could amount to an additional 30,000 MUSD of revenue each year by 2050 [33]. Meanwhile EU estimates a net export profit of EUR 50,000 MUSD by 2030, as well as an annual 2250 TWh of hydrogen production by 2050 [22]. There are pathways

[4] United States of America Department of Energy - http://energy.gov

to make hydrogen technology viable, but it will require further investment in R&D and infrastructure.

2.4.2 Cost of water electrolyzers and hydrogen production

As the demand for clean hydrogen increases, the manufacturing costs of electrolyzers will decrease. NREL[5] estimates that the cost of PEM electrolyzers could reach values as low as 1000 USD/kW by 2030 and 550 USD/kW by 2050 for MW-scale electrolyzers [34]. This is similar to an analysis performed by IRENA[6], estimating a cost of 307 USD/kW by 2050, culminating in a price for green hydrogen at between 1-3 USD/kgH2[35]. DNV estimates a cost of hydrogen using PEM electrolysis at 25-52 NOK/kgH2 by the year 2030 for a 100 MW electrolyzer [4]. The test site study at Utsira concluded that a more dynamic and efficient electrolyzers are necessary to make micro-electrolysis systems feasible [2]. Reducing the cost of PEM electrolyzers, that are more flexible than alkaline alternatives will thus be an important factor in making self sustained micro grids profitable, allowing for increased power utilization from VRE.

Hydrogen from water electrolysis is often referred to as green hydrogen as it has zero direct emissions at the point of production due to the lack of fossil fuels included in the process. Countries like USA, Australia and even Chile have set goals of achieving lower costs for green hydrogen within the next decades. Australia inoitiated the 'H2 under 2' program in 2020 aiming at less than 2 AUD/kgH2, Japan aims at 3.3 USD/kg, while Chile wants to achieve 1.5 USD/kgH2 by the year 2030 [35]. By kick-starting the push towards green hydrogen it is expected that the cost of production could drop below 1 USD/kgH2 by the year 2050.

2.5 Environmental impact of FC and CHP technologies

Motivated by the rising oil prices through the 1970s [36], and the increasing focus on the harmful effects of GHG during the 1980s, CHP systems gained attention due to their high efficiencies, high degree of fuel utilization and low levels of GHG emissions [37]. In addition, the technology allows for decentralization of energy production, which in turn reduces potential transmission losses. All the above mentioned benefits could have net a positive effect on the Global Warming Potential (GWP) of energy production. It is estimated that CHP solutions reduce CDE by as much as 30 %, compared to producing electricity and heat separately [38],

[5] National Renewable Energy Lab - http://nrel.gov
[6] International Renewable Energy Agency - http://irena.org

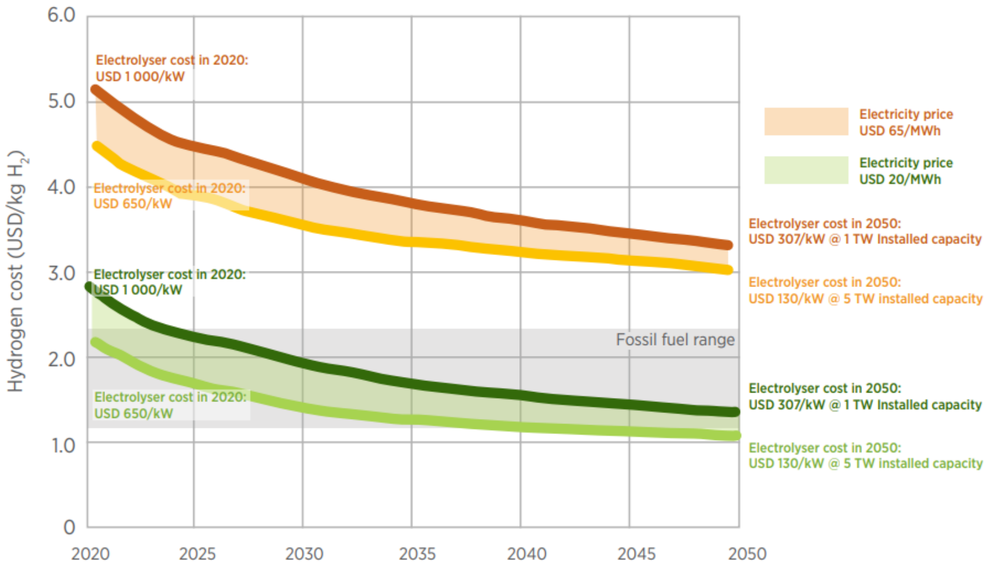


Figure 2.4: Estimated future cost of green hydrogen, dependent on the cost of electricity and installed capacity (Figure ES2 from [35]).

and could contribute to a reduction in CDE of more than 10 % from new energy generation in 2030 [37].

Even if Natural Gas (NG) is used as a fuel, FCs will reduce the emissions of CO_2 and NO_x in comparison with burning the same amount of fuel in a combustion plant [39]. It has been estimated that an FCs could emit 49 % less CO_2, 91 % less NO_x, and up to 93 % less harmful volatile organic compounds than fossil based alternatives[40]. Cogeneration processes are however not exclusive to FCs, and CHP in particular can come from any power plant based on combustion of fuels. Coal and natural gas CHP-plants have been around since the 1970s, but biomass based technologies are gaining more attention, as a more climate neutral alternative to fossil fuels. Today, Norway gets $\approx$ 7% of it's energy from biomass [41], where a tiny fragment of this comes from Bio-CHP.

3 Background Theory

Chapter 3 presents relevant background theory concerning hydrogen, fuel cells, Photo Voltaic (PV) and other aspects of energy systems to give the reader a better foundation for interpreting the results of this thesis. This chapter is in large based on the chapter outlining the theory from the writer's specialization project thesis of 2020, which also focused on the potential for FC CHP solutions in Norway [9].

3.1 Hydrogen

Hydrogen can be used as an energy source for fuel cells. Although it is the most abundant element in the universe, it does not appear in its pure form on earth. This means that hydrogen will have to be produced and stored in order to be made useful.

3.1.1 Hydrogen production

The two most common ways of producing hydrogen are water electrolysis and steam reformation. Steam reforming accounts for ≈95 % of the hydrogen produced worldwide today. Steam Methane Reforming (SMR) is the most popular, and can in simplicity be described by equation 3.1.1. SMR will in other words be made from fossil-based petroleum products, and have carbon emissions associated with the production.

$$CH_4(g) + H_2(g) \longrightarrow 4\,H_2(g) + CO_2(g)$$

Water electrolysis is a clean alternative to SMR, separating hydrogen and oxygen within water molecules through an electrolytic cell. There are different configurations of electrolysis equipment, but they generally consist an Membrane Electrolyte Assembly (MEA) containing two electrodes (anode and cathode) and an electrolyte. Today, water electrolysis amounts to ≈5 % of the worlds hydrogen production.

A standard classification used to categorize hydrogen is the color coding shown in Figure 3.1. Water electrolysis using environmentally friendly energy sources is hence known as *green hydrogen*, as this is the least carbon intensive alternative. Hydrogen from fossil based products can be either *grey* if only steam reforming is utilized, *blue* if the subsequent carbon is captured in the process, or in some cases, *brown* when it is produced from gasification of coal.

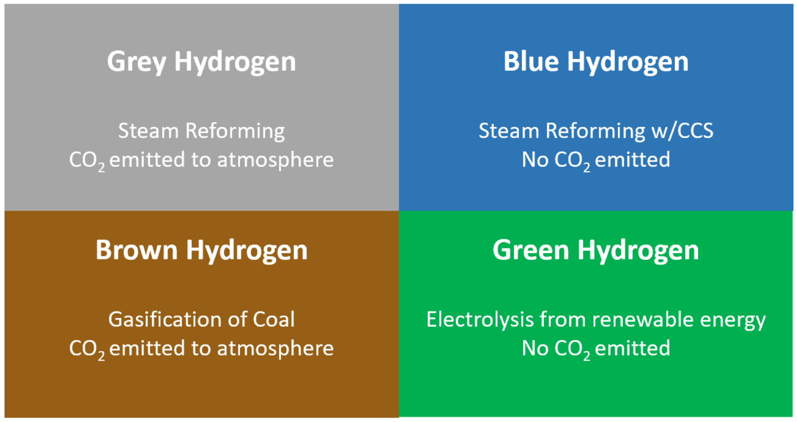


Figure 3.1: Color classification for hydrogen.

3.1.2 Hydrogen storage

Hydrogen has a high Gravimetric Energy Density (GED) of 33 kWh/kg Lower Heating Value (LHV), but in its natural form on earth it has a low Volumetric Energy Density (VED). Table 3.1 show the energy content of some common energy carriers and fuels, illustrating the high potential for hydrogen given the right circumstances. To make hydrogen technologies a viable option, the hydrogen will have to be stored under correct conditions. There are many alternatives, each with their own pros and cons.

Table 3.1: Energy density for common energy carriers/fuels [42].

Energy Carrier	**Gravimetric Density** [kWh/kg] LHV	**Volumetric Density** [kWh/m^3] LHV
Hydrogen (1 bar)	33	0.0027
Hydrogen (700 bar)	33	1.6
Hydrogen (liquid)	33	2
Liquid Natural Gas	13.9	6.1
Gasoline	13	9
Diesel	13	10
Jet-A Fuel	13	10
Li-ion Battery (LCO)	0.19	0.56

Compressed and liquid hydrogen are two of the most mature storage methods for hydrogen. When the hydrogen is compressed the volume is significantly decreased, so this is particularly desirable for transport applications. A common pressure level used in automotive FCEV is 70 bar, allowing the VED to multiply by a factor of abut 600 compared to ambient pressure, in addition to making refueling faster. By cooling hydrogen to 20-33 K it is cryogenically liquefied, increasing the VED even further than plainly compressed hydrogen.

Metal hydrides and Metal Organic Framework (MOF) are two less mature means of storing hydrogen. Both of these utilize adsorption of hydrogen ions, H^{-}, to store hydrogen in metallic structures. Metal hydrides stores dissolved hydrogen on the surface, while MOF are porous compositions that stores hydrogen in geometric crystalline structures at a molecular level. The advantages of both these technologies is that they both store and release hydrogen at ambient temperatures, requiring less energy. Adsorption is an exothermic reaction, meaning that hydrogen is stored until heat is reapplied, in addition to the process being fairly slow making it less suitable for non-stationary applications. More RD is needed for the techniques to become viable alternatives to hydrocarbons, and compressed or liquefied hydrogen.

On a molar level, hydrogen makes up the majority of all hydrocarbons, indicating that they are a good source for hydrogen. NG is a mix of multiple types of hydrocarbons but consists of $\approx 75-95\%$ methane (CH_4). The gas is liquefied (LNG) at $\approx$111 K, making it less energy intensive than liquefying pure hydrogen. Liquid hydrocarbons are hence suitable for long distance transportation, storage, and is also by far the most affordable means of storing hydrogen. The price of pure hydrogen from a refueling station is approximately 90 NOK/kgH2 [43] compared to 12 NOK/kgH2, effectively reducing the cost by 88 % per unit of mass. The major hurdle while using hydrocarbons as a fuel with FC is the fact that there will be carbon emissions associated with the process. Whether the hydrocarbons are reformed to hydrogen internally or externally, both CO and CO_2 will be produced during the process, though it is worth noting that emissions of SO and NO_x are considerably less than burning the same amount of hydrocarbons in a thermal plant. Some FC are more suitable for hydrocarbons than others.

3.1.3 Hydrogen transportation

The mode of transportation chosen for the hydrogen fuel will be dependent on the chosen storage method.

3.2 Hydrogen fuel cells

Fuel cells allow hydrogen to operate as an energy source within a galvanic cell. They utilize the same principles as electrolyzers yet the the current travel in the opposite direction, allowing them to transform hydrogen into energy with water vapor as the only exhaust. Some of the main advantages of using fuel cells as a source of power is efficiency compared to other fuel based generators, and simplicity of the system due to the lack of moving parts. Both these factors allows FCs to be considered both reliable and long-lasting. In addition they are quiet and have reduced emission intensities during operation.

Many different variants of fuel cells have been developed, each having their own sets of advantages and disadvantages. Some of the most notable fuel cell technologies will be presented in this section.

3.2.1 Polymer electrolyte membrane fuel cells

PEMFC works using the same proton exchange principle as the PEM electrolysis. A working principle for this fuel cell is presented in Figure 3.2. It is the most common fuel cell used in micro CHP systems, due to its maturity and ability to work at both low and high temperatures. Another argument for utilizing PEMFC is the scalability of the stack, allowing for customized power output to meet specified demands.

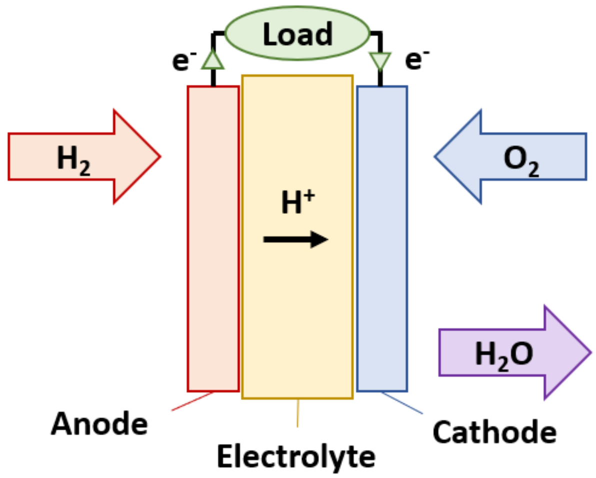


Figure 3.2: Simple schematic of Polymer Electrolyte Membrane Fuel Cell.

PEMFC can operate at both low and high temperatures depending mainly on the composition of the polymer membrane, which makes them flexible, particularly when it comes to start-up time. The solid electrolyte eliminates liquid components within the cell, allowing the cells to operate efficiently in every orientation. PEMFC are also very flexible when it comes to varying power output, as well as being more compact than the other alternatives.

3.2.2 Solid oxide fuel cells

Solide-Oxide Fuel Cells (SOFC) use solid oxides as electrolytes. Due to their construction, they operate at very high temperatures of 600-900 $^{\circ}C$. Reformation of Liquid Natural Gas (LNG) to pure hydrogen is an endothermic process and the high temperatures ensures that this process can happen either internally or externally, making use of the excess heat from the FC process. This allows SOFC to consume most any form of LNG directly as a fuel, in addition to pure hydrogen. The high temperature also makes the SOFC a good choice for CHP systems, providing high quality heat. It is a less developed technology than its PEM counterpart, but is being used in some test and commercial FC systems that require more output of both power and heat. Investment costs are generally lower for SOFC compared to the other common fuel cell types. One of the largest drawbacks to utilizing

SOFC are their slow start-up time and slow response in output power, making them less suitable for stationary solutions where dynamic response is crucial, like for instance backup energy systems or peak shaving.

3.2.3 Alternative fuel cells

Many other forms of FC have been proposed and developed over the years and some notable ones are Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cells (MCFC), Phosphoric Acid Fuel Cells (PAFC) and Direct Methanol Fuel Cells (DMFC). AFC were some of the earliest examples of fuel cells, being historically used by NASA during their luanr missions of the 1960s. They operate at LT, are cheap to manufacture, and are the most efficient fuel cells described in this section. The main disadvantage of AFC is the fact that they use a liquid electrolyte, however there have been advancements indicating that solid-state alkaline alternatives could make them more suitable for commercial applications in the future. MCFC and PAFC are High-Temperature (HT) alternatives operating at 500-800 $°C$ and 150-200 $°C$ respectively. MCFC are able to reform hydrocarbons internally like the SOFC, while PAFC require pure hydrogen or an external reformer. They have both been used in pilot projects for large-scale sub-megawatt power plants with varying degrees of success. DMFC are variants of PEMFC that are able to utilize the hydrocarbon, methanol directly as a fuel, operating at temperatures of 50-120 $°C$. They experience lower efficiencies than conventional hydrogen-based PEMFC, the lowest of all FC technologies mentioned at ≈30 %, and are hence not a fully realizable alternative as of this paper being written. Table 3.2 shows key parameters for the different FC technologies discussed in this chapter.

Table 3.2: Types of fuel cells with key parameters.

Technology	**Power [kWe]**	**T$_{op}$[^{o}C]**	$\eta_{\mathbf{volt}}[\%]$	**Require Reformer**
AFC	10-200	0-80	60-70	Yes
DMFC	≤ 1	90-120	20-30	No
PEMFC	≤ 500	-20-200	35-60	Yes
SOFC	≤ 100	500-1100	60-65	No
MCFC	$\leq 10{,}000$	600-650	65	No
PAFC	100-200	150-200	40	Yes

3.3 Fuel cell systems

Like conventional power generators FCs require a number of control, regulating and processing components to operate as desired. These components are needed to ensure proper distribution and handling of heat, fuel, oxygen, etc. and are commonly referred to as Balance of Plant (BOP). A fuel cell system consists of:

- *Fuel cell stack*
- *Fuel processor*
- *Power management*
- *Thermal management*
- *Air management*
- *Water management*

Figure 3.3 shows a simplified schematic of a fuel cell system with the needed BOP components. A PEMFC stack is a number of fuel cells connected in series, and includes the MEA together with a flow field channels allowing for transport of reactant gases and exhaust as well as a gas diffusion layer for transport of reactants to the catalyst layer. Connecting cells in series provide increased voltage, and thus increased power output, approximately proportional to the number of cells in the stack. To increase the power output further, multiple stacks can be connected in series as well. This allows for a high degree of scalability for FC systems. Fuel processors are needed to ensure that the stack receives the appropriate amount of fuel for the given operational point. Whenever hydrocarbons are used as a fuel, this will also have to be reformed before it can be converted to electricity in the MEA. This reformation can be both internal and external. The power output of the stack will also have to be managed by converting DC to AC and ensuring proper voltage levels through power electronic converters and transformers respectively.

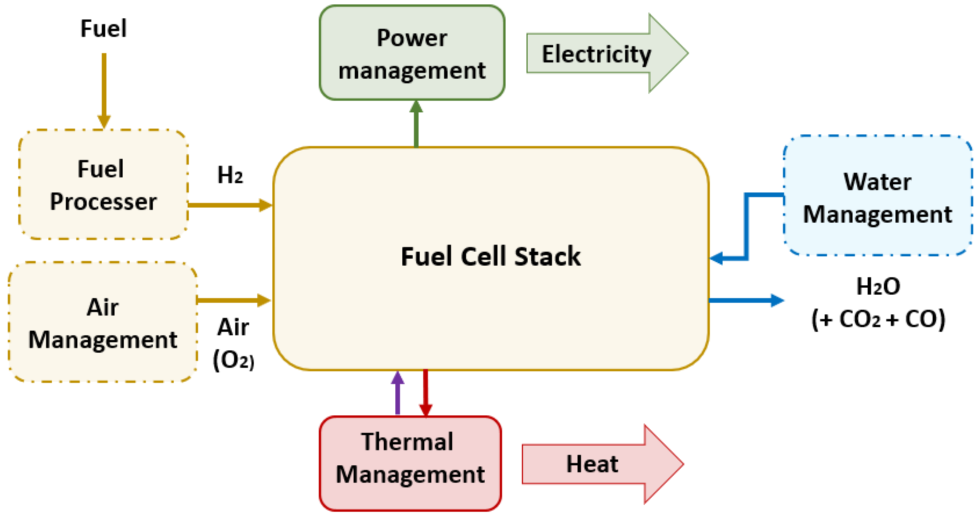


Figure 3.3: Fuel cell system including balance of plant (BOP) needed for correct operation.

Air and water management is mainly needed to allow for sufficient inlet of air, and outlet of water for the FC stack during operation. Some components in the stack does however require water or humid air to function properly, so water management also provides humidification for these components. One such component is the polymer electrolyte of low temperature PEM fuel cells, which require water to initiate the current. Thermal management has as its main purpose to ensure correct operational temperature for the fuel cell system. This includes heating the system at start-up and cooling the system during operation, in addition to managing heat recovery for processes that increase efficiency. Excess heat can for instance be redirected to the fuel processor, which require high temperatures to operate, or indeed used to cover an external heating load. Additional pumps and compressors are also essential to ensure correct pressure levels for fuel, air and MEA.

3.3.1 Control of fuel cells

There are many parameters that alter the operating point of a FC. One obvious factor is the air stochiometry, as oxygen is one of the central reactants. All fuel cells require an inlet for air or oxygen to enter the MEA, and the larger the fraction of oxygen is within the inlet air, the faster and more efficiently the fuel cell reaction will be. Other factors include operating temperature, partial pressure of reactants at anode and cathode side, as well as humidification.

3.3.2 Efficiency and losses

The electric efficiency, η_{volt}, or voltage efficiency of fuel cells is described by the relationship between maximum potential energy and the actual voltage of the cell as described by equation 3.1. For consistency the cell potential will be referred to as the cell voltage in this report, with the exception of the Nernst potential, E_{rev}

$$\eta_{volt} = \frac{V_{cell}}{E_{rev}} \tag{3.1}$$

E_{rev} is the theoretical reversible or maximum cell potential which is given by 3.2.

$$E_{rev} = -\frac{\Delta G}{nF} \tag{3.2}$$

F is the Faraday constant, $F = 96486C$ and n the number of transferred electrons. Assuming constant operating temperature and pressure, equation 3.3 gives a simplified expression the thermodynamic efficiency, η_{th}.

$$\eta_{th} = \frac{\Delta G}{\Delta H} = \frac{\Delta H - T\Delta S}{\Delta H} = 1 - T\frac{\Delta S}{\Delta H} = \frac{E_{rev}}{-\Delta H^{(HHV/LHV)}} \tag{3.3}$$

ΔG is the Gibbs free energy, ΔH and ΔS are the changes in enthalpy and entropy respectively, while T is the operating temperature. Multiplying 3.1 and 3.3 with the fraction of inlet hydrogen consumed by the cell, μ_f gives the fuel cell or electrocehmical efficiency, η_{FC}. This is reflected in equation 3.4.

$$\eta_{FC} = \mu_f \cdot \eta_{volt} \cdot \eta_{th} = \mu_f \cdot \frac{E_{rev}}{-\Delta H^{(HHV/LHV)}} \frac{V_{cell}}{E_{rev}} \tag{3.4}$$

$$\tag{3.5}$$

By inserting values for Higher Heating Value (HHV) or LHV of hydrogen, the following equations for total efficiency of a fuel cell is derived:

$$\eta_{FC}^{HHV} = \mu_f \cdot \frac{V_{cell}}{1.48} \tag{3.6}$$
$$\eta_{FC}^{LHV} = \mu_f \cdot \frac{V_{cell}}{1.25} \tag{3.7}$$

In the case where pure hydrogen is used, the unutilized fuel could be recirculated into the fuel stack, and thus $\mu_{fu} \approx 1$ allows this fraction to be neglected. The power output of a fuel cell stack is dependent on the cell voltage, V_{cell}, current, I_{cell}, and the number of cells connected in series, N_{nc}.

$$P_{FC} = N_{nc} \cdot V_{cell} I_{cell} \tag{3.8}$$

Irreversible losses within a fuel cell are generally parted into four main categories: Ohmic losses, activation overvoltage losses, concentration overvoltage losses, and hydrogen cross-over losses. Concentration overvoltages are sometimes called transportation voltage losses and are caused by an insufficient fraction of one of the reacts, either hydrogen or oxygen. Activation overvoltages relate to reactions at the interfaces between electrodes, whereas ohmic losses are caused by the internal resistances within the different components. Figure 3.4 shows a generic polarization curve for a cell, with the current levels where the different losses occur are indicated.

The cell voltage can thus be described by the simplified equation 3.11 [45].

$$V_{cell} = V_{rev} - V_{loss} \tag{3.9}$$
$$V_{cell} = V_{rev} - (\Delta V_{act} + \Delta V_{conc})_a + (\Delta V_{act} + \Delta V_{conc})_c + \Delta V_{ohm} \tag{3.10}$$
$$V_{cell} = V_{rev} - a \cdot log(\frac{i + i_{loss}}{i_0}) - b \cdot log(\frac{i_L}{i_L - i}) - R_i \cdot i \tag{3.11}$$

3.3.3 Fuel utilization

Computing the hydrogen utilized during operation can be done easily, given that the output power, P_{FC} and the concurrent cell voltage, V_c as in Equation (3.13)[46]. $\dot{n}_{H2}$ is the hydrogen usage in [moles s^{-1}], while $\dot{m}_{H2}$ is [kg s^{-1}].

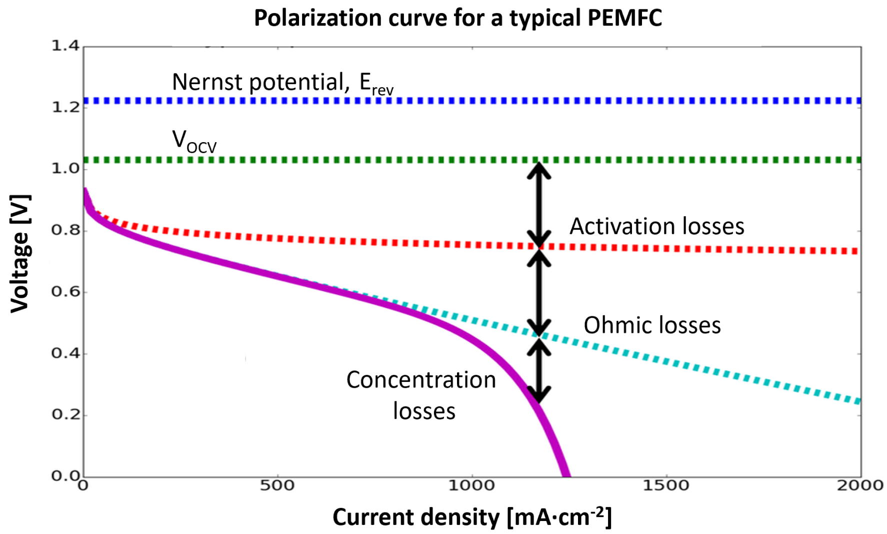


Figure 3.4: Sketch of a polarization curve, indicating cell voltage of as a function of the current density. The activation losses, ohmic losses and concentration losses are indicated (Based by Fig. 1 [44]).

$$\dot{n}_{H2} = \frac{I \cdot n}{2F} = \frac{P_{FC}}{2F \cdot V_c} \tag{3.12}$$

$$\dot{m}_{H2} = M_{H2} \cdot \frac{P_{FC}}{2F \cdot V_c} = 2.02 \cdot 10^{-3} \cdot \frac{P_{FC}}{2F \cdot V_c} = 1.05 \cdot 10^{-8} \cdot \frac{P_{FC}}{V_c} \tag{3.13}$$

Here, M_{H2} is the molar mass of hydrogen molecules, while, F is Faraday's constant.

3.3.4 Durability of PEMFC

The ability of an FC to operate at rated power and efficiency is referred to as durability. Degradation within the MEA is related to loss of Open-Circuit Voltage (OCV) and conincidingly loss of power output, which leads to poorer performance from the FC stack. The degradation is in large part caused by platinum and carbon corrosion, as well as CO poisoning for LT-FCs. A common feature of the degradation mechanisms is that they reduce the active area for the Pt-catalyst at the cathode side, and thus decrease the electrochemical potential driving the current through the circuit.

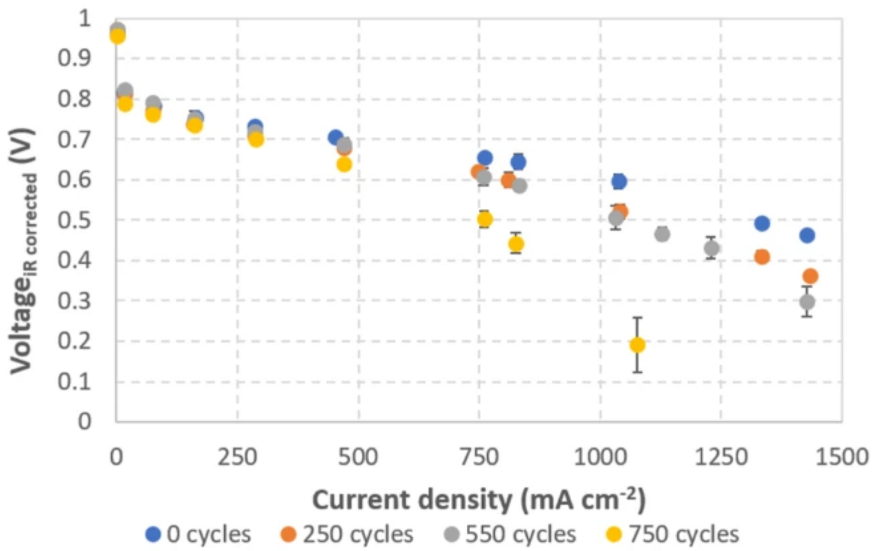


Figure 3.5: Cycle degradation of PEMFC for 0, 250, 550 and 750 start/stop-cycles (Figure 7 a) [48]).

Degradation occurs at a much faster rate when the cell is being operated, as well as during start/stop-cycles [47]. The cycle-degradation during start/stop-processes have been verified using accelerated stress test, where multiple start/stop-cycles are performed while conditions are kept constant. At set intervals during the test, the polarization curves were measured, and Figure 3.5 shows an example of cycle degradation for a PEM-FC during a such stress test.

Depending on the operating conditions for the FC stack, i.e. relative humidity level, operating temperature, etc. the apparent durability losses during start/stop-cycles are in the range of 0.1-0.3 mV/cycle [47]. Similar to conventional generators, the correlation between operating hours of the FC and reduction i OCV leads to most manufacturers and researchers referring to lifetime of FCs in hours rather than years. It is useful to distinguish between the economic lifetime and operating lifetime of these units, where the latter defines the hours of operation at an acceptable level of performance and the prior relates to economic analysis.

3.3.5 Efficiency of cogeneration systems

Cogeneration is a term describing a process providing two forms of energy simultaneously. The most common form of cogeneration is CHP. When evaluating both the efficiency of an FC or a CHP system, it is important to emphasize which metrics the efficiency is based on.

Heat is produced in a FC during operation. Equation 3.7 gives the efficiency for the FC in question, but equation 3.14 gives the efficiency of an CHP system is given by equation 3.14.

$$\eta_{CHP} = \eta_{volt} + \eta_{th} \tag{3.14}$$

In other words, both the electricity produced and excess heat supplied by the system are considered useful energy fractions. CHP efficiency can be based on the energy of the fuel input to the system as shown in equation 3.16. The generated heat within the FC will either exit the fuel cell through the reactant gases leaving the cell, $Q_{react,in}$ and $Q_{react,out}$, dissipate to the surroundings via convection through body surface of the stack, Q_{dis}, or be passed on to the fluid within the cooling circuit of the stack, Q_{cool} [45].

$$Q_{FC} + Q_{react,in} = Q_{dis} + Q_{react,out} + Q_{cool} \tag{3.15}$$

It is the latter of these fractions, Q_{cool} that can be used in the cogeneration process [49]. The dissipated heat usually only accounts for a few percent of the generated heat, and assuming an ideally isolated FC system, this can be neglected. The fraction of heat used for evaporation of water within the fuel cell can be equated to the difference between HHV and LHV [50]. This means that by combining 3.7 and 3.17, the useful heat for CHP purposes can be represented as in equation 3.18.

$$\eta_{CHP} = \frac{P_{FC} + Q_{CHP}}{\dot{m}_{fuel} \cdot LHV_{fuel}} \tag{3.16}$$

The useful heat produced during operation of the FC, Q_{CHP}, is caused by irreversiblities within the cell, and is given as in equation 3.17.

$$Q_{CHP} = P_{FC}(\frac{1}{\eta_{FC}} - 1) \tag{3.17}$$

Q_{CHP} will be equal to the cooling heat, so by inserting values in equation 3.17 the useful heat from an FC referred to LHV is given in equation 3.18.

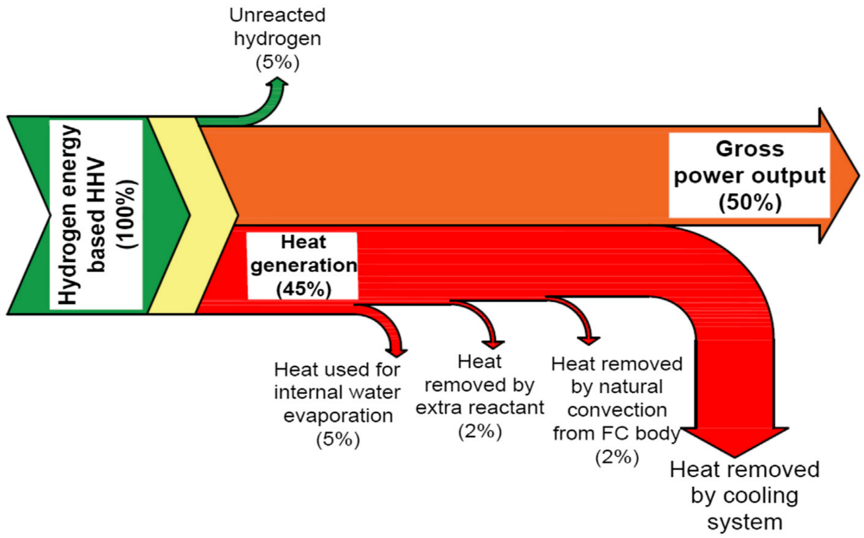


Figure 3.6: Sankey Diagram illustrating pathways for the energy within a fuel cell system [50].

$$Q_{CHP} = Q_{cool} = P_{FC}\big(\frac{1}{\eta_{FC,LHV}} - 1\big) = P_{FC}\big(\frac{1.25}{V_{cell}} - 1\big) = N_{nc} \cdot I_{cell} \cdot (1.25 - V_{cell}) \quad (3.18)$$

Figure 3.6 shows a Sankey diagram, illustrating the pathways for energy input of a fuel cell.

Air cooling is most often used in FC stacks with ≤ 2 kWe of output power. Above this threshold, liquid cooling systems are used, with for instance water as cooling fluid [51]. Liquid cooling is beneficial when incorporating heat production from FCs, as they allow for lower thermal losses in the transport of the heat to the desired area.

3.4 Energy storage solutions

This section will take a look at potential Energy Storage Systems (ESS), compare their advantages and disadvantages, as well as uses for them separately and in a hybrid system.

3.4.1 Hydrogen for ESS

Hydrogen technologies can, as previously mentioned, be used as an ESS by combining hydrogen production, storage, fuel cells and power electronic components. Many have investigated the possibility of using excess power from VRE to produce green hydrogen with a low life cycle impact [31, 52, 53, 54, 55]. To get a better understanding of what the advantages or disadvantage of such a system will be, it will have to be compared to other ESS solutions like batteries and flywheels.

Assuming a continuous supply of hydrogen fuel, a fuel cell system could work as a distributed generator within a energy system, potentially replacing other fuel driven power providers. Replacing diesel or other petroleum based generators in remote locations, disconnected from common supply chains or utility grids allows for reduced amounts of pollutants like CO_2 and $NO_x\dot{}$ In addition hydrogen could be produced locally through electrolysis, increasing the degree of self-supply for the location.

Due to the heat produced during operation of fuel cells, they could also replace common broilers, providing both heat and energy through cogeneration. Many research studies have been performed to investigate the techno-economic potential of such solutions, and will also be the focus of this paper. The largest disadvantage facing hydrogen based energy systems is one of the most import, the cost. However, particularly when replacing fossil based power generation, fuel cells can be expected to reduce carbon emissions by about 30 % [56], dependent mainly on technology of choice and production method for hydrogen.

3.4.2 Batteries

Stored energy in batteries generally occupies less space than stored hydrogen, however stored hydrogen weighs only a fraction of a battery for the same amount of stored energy. In addition, as can be seen from Figure 3.7, there are more steps involved in the round-trip process of a Hydrogen Energy Storage System (HESS), which also increases the overall losses. The losses given in the figure are not necessarily actual losses, but in the case of for instance compression, it is illustrative of the additional power needed for the system to compress the hydrogen. If round-trip efficiency is the only concern, batteries will get you two to three times as high values. However, in long-term and seasonal storage the lower round-trip efficiencies of a HESS are potentially out-weighed by the positives, as stored hydrogen, compared to batteries experiences low to no self-discharged [57]. This indicates that battery and hydrogen energy storages could fill different roles within modern energy systems.

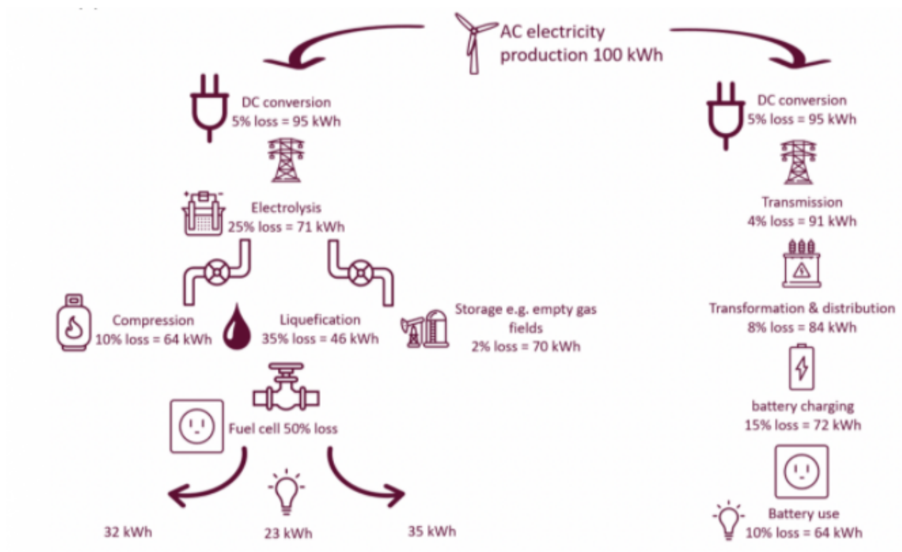


Figure 3.7: A comparison between the processes involved in HESS and Battery Energy Storage System (BESS) from delivered power through storage and utilization.

3.4.3 Thermal energy storage

Therma Energy Storage (TES) are storage tanks filled with a heating medium, designed to store energy in the form of heat. Like other forms of energy storage, a correctly dimensioned TES can help reduce cost, energy consumption, and CDE, as well as contribute to peak shaving during high energy demand. There are many variants of TES, but the most common are hot water tanks utilized for both residential and commercial use.

Hot water tanks are a common form of TES, storing energy as heat in an isolated tank. The amount of stored heat can be expressed as in equation 3.19

$$E_{TES} = m_{water} \cdot c_p \cdot \Delta T \tag{3.19}$$

c_p =4.2 [kJ/kg ^oC] is the specific heat value for water, dT is the difference between temperature at the inside and the outside of the tank, while, m_{water} is the mass of water inside the tank. The water can be heated by many means, where electric water heaters and District Heating (DH) are the most common in Norway. Losses in hot water tanks can be described by using heat conduction as in equation 3.20.

$$\dot{Q}_{store,loss} = UA\Delta T \tag{3.20}$$

U is the heat transfer coefficient $[W/m^2K]$ for the specific material composition of the are between the temperature differentials, A is the surface area of the tank $[m^2]$ and ΔT is the difference in temperature between the stored water and the ambient temperature outside of the tank. Heat transportation from the tank to and from the tank are done through pipelines. The transmission loss in pipelines can be described in a similar fashion to the storage losses, as seen in Equation (3.21). This is a very simplified relationship assuming steady state flow under constant conditions.

$$\dot{Q}_{trans,loss} = \dot{m} \cdot c_p \cdot \Delta T \tag{3.21}$$

$\dot{m}$ is the mass flow of water through the pipe.

3.4.4 Alternative ESS

Flywheels store mechanical energy which can be released have high power densities, high efficiency and a long cycle life, but also have a high degree of self-discharge as well as a short operation time. Since Flywheel Energy Storage (FES) are not electrochemical solutions like fuel cells and batteries, they do not require precious metals and will have a lower degree of resource depletion of precious minerals.

Pumped hydro is the largest and most mature energy storage technology. It works by having two water reservoirs close to each other, where one is at a higher elevation than the other. Water is then transported from the lower reservoir to the higher one using pumps. The most elevated reservoir is further equipped with a hydro electric power plant. The amount of energy store will depend on the height difference as well as the volume of the higher reservoir. Advantages feature high efficiency, long lifetime and cheap specific costs. Some disadvantages of Pumped Hydro Energy Storage (PHES) are the fact that they have a slow response to deviations in power output, and they are of course very dependent on geographical location.

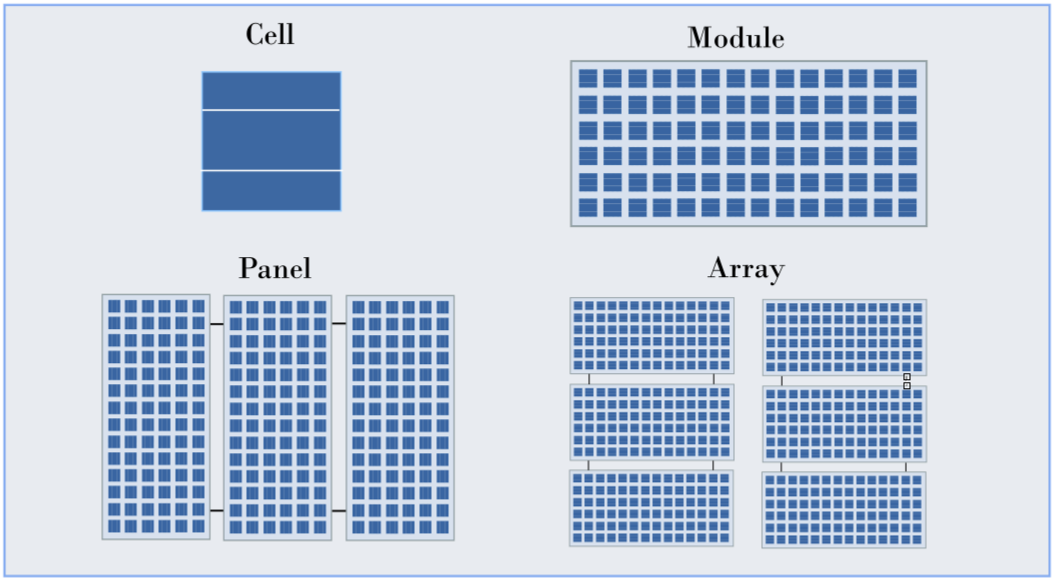


Figure 3.8: Configurations of PV cells. PV arrays consist of interconnected panels, which are made up of modules. Modules consist of multiple cells.

3.5 Solar power

The sun is responsible for most energy available on earth, however there are only a couple of technologies that are able to convert solar rays into energy directly. The two most common are solar thermal collectors and PV cells.

3.5.1 PV systems

PV cells are electrical components generating voltage from Ultra Violet (UV) light, most often utilizing the sun as a light source. They are generally meshed together in modules, and panels, which are further series and parallel connected in an array to achieve the desired current and voltage levels. PV cells have a lower amount of land use per unit of power compared to most other conventional power plants [58]. In addition they can be installed on roofs, walls and other areas with buildings already constructed making the areas easily accessible for technicians. Figure 3.8 shows a schematic of the interconnections for PV cells. In addition to cells, PV systems need simple power electronics like DC/AC-inverters and DC-converters as well as blocking and bypass diodes to ensure correct current flow and avoid problems during periods of shading respectively.

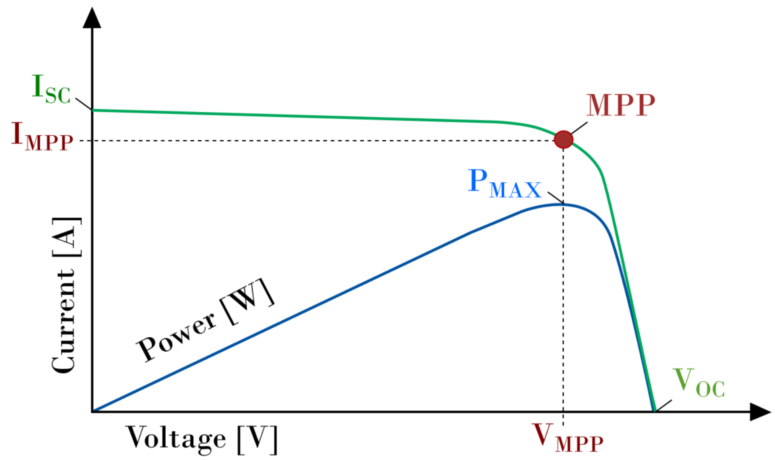


Figure 3.9: Voltage and current characteristics of a PV cell. 'MPP' is the the maximum power point, indicating which current and voltage levels will provide the largest power output.

3.5.2 PV power characteristics

Another draw towards PV is the fact that they are, as FCs, modular energy systems that can easily be scaled over time allowing for smaller investments over time. Increasing the number of panels connected in series will increase the voltage output of the array linearly. The characteristics of a single PV cell is illustrated in Figure 3.9. The green curve is known as the IV-curve, and its characteristic shape is common for all PVs.

3.5.3 Solar thermal energy

Another way of harnessing the energy from the sun, is by utilizing the heat directly. Solar thermal energy systems are a form of TES where the heat from solar radiation is 'collected' by thermal energy collectors and transported to a thermal storage tank. The thermal collectors are pipes filled with a heating medium, either liquid or gas, exposed to a heat source. The collectors are commonly placed on roofs of buildings to decrease land use and reduce shadow formation. Combined systems of PV arrays with integrated Solar Thermal Energy System (STES) are increasingly popular solutions for solar energy projects, providing both electricity and heat. The efficiency of a solar thermal system will depend on the difference in inlet and outlet temperature of the heating medium as in seen in equation (3.22) Assuming stationary operation of a STES unit and constant efficiency, the useful heat delivered can be estimated using equation (3.23).

$$\eta_{st} = \frac{\dot{m}C_p(T_{out} - T_{in})}{I_{solar} \cdot A} = \frac{Q_{useful}}{I_{solar} \cdot A} \tag{3.22}$$

$$Q_{useful} = I_t \cdot \eta_{st,t} \cdot A \tag{3.23}$$

Q_{useful} is the heat delivered to the hot water storage tank, A is the area covered by the solar collectors, $I_{solar,t}$ and $\eta_{st,t}$ are the local solar irradiance and efficiency of the solar thermal system at the given time, t.

3.6 Electrical power transmission

Voltage drops in the transmission line can be described as in equation (3.24), and the power loss can be described as in (3.25). Both the impedance, Z, and resistance, R are dependent on the length of the transmission line. I is the current through the transmission line.

$$\Delta U = Z_{linje} \cdot I[V] \tag{3.24}$$

$$\Delta P_{line} = R \cdot I^2[W] \tag{3.25}$$

4 Model energy system and FME ZEN

Chapter 4 describes what FME ZEN is and details about their pilot project at Campus Evenstad. Campus Evenstad is used as the foundation for the case study within this thesis, so the general composition of the model energy system is also presented.

4.1 Description

FME ZEN is a joint scientific initiative spearheaded by the academic institutions SINTEF Energy, SINTEF Community, and NTNU. The idea of Zero-Emission Neighborhood (ZEN) aims at making communities and neighborhoods carbon neutral and self sufficient by introducing distributed energy solutions and microgrid systems in neighborhoods, apartment buildings, or other living facilities. The definitions of what constitutes 'zero-emission' varies between institutions and organization, but that is considered out of the scope of this thesis.

4.2 Case Campus Evenstad

One of the pilot projects FME-ZEN is monitoring is the microgrid at the university campus inampus Evenstad. Campus Evenstad is a one of the grounds associated with Høgskolen i Innlandet (HINN). It is located in Stor-Elvdal municipality, one of the primary locations for forestry in Norway, and as such, the campus focuses on fields of study related to forest management, nature and ecology. Figure 4.1 shows an overview of the buildings at Campus Evenstad.

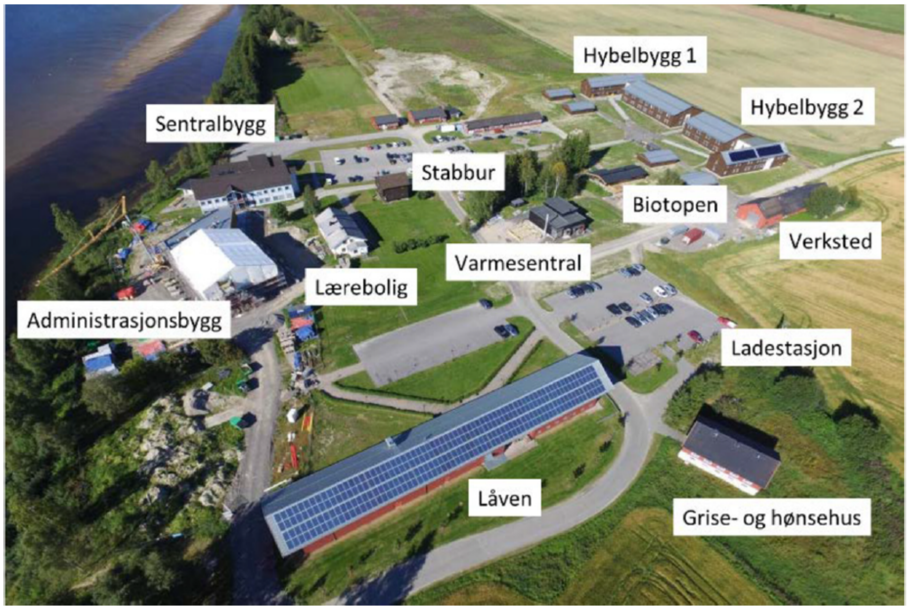


Figure 4.1: Overview image of the test site Campus Evenstad [59].

There are ten different main buildings at Campus Evenstad, and Table 4.1 displays the construction year and total heated area for each building.

Table 4.1: Heated area of the main buildings at Campus Evenstad [59].

Building	**Area** $[m^2]$
Hybelbygg 1+2	4,200
Sentralbygget	1,570
Adm. bygg	1,141
Låven	1,119
Lærerbolig	166
Energy central	120
Stabbur	90
Verksted	45
Grisehus	5

The campus is equipped with a PV system, solar thermal energy storage, Biomass-CHP combustion unit utilizing locally sourced wood chips, electric boiler and a battery. It is a grid connected microgrid system. The basic specifications for these components are presented in Table 4.3.

Table 4.2: Installed energy generators at campus Evenstad [59].

Generator	Thermal	Electricity	Annual generation
Bio CHP, Th	100 kWt	-	400,000 kWh
Bio CHP, El	-	40 kWe	160,000 kWh
Bio Boiler	350 kWt	-	300,000 kWh
El Boiler	315 kWt	-	275,000 kWh
Solar Thermal	100 m^2	-	40,000 kWh
PV	-	60 kWe	62,000 kWh

4.3 Choice of model energy system

To examine the potential of FC units to provide both electricity and heat it is of interest to develop an energy system model and optimize the performance of the system components. FC units come in all sorts of sizes form residential single-housing systems below 1 kWe to large industrial systems. Caused by an asserted effort to decarbonize the heating of buildings in Norway there has been a push towards installing heat pumps in both existing and newly constructed houses, culminating in over 100,000 Heat pump (HP) units installed in 2019 alone [60]. During an Enova survey in 2006 it was found that more than 62 % of non-residential buildings were equipped with hydronic central heating networks [61], while SSB[7] comparatively estimated that only 14 % of residential households had installed central heating [62] in 2019. By investigating buildings where a hydronic system are or will most likely be present the costs associated with distributing the heat from a CHP unit could reasonably be neglected.

Campus Evenstad is composed of a variety of building types, from residential facilities to a seasonally utilized educational building which is largely empty during summer as can be seen from Table 4.1. The energy system also includes renewable energy sources as well as a bio-CHP allowing for a comparison between different configurations. These factors among others indicate that Campus Evenstad can serve well as a basis for an energy system model to examine in this thesis.

[7]Statistics Norway (Statistisk Sentralbyrå) - https://www.ssb.no/

Table 4.3: Installed energy generators at campus Evenstad [59].

	Annual consumption
Electricity	1,000,000 kWh
Heat	620,000 kWh

5 Method

Chapter 5 presents the methodology used for system analysis during this thesis, the basic configuration of the energy system and the setup of the optimization model. The chapter is split into five sections, where the first section presents a general explanation of the optimization model, and describes the equations making up the MILP problem used in this thesis. The second focus on the modelling of the power and thermal demand for the system, while the third aims at describing the separate system components. The fourth section defines the case conditions used during the optimization. Lastly, section five summarizes the key assumptions that were made for the model.

5.1 Optimization and linear programming

5.1.1 Energy system analysis

There are many possible ways of examining operational performance and profitability of an energy system. One metric useful for gauging profitability of a technology is Levelized Cost of Electricity (LCOE), which aims at establishing a comparable value for the cost related to generating one unit of electricity. The LCOE method has been used by multiple national and international energy agencies, like NVE[8] and IEA, but this method falls short when attempting to assess profitability and operational performance simultaneously. The LCOE can be calculated using Equation (5.1).

$$LCOE = \frac{C_0 + \sum_{t=1}^{n} \frac{C_t^{maint} + C_t^{fuel}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{5.1}$$

C_0 is the investment cost occurring during year one of the analysis, C_t^{maint} and C_t^{fuel} are the costs for maintenance and fuel respectively, while E_t is the electricity output in year t. For CHP technologies the LCOE should take the useful heat production into account. This can be done utilizing the heat credit method, where the generated heat is interpreted as substituting heat from another reference unit. This method is used by NVE in their long-term energy technology analysis [63], and is given by Equation (5.2).

[8] The Norwegian Water Resources and Energy Directorate (Norges Vassdrags- og Energidirektorat) - https://nve.no/

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{M_t+F_t}{(1+r)^t} - C_{heat}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{5.2}$$

$$C_{heat} = LCOE_{heat} \cdot Q_{CHP} \tag{5.3}$$

C_{heat} is the heat credit representing the saved costs from producing heat, and $LCOE_{heat}$ is the reference value the CHP is substituting. Suitable reference technologies could in this energy system be e.g. bio-CHP, electric boiler or DH.

To find the optimal dispatch of energy from each unit in an energy system, another useful tool is optimization through linear programming. Linear Programming (LP) utilizes a mathematical approach to find the most promising alternative for a decision-making scenario based on a logical objective. For this master's thesis, cost-minimisation was chosen as an objective to find the optimal dispatch between the different generators and heaters in the energy system. Linear programming can be simplified as in (5.4).

$$minC(x) \tag{5.4}$$

$$s.t. \quad g_i(x) \tag{5.5}$$

$C(x)$ is here the cost of the energy system, subject to the set of constraints $g_i(x)$. Both $C(x)$ and $g_i(x)$ conventionally have to be linear. MILP is a form of linear programming that incorporates binary decision variables, b_i into the problem. This is particularly useful for investment opportunities. MILP problems can be solved using the simplex method, which is given in a simplified form in Figure (5.1).

Net Present Value (NPV) the most widely utilized tool for deciding on an investment decision. It factors in the time-value for the cash flow over the lifetime of the components and the system. This allows for an accurate comparison between different investment scenarios. Equation (5.6) shows the formula for NPV.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0^{inv} \tag{5.6}$$

The net benefit Net Benefit (NB) is given by subtracting the NPV of an investment opportunity from a reference value. This relationship is given in equation (5.7).

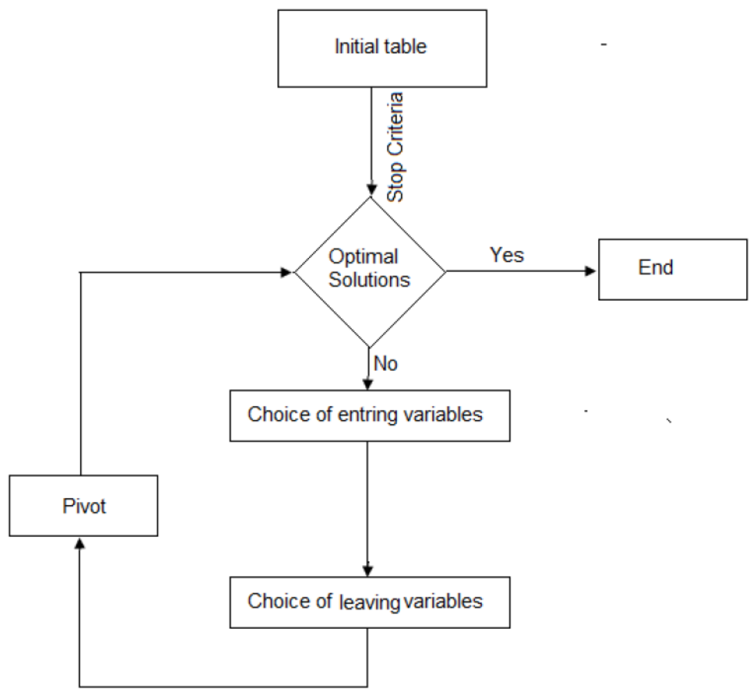


Figure 5.1: The simplex algorithm for solving optimization problems [64].

C_{new} is the annualized NPV of the solution that is to be evaluated, and C_{ref} is a reference value, often a base case alternative.

$$NB = C_{ref} - C_{new} \tag{5.7}$$

Investment costs can be annualized by accounting for time value by multiplying it with the annuity factor, $\varepsilon_{r,T}$ as shown in Equation (5.8).

$$C_0^{Annualized} = I_0 \cdot \varepsilon_{r,T} = I_0 \cdot \frac{r}{1-(1+r)^{-T}} \tag{5.8}$$

5.1.2 Optimization model

To evaluate how the system would operate when introducing an FC-CHP unit, an MILP model was developed. As the aim of the model was to assess the potential for FC units to provide electricity and heat. The model was created using Pyomo in the programming language Python, and was solved with the Gurobi solver. A general glossary for the optimization model can be found in nomenclature.

5.1.3 Objective function

Two different objective functions were developed for the model focusing on: minimization of the costs associated with the energy system at Campus Evenstad, and minimization of the power imported from the grid. Both of the objective functions use the same set of constraints, so cost of the energy system was not optimized nor constrained in cases where import minimization was used as the objective function. The same applies to import minimization where cost was not constrained.

For cost minimization of the energy system, the objective function was as given in equations (5.9) through (5.13).

$$min \frac{1}{\varepsilon^{p}_{r,D}} \cdot \sum_{i} C^{disc}_{i} \tag{5.9}$$

$$+ \sum_{i} C^{maint,p}_{i} \tag{5.10}$$

$$+ \sum_{t} \sum_{i} f_{i,t} \cdot C_{i,f} \tag{5.11}$$

$$- C^{gc} \cdot \sum_{t} E^{gc}_{i} \tag{5.12}$$

$$+ \sum_{t} \sum_{i} (P^{imp}_{t} \cdot (C^{spot}_{t} + C^{tariff}) - P^{exp}_{t} \cdot C^{spot}_{t}) \tag{5.13}$$

Equation (5.9) represents the discounted investment cost, referred to as the Capital Expenditure (CAPEX) of each technology in I. The subsequent term (5.10) represent the maintenance cost of each technology in I, discounted over the period, p, which represents the duration of the analysis. Operational costs for each generator technology is related to the cost of fuel, $f_{i,t}$, at time, t. Equation (5.11) sums the cost of fuel for the generator units that require fuel to operate, and is given in EUR/kWh. It was assumed that solar technologies (PV and ST) had a zero operational cost during the entire duration of the analysis. C^{gc} is the cost of Green Certificates (GC), which are rewarded to power providers for producing a unit of renewable energy (1 MWh in Norway [65]). In equation (5.12) this is multiplied by the sum of energy delivered by renewable energy technologies in the energy system, which in this case includes PV and generators based on biomass. The last term (5.13) summarizes the net cost of exchange to and from the grid. The microgrid was able to sell surplus energy from the generator units at spot price, all the while a tariff, C^{tariff}, is paid to the grid operator and power provider as described later in 5.2.

For import minimization, the objective function was given as in equation (5.14).

$$min \sum_{t} P^{import}_{t} \tag{5.14}$$

5.1.4 Constraints

There were a number of constraints given to ensure correct operation of the system. The constraints can be placed in one of two main categories; 1) ensure correct operation of each technology or 2) ensure proper distribution of energy within the system. The first category aims at limiting the range of operation for generators and heating units to within their respective minimum and maximum states of operation. The latter category ensures that all loads, both electrical and heating, are met at each moment.

Equations (5.15) to (5.18) ensure that each generator or heating unit, $p_{g,t}$ or $q_{h,t}$ stays within their respective limits, or was shut off during any point in time. This semi-continuous constraint was significant especially when a constant efficiency was assumed for every generator unit over the entire range of operation, which was the case in this thesis.

$$p_{g,t} = 0 \tag{5.15}$$
$$\vee$$
$$P_g^{min} \leq p_{g,t} \leq P_g^{max} \tag{5.16}$$

$$q_{h,t} = 0 \tag{5.17}$$
$$\vee$$
$$Q_h^{min} \leq q_{h,t} \leq Q_h^{max} \tag{5.18}$$

Equations (5.19) and (5.20) represent the power and heat balances for the model respectively. At any given point in time, the energy input to the system must be equal to the energy out of the system. Energy input included local production, import from grid, and dispatch from energy storage, while out going energy were demand, export to grid and charging of energy storage. This also includes the electricity used locally for space heating purposes through electrical boilers (as described in Equation (5.27)).

$$\sum_g p_{g,t} + p_t^{PV} + p_t^{import} + p_t^{bat_{dis}} = p_t^{demand} + p_t^{bat_{ch}} + p_t^{boiler} \tag{5.19}$$

$$\sum_h q_{h,t} + q_t^{st} + q_t^{dh} + q_t^{tes_{dis}} + q_t^{boiler} = q_t^{demand} + q_t^{tes_{ch}} \tag{5.20}$$

Both the battery and TES units are subject to the same set of reservoir constraints, where the dispatch of energy from the units at time, t, can not exceed the available stored energy. These constraints are given in Equations (5.21) and (5.22).

$$\frac{p_t^{bat_dis}}{\eta_{bat}} \leq e_{bat,t} - E_{bat}^{Min} \tag{5.21}$$

$$\frac{q_t^{tes_dis}}{\eta_{tes}} \leq e_{tes,t} - E_{tes}^{Min} \tag{5.22}$$

$b_{i,t}$ are binary variables tied to each technology, i, at time, t. They have the value 1 if the given technology was active at the given moment, or 0 otherwise. The purpose of equation (5.23) was to ensure that number of hours of operation does not exceed the maximum hours of operation, T_i^{max} for each generator or heater in $\mathcal{I}$.

$$\sum_t b_{i,t} \leq T_i^{max} \tag{5.23}$$

Equations (5.24) and (5.25) ensures that energy transfer between Campus Evenstad and the electrical grid or DH network respectively are below the maximum transfer limits.

$$p_t^{import} \leq P_{grid}^{max} \tag{5.24}$$

$$q_t^{dh} \leq Q_{dh}^{max} \tag{5.25}$$

5.2 Modelling of power and thermal demand

Both the electricity and thermal demands for the entire system model were estimated using the energy demand load profile estimator tool, PPROFEt [66]. The tool uses data from over 100 non-residential buildings to generate long-term hourly energy forecasts for electric specific power, space heating and Domestic Hot Water (DHW) in individual or multiple buildings through panel data analysis. The only required input to the PROFEt tool are building type and total heated area for

Table 5.1: Buildings in energy system model.

Building	Area	Class	Category
Student dormitories	4,200	Very efficient	Apartment
University	1,570	Efficient	University
Administration	1,140	Efficient	Office
Barn	1,120	Efficient	Other
Remaining	600	Efficient	Other
Teacher facility	170	Efficient	House
Energy central	120	Normal	Other

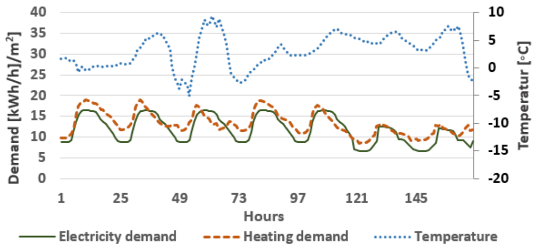
each building in the system, as well as a start date for analysis period and the coinciding outside ambient temperatures for each subsequent hour. The areas fed into the tool for this thesis were based on the areas given in Table 4.1. There are currently 12 different building types to choose from in the PRFOEt tool, so each building was mapped to the most suitable alternative. In addition to the general building types, it is also of interest whether each building is considered 'efficient' or 'very efficient' corresponding to TEK10 building regulations[9] or passive house standards respectively. A third alternative is 'Normal' which encompasses all buildings built before 2011 unless otherwise stated. This is referred to as the 'class' of each building. Table 5.1 gives an overview of which parameters were input to the tool.

During the optimization for the energy system in this thesis, the demand profile for all the buildings were viewed as one aggregate for the entire site. This means that there were only one demand profile for each of the three categories: electrical power, space heating and hot water. When outside, and coincidingly inside temperatures rise, the space cooling demand was reflected in the electrical power demand. The temperature data was collected from Norsk Klimaservicesenter and measurements from Evenstad climate station (SN8140) during the period of January 1st through December 31st 2019 [67].

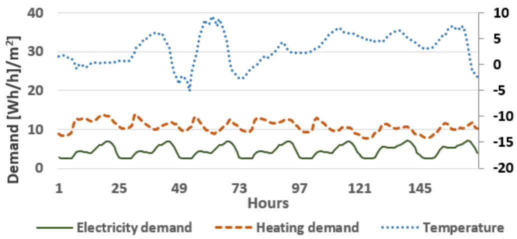
5.2.1 Building characteristics

In addition to the collection of buildings at Campus Evenstad, the fuel cell will be simulated for standalone buildings with different characteristics. Figures 5.2

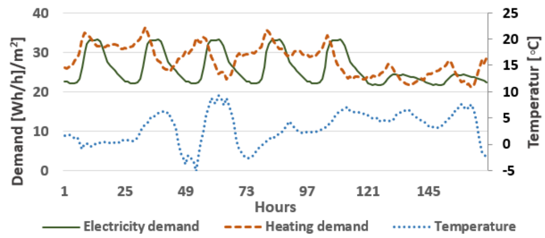
[9]Building quality regulations enforced by The Directorate of Building Quality (DIBK - Direktoratet for Byggkvalitet) - https://dibk.no/regelverk/tek/



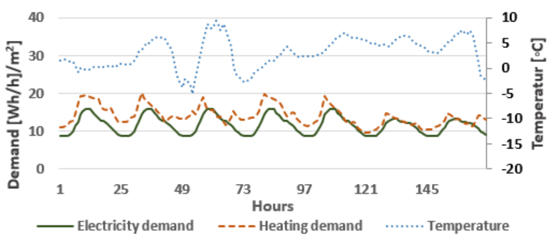
(**a**) Demand characteristic for Campus Evenstad



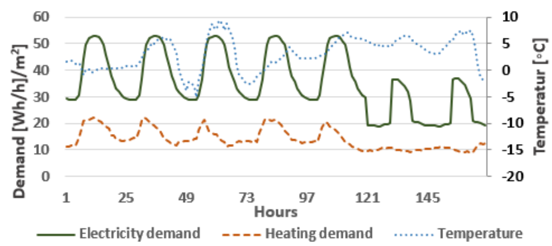
(**b**) Demand characteristic for apartments



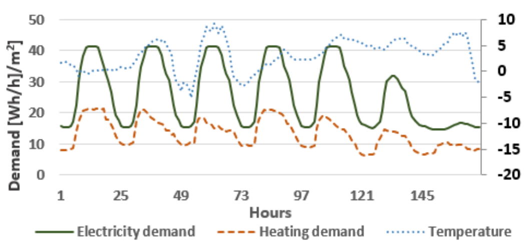
(**c**) Demand characteristic for hospital buildings



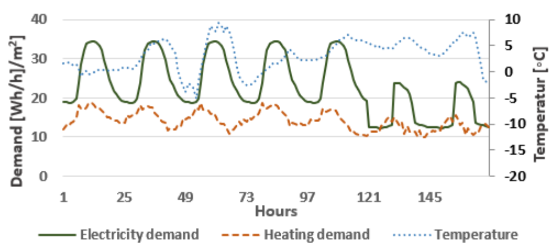
(**d**) Demand characteristic for nursing homes



(**e**) Demand characteristic for office building



(**f**) Demand characteristic for a shops



(**g**) Demand characteristic for universities

Figure 5.2: Demand characteristics for various building types based on PROFet Tool [66]. The characteristics are given for the same week during April of 2019, and all buildings are classified as 'efficient' (TEK11 standard). The left axis for office and shop are slightly larger due to their high electricity demands.

shows the energy demand profiles for the buildings at Campus Evenstad,as well as for apartment building, hospital, nursing home, office building, shop and university building. All the demands are calculated using temperatures from May 6th to May 12th 2019 and all buildings were assumed 'efficient'.

5.3 Modelling of energy system components

The energy system at Campus Evenstad was used as a basis for the energy system modelled in this thesis [59]. The model included most of the components in the real system, but also incorporated an FC-CHP unit. All energy system components were assumed to operate stationary on an hourly basis. This means that the dynamic response of each component was only limited by their respective slew rates or rate of change. The electrical efficiency of each component was assumed to be constant over the entire range of operation. Figure 5.3 shows a simple sketch of the energy system used in this model.

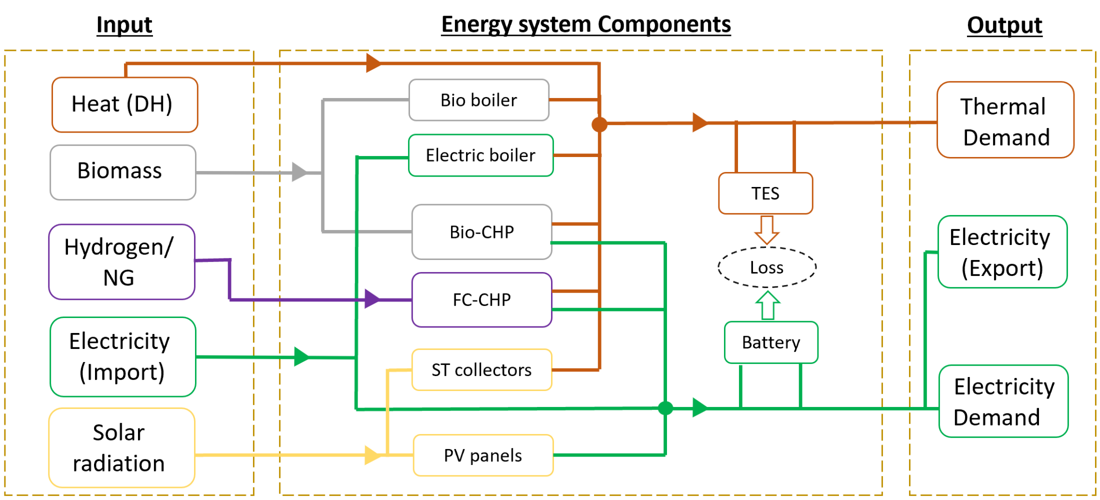


Figure 5.3: Sketch showing the interconnection between the electrical power and heating components in the modelled energy system. Red lines indicate thermal energy flow while green lines indicate electrical energy flow.

5.3.1 Fuel cells

As an FC is not included in the real life case of Campus Evenstad, there were no reference for which type of FC to use in the model, or at what power ratings. Due to the peak electrical power demand at about 180 kWe, a 100 kWe FC stack was chosen. In addition to the stack having a comparable power output to the other components in the system, it is also comparable to similar pilot project systems like the 100 kWe PEM unit at Byneset [68] and Toshibas FC-CHP [14] as presented in Chapter 2.

An LT-PEMFC was chosen as the type for this thesis. As described in Chapter 3 PEMs are a suitable choice due to their relative maturity in the field of CHP compared to competing technologies, as well as faster dynamics smaller footprint. Depending on whether FCs are used for primary or backup power, the long start-up times and slow response of SOFC, MCFC, and other alternatives could be a limiting factor on the overall flexibility of the energy system. The FC unit was assumed to be able to consume both pure hydrogen or hydrocarbons. Using hydrocarbons, like NG would however require an added fuel reformer before feeding hydrogen to the MEA. This was reflected in lowered costs for fuel compared to pure hydrogen at the expense of increased investment and maintenance costs as well as lowered system efficiency due to the losses in and energy required by the reformer.

For simplicity, a constant electrical efficiency of the FC was proposed over the entire lifetime and across the limited range of operation for the FC-CHP unit. This was set to $\eta_{el} = 0.40$. In both cases where pure hydrogen or NG was used as fuel for the FC, a constant supply of fuel was assumed for the initial cases, and the fuel utilized was calculated using Equation (3.13).

5.3.2 Combined heat and power units

The CHP units in the system were given electrical power ratings and corresponding heat to power ratios, ϕ_{chp}. As the electrical efficiencies were assumed constant, so were the thermal efficiencies. The linear relationship between heat and power output of the CHP units is given in equation (5.26)

$$Q_{chp} = \phi_{chp} \cdot P_{chp} \tag{5.26}$$

5.3.3 Solar energy

For hourly output of the solar energy technologies, a model was developed using the software PVsyst. The power output of the PV system was created directly by selecting the components in PVsyst coinciding with the actual PV-cells. These parameters can be found in appendix A.2. By utilizing the values for local irradiance given by the PVsyst model, a simplified estimate for the heat delivered by the solar thermal collectors was approximated using equation (3.23). The solar thermal panels occupy an area of 100 m^2.

5.3.4 Energy storage solutions

There were two main energy storage solutions in the modelled system; Li-ion battery and TES in the form of hot water storage. Both of these components were modelled similarly, as reservoirs of stored energy. The limiting factors of operation were the maximum capacity of stored energy, maximum charge and discharge rates, in addition to only allowing either charging or discharging separately during each hour. Campus Evenstad has a number of hot water storage tanks placed in different buildings, in addition to a buffer tank connected to the Bio-CHP unit. For simplicity, the aggregated capacity of all the hot water tanks are modelled as one large TES unit. The stored energy in the TES were calculated utilizing equation 3.19.

5.3.5 Electrical boiler

Electrical boilers are based on simple resistive circuits that convert electrical energy to heat. Most electrical boilers are assumed to be 100 % efficient in converting electricity to heat, while some energy loss could be expected in the storage and transmission of heat. Even so, no storage or transmission losses were considered for TES in this model. Electricity could thus be used for space heating purposes through these boilers if it was found to be the most suitable solution. The simple mathematical relationship between electrical power in and heat out of an electrical boiler is shown in equation (5.27).

$$P_{in}^{boiler} = Q_{out}^{boiler} \tag{5.27}$$

5.3.6 Utility-side services

Utility-side services encompasses both the electricity grid and district heating. The electrical power grid was modelled by utilizing simple mathematics, and consisted of two parameters: grid import and grid export. Grid import is the amount of energy that is bought from the grid, while grid export is the surplus energy produced locally that could be sold to the grid. There were no set limitations on the amount of power that could be imported from the grid at any given time. Campus Evenstad has a 'plusskunde' agreement[10], allowing them to deliver up to 100 kWh/h of power to the grid.

In 2019 Campus Evenstad had power transfer agreements with electricity retailer Ishavsskraft and Distribution System Operator (DSO) Eidsiva Nett. The cost estimates for power purchase were as given in Table 5.2. The energy part marked with (GC) is the cost of renewable energy certificates, while the value of 0.1658 NOK/kWh is the consumer excise tax [59].

Table 5.2: Power transfer agreement for Campus Evenstad [59].

	Fixed part	**Energy part**	**Power part**
Energy rates	49 NOK/Month	Spot price	-
Grid tariffs	13,200 NOK/yr	0.04 NOK/Month	432 NOK/kWh/h
Tax charges	800 NOK/yr	0.1658 + 0.02 NOK/kWh (GC)	-

For each unit of energy imported all rates and charges are included. Export of energy was met with a net monetary gain equal to the electrical spot price at the time of export and cost of GC when relevant. The net cost of exchange with the electrical power grid could thus be defined as in equation (5.28). The power part of the grid tariff was calculated by the hourly maximum power transferred during the year. Spot costs of electricity were found for Norwegian bidding zone 1 (NO1) in Nordpools database [69].

$$C_{grid} = C_{grid}^{import} - C_{grid}^{export} \tag{5.28}$$
$$= P_{grid}^{import} \cdot (c^{spot} + c_{energy}^{tariffs} + c^{gc}) + c^{tax} + c_{power}^{tariffs} \tag{5.29}$$
$$-P_{grid}^{export} \cdot (c^{spot} + c_{energy}^{tariffs} + \lambda_{renewable} \cdot c^{gc}) \tag{5.30}$$

Along with PV energy systems, Bio-CHP units are recognized as a renewable source of electricity. This means that each unit of electrical energy generated by the PV and Bio-CHP units were rewarded with renewable energy certificates (REC), regardless of whether the energy was exported to the grid or not. Neither standalone FCs nor FC-CHP units were, as of this thesis, universally recognized as renewable

[10]Plusskunde - https://www.nve.no/reguleringsmyndigheten/nettjenester/nettleie/tariffer-for-produksjon/plusskunder/

energy sources due to the fact that the emissions associated with hydrogen technologies depends on where the utilized hydrogen fuel comes from, and which processes were used to refine it. This means that there are no GC revenues from the FC system considered in the model. The system boundaries are set at the boundaries for the microgrid, so no transfer losses in the power grid were considered. The maximum import limit from the grid was set to 500 kWh/h. As the model is not able to optimize for the maximum value in a set of variables, the power part of the grid tariffs were calculated using a constant value.

The cost of heat delivered by DH were gathered from Fortum Fjernvarme [70]. The economic values for DH were calculated using the statistics from the year 2019 and the costs and commissions from the agreement for business customers. Emissions were calculated assuming all DH in the area were from biomass heating units having a CDE of $\approx$ 7 kgCO2/kWh. No transmission losses were considered for the local heating grid.

5.4 Case definitions

To get a foundation for the comparison between the different cases used in optimization process, a simple base case was computed. The base case was defined as the microgrid operating without a CHP unit. This includes solar collectors and PV as well as a Li-ion battery and thermal energy storage. For the remaining case definitions, there were three main parameters that were altered during the initial simulations; energy system configuration; periods with varying outside temperatures; objective function. The case definitions presented in this section will be referred to as the initial cases.

The pilot system at Campus Evenstad already includes a CHP unit fueled by locally sourced wood chips. Simulations performed for a variety of configurations of the energy system, including the FC- and bio-CHP units separately, as well as both together. The demand profiles are very different during periods with warmer outside temperatures and colder outside temperatures. Figure 5.4 shows the estimated demand profiles for power and heat during two periods with mean temperatures of -5.5^oC and 15.2^oC respectively.

When presented later in this thesis, the cases are denoted by simple indicators referring to the conditions of the particular case configuration. Table 5.3 shows the different symbols used for the case definitions along with a simple description of what they indicate.

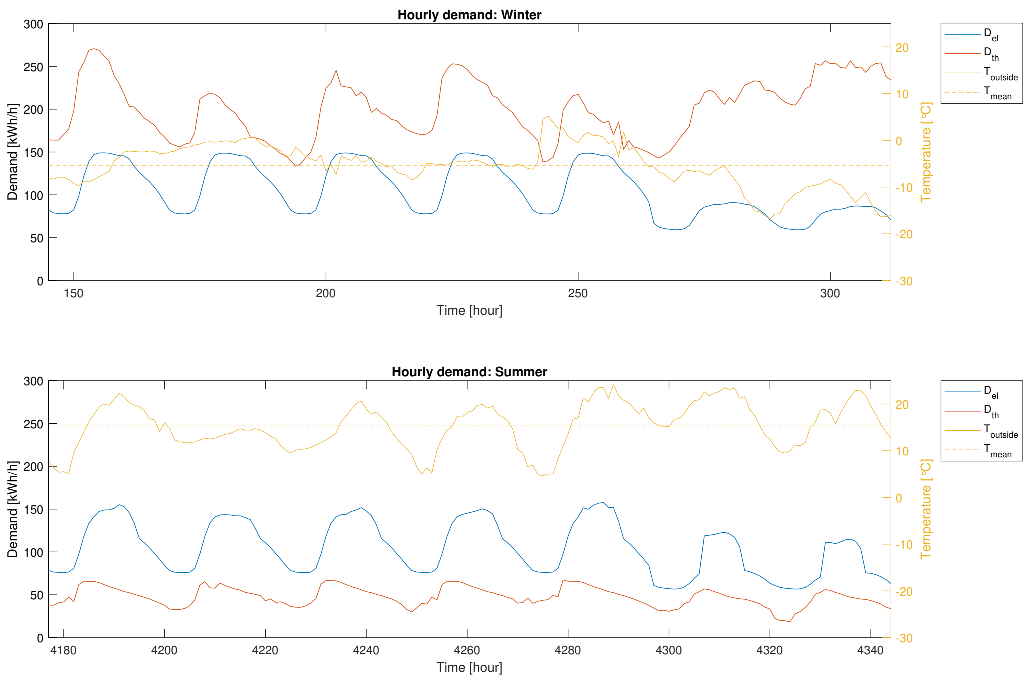


Figure 5.4: Demand profiles for Campus Evenstad during winter and summer periods with mean temperatures of -5.5^oC and 15.2^oC respectively. The profiles were created using the PROFEt tool and the hours are representative for the period of the year between January 7th and 13th for winter, and June 24th and 31st for summer.

Table 5.3: Symbols indicating the various case conditions.

Symbol	Description
Y	Year
S	Summer week (Warm outside temperatures)
W	Winter week (Cold outside temperatures)
FC	Includes the possibility of FC-CHP unit
Bio	Includes the possibility of Bio-CHP unit
CMin	Objective function: Minimize cost of energy system
IMin	Objective function: Minimize import from grid
PO	Includes a period with power outage of the grid
2020	Investment occurs in the year 2020
2050	Investment occurs in the year 2050

Year, summer and winter are mutually exclusive, but the other conditions could in large part be combined together in different configurations. FC and Bio indicate which of the CHP technologies the system has the opportunity to invest in. Each of the cases were associated with multiple different symbols, where e.g. 'Case: S+FC+BIO' indicates that the simulation included demand profiles for a week long period of warmer outside temperatures (summer), with the possibility of investing in both FC- and bio-CHP units in the energy system. In addition to the parameters mentioned above, the energy system was optimized using both financial data from 2020, and future estimates for 2050.

5.4.1 Data set

The data used for the energy system components were in large part collected from The Danish Energy Agency's Technology Report [71].The parameters that was used during simulations can be found in Appendix A.1.

5.5 Overview of key assumptions made during modelling

The solar and hourly demand profiles as well as spot prices were assumed equal for the cases in 2020 and 2050. The energy system due to it's size was not subject to the Greenhouse Gas Emission Trading Act[11]. Biomass is also exempt from the carbon tax under §3. Although a ZEN pilot project was used as a basis for the energy system in this thesis, ZEN-conditions were not considered in any of the analysis presented in this thesis, meaning that there were no restrictions on the emissions from operation of the system.

A number of key simplifications were made during the simulations and they can be summarized in the three following categories:

1. **Economic simplifications**
   - *Cost of the local distribution grid for electricity or heat were not considered*
   - *Cost of thermal energy storage was not considered*
   - *Cost of transporting and storing fuel was not considered*
   - *No salvage value or end-of-life costs were considered*
2. **Operational simplifications**
   - *All electrical and heating demand for the buildings in the energy system are combined into a single load. The heating load is the sum of space heating and hot water demand*
   - *All energy technologies could provide energy to the combined load*
   - *Transmission losses in local distribution grid for electricity or heat were neglected*
3. **Fuel cell**
   - *A continuous supply of fuel was assumed*
   - *Power electric losses are accounted for in the overall efficiency of the fuel cell*

[11] Enacted by The Norwegian Government in December 17th 2004. The law aims at incentivizing industrial actors in multiple segments of the economy to opt for less carbon intensive solutions by taxing CDE. LOV-2004-12-17-99 - https://lovdata.no/dokument/NL/lov/2004-12-17-99/

6 Results and analysis

Chapter 6 presents the results found through the case simulations. The first section describes which performance indicators were used to analyze the results and to which degree the performance of the energy system was altered by the given altercation of the relevant cases. The subsequent section shows relevant findings and results from the different case, and the chapter ends by posing some research questions that was raised by analyzing the results.

6.1 Interpreting results

For interpreting the system performance a set of Key Performance Indicator (KPI)s were defined. These were used as a basis for further discussion and comparison between the different cases.

6.1.1 Key performance indicators

As economic incentives are a driving force behind technological development, one important aspect of a microgrid system will be the the cost of the system. The total cost consists of annualized discounted investment cost, operational cost, and maintenance cost for each technology, as well as utility costs for importing heat from district heating and the electricity from the power grid. Other relevant KPIs are the degree of Self-Generation (SG) [%], to what degree the energy system is able to cover its own demand, energy output of the FC-CHP unit and CDE from operation of the energy system. These KPIs are presented with generalized equations and units of measurement in Table 6.1.

Table 6.1: KPI's used for energy system analysis in this thesis.

KPI	Expression	Unit
Self-generation (SG)	E_{prod}/E_{demand}	[%]
Cost of energy system	C_{total}	[EUR]
Net benefit (NB)	C_{ref} - C_{total}	[EUR]
Electrical energy output of fuel cell	P_{fc}	[kWh]
Capacity factor (CF)	$P_{fc}/(P_{fc}^{max} \cdot T)$	[-]
CO2 emission from operation	$\sum_i P_i \cdot \Phi_i$	[kgCO2]

The duration for the simulations is one year unless otherwise stated, so an annualized NPV was chosen as the basis for the total cost. The investment costs were thus computed using the annuity factor as presented in (5.8). For cases lasting shorter than a year the investment costs were divided by the proper numerator e.g. 52 for durations of a week.

6.2 Results form initial simulations

In this section the results from the initial simulations of cases described in Chapter 5.4 will be presented. For a reference, the results from the base case scenario will be presented firstly. Following will the cases with investment in 2020 and 2050, as well as during summer and winter periods.

6.2.1 Results from base case

As stated in Chapter 5, the base case scenario was calculated by assuming on-site solar energy production and import from electricity grid and DH. The KPIs are given in Table 6.2. The table also shows the energy demands and Thermal-to-Electricity ratio (TEr) for each of the periods. The emissions are here the indirect emissions related to the energy imported from the electrical grid and DH.

Table 6.2: KPIs of the base case for year, winter and summer periods at Campus Evenstad.

	Year	**Winter**	**Summer**
TEr	1.74	1.90	0.46
Net benefit (NB)	-	-	-
Self-generation	5.0 %	0.5 %	13.4 %
CDE [kgCO2]	30,853	750	326
Total cost [EUR]	205,200	5,906	2,042
El demand [kWh]	902,809	17,684	17,547
DH demand [kWh]	1,054,488	30,619	7,758

6.2.2 Results from year 2020 and 2050

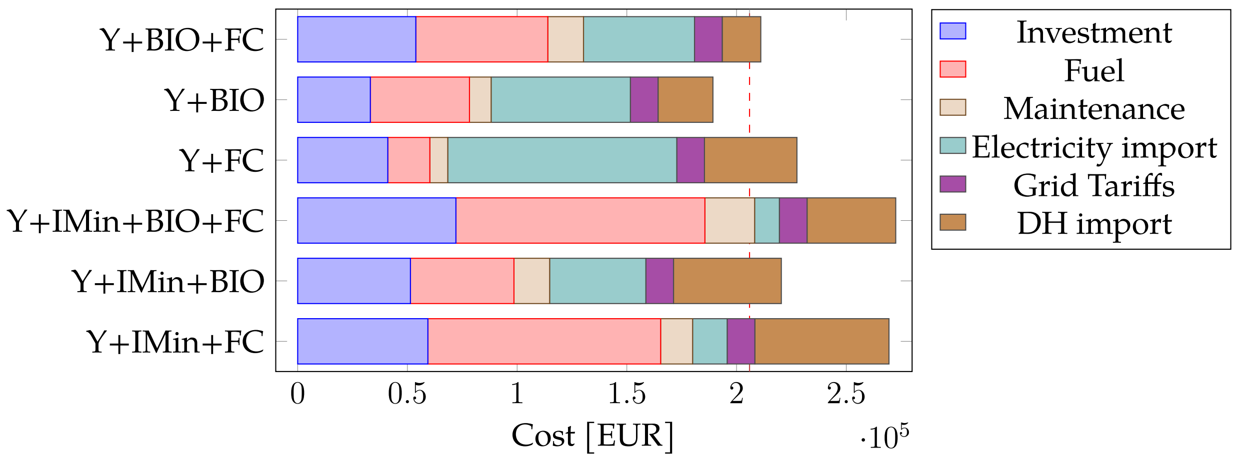
The results for the cases during year 2020 and 2050 are presented in Table 6.4. The 'FC' and 'Bio' columns indicate whether the model chose to invest in either of the technologies. Figure 6.2 shows the results for cases during year 2020, and Figure 6.3 shows results for cases during year 2050.

Table 6.3: KPIs for cases during year 2020 and 2050.

	Cost	Self-gen.	Emissions	Bio	FC
Base Case	205,200	5.0	30,853	-	-
2020+BIO+FC	188,959	54.2	19,697	-	-
2020+BIO	189,026	54.2	19,703	-	-
2020+FC	205,596	5.0	30,842	-	-
2020+IMin+BIO+FC	271,801	79.3	5,648	X	X
2020+IMin+BIO	220,193	54.7	16,398	X	-
2020+IMin+FC	268,669	67.2	6,775	-	X
2050+BIO+FC	183,573	69.7	10,026	-	X
2050+BIO	185,769	54.2	19,698	X	-
2050+FC	183,276	69.8	10,015	-	X
2050+IMin+BIO+FC	215,954	79.3	5,648	X	X
2050+IMin+BIO	211,825	54.7	16,398	X	-
2050+IMin+FC	212,229	67.2	6,775	-	X

For the year 2020, the energy system relies heavily on Bio-CHP and import from the grid. Meanwhile, the estimated cost reduction for FCs towards 2050 makes investment in this technology a profitable solution. This is both due to the reduced CAPEX costs and the cost of hydrogen itself. By investing in FC, the self-generation increases to 69.5 % as opposed to 54.1 % with the bio-CHP.

A) Economic results with investment in 2020



B) Economic breakdown with investment in 2050

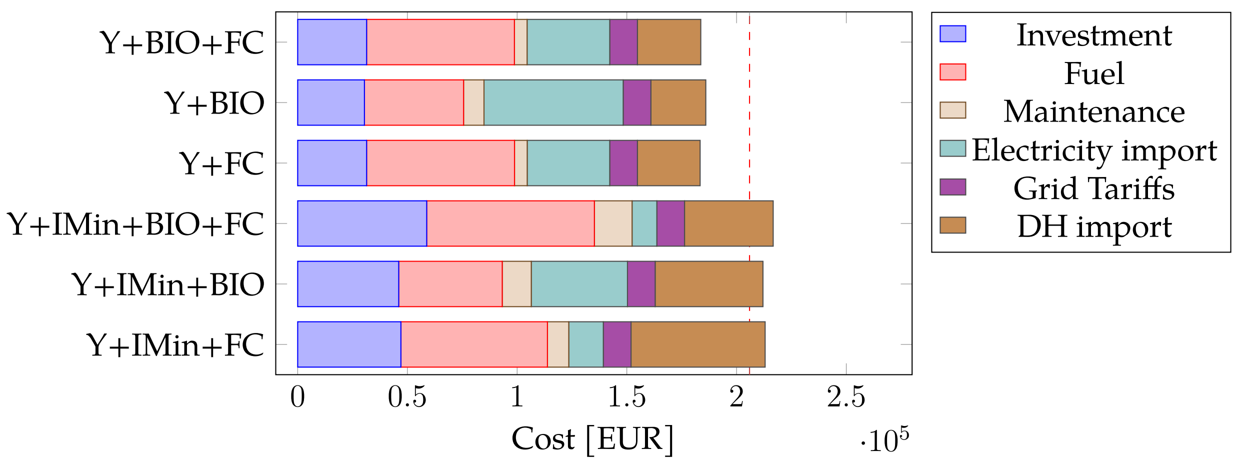


Figure 6.1: Breakdown of the costs associated with the operation of the energy system during the year 2020 in A) and 2050 in B). Investment represents the discounted capital cost during the one week period.

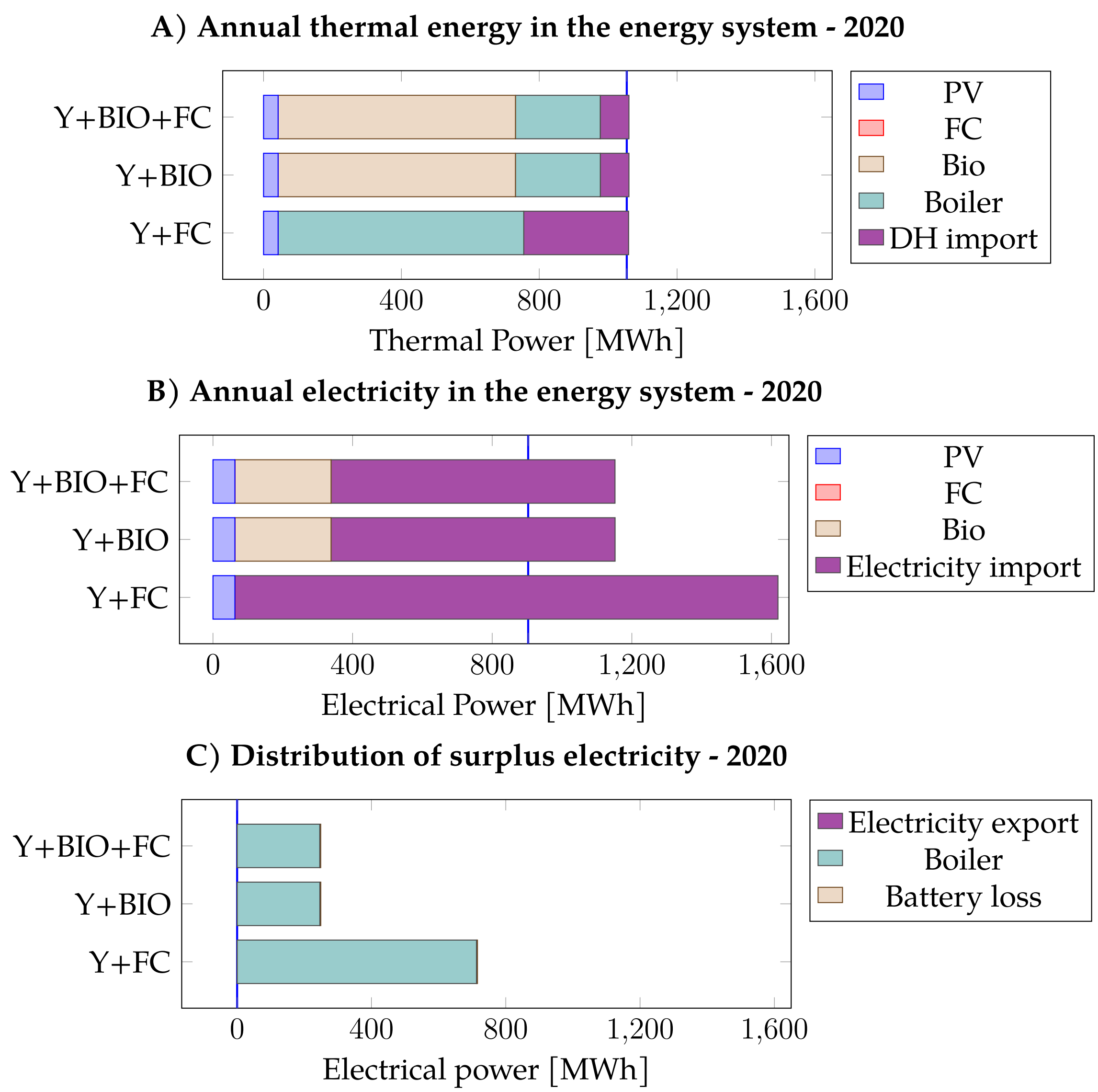


Figure 6.2: Electrical and thermal energy quantities in the energy system from each technology at Campus Evenstad in 2020. A) shows the thermal energy, B) shows the electrical energy, and C) shows where the excess electricity surpassing the demand is utilized. Case duration is 365 days. The vertical, blue lines in A) and B) indicates the thermal demand and electricity demand respectively.

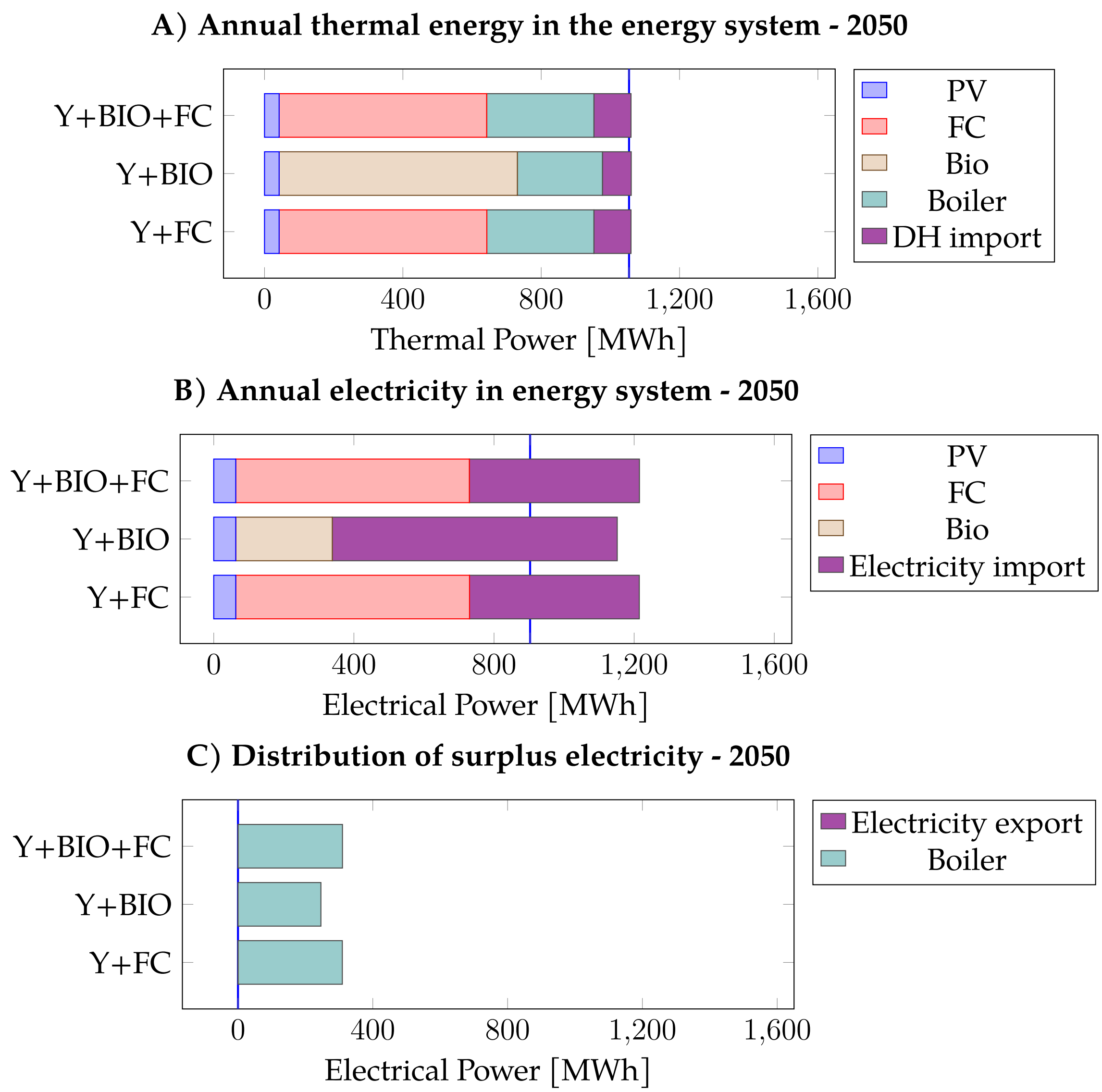


Figure 6.3: Electricity and heat quantities in the energy system from each technology at Campus Evenstad in 2050. A) shows the thermal energy, B) shows the electrical energy, and C) shows where the excess electricity surpassing the demand is utilized. Case duration is 365 days. The vertical, dashed lines in A) and B) indicates the thermal demand and electrical power demand respectively.

6.2.3 Results from summer and winter cases 2050

The costs associated with each of the different cases was divided into investment, fuel, maintenance, grid import, grid tariffs, and DH import costs. Figure 6.4 shows this economic breakdown for the winter and summer cases respectively. The objective is to minimize the total cost of the energy system during the duration of the simulations. Pure hydrogen was used as fuel, at a price of 1.5 EUR/kgH2.

Table 6.4: KPIs for cases during winter and summer 2050

	Cost [EUR]	**Self-gen.** [%]	**Emissions** [kgCO2-eq]	**Bio**	**FC**
Base Case: W	5,906	0.5	750	-	-
W+BIO+FC	3,695	100.0	105	X	X
W+BIO	4,839	49.2	493	X	-
W+FC	4,574	66.6	250	-	X
W+IMin+BIO+FC	5,454	81.3	111	X	X
W+IMin+BIO	5,612	49.4	365	X	-
W+IMin+FC	5,552	63.5	138	-	X
Base Case: S	2,042	13.4	326	-	-
S+BIO+FC	2,042	13.4	326	-	-
S+BIO	2,042	13.4	326	-	-
S+FC	2,042	13.4	326	-	-
S+IMin+BIO+FC	3,014	70.9	117	X	-
S+IMin+BIO	2,680	50.6	243	-	X
S+IMin+FC	2,645	70.9	117	X	-

From Figure 6.4 it can be seen that the model did not prioritize investment in fuel cells for neither of the cost-minimizing scenarios. During the summer week, the energy system only consists of solar power and energy storage, while all additional energy demand is covered by importing from the electrical grid and DH-network. During the winter week however, it was shown beneficial to include a bio-CHP unit to cover some of the thermal demand.

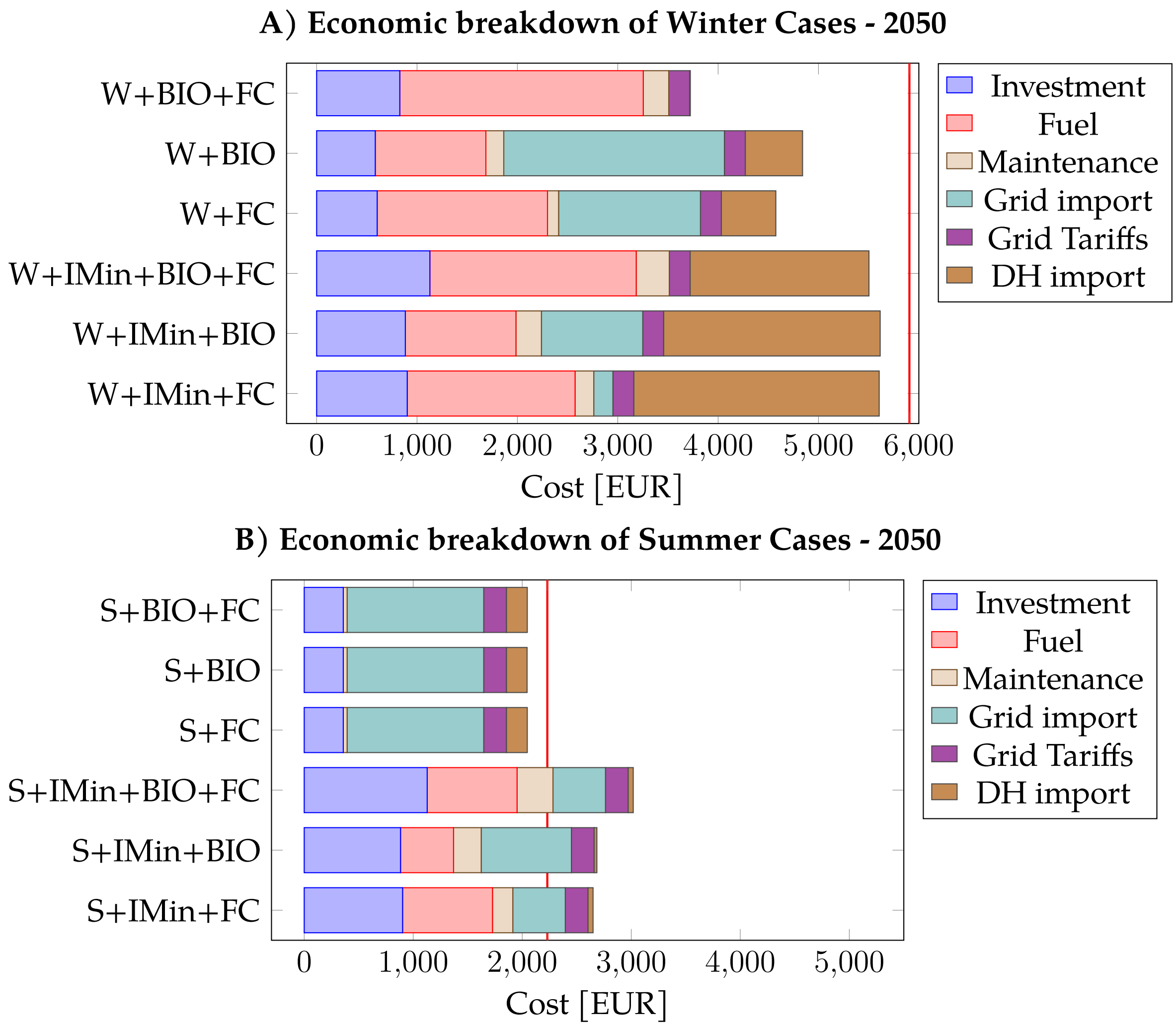


Figure 6.4: Breakdown of the costs associated with the the energy system during a 7 day period with a mean temperature of -5.5^oC in A) and 15.2^oC in B). The base case cost is indicated by the vertical, red line. For the winter case the base case out of the axis at 8,916 EUR.

The PV and ST are contributing to reducing the total cost by approximately -2.1% compared to covering all demand by means of utility-side services. This is evident by the cost minimization chose to invest in neither of the CHP technologies. It is interesting to note that for the import minimizing cases during winter (W+IMin), the energy system with both Bio- and FC-CHP units were actual found to be less costly. As can be seen in sample A) in Figure 6.4, the added generators in the energy system results in significantly lower import costs of both thermal and electrical power. Figure 6.5 shows how the total costs for each case relates to their respective degree of self-generation.

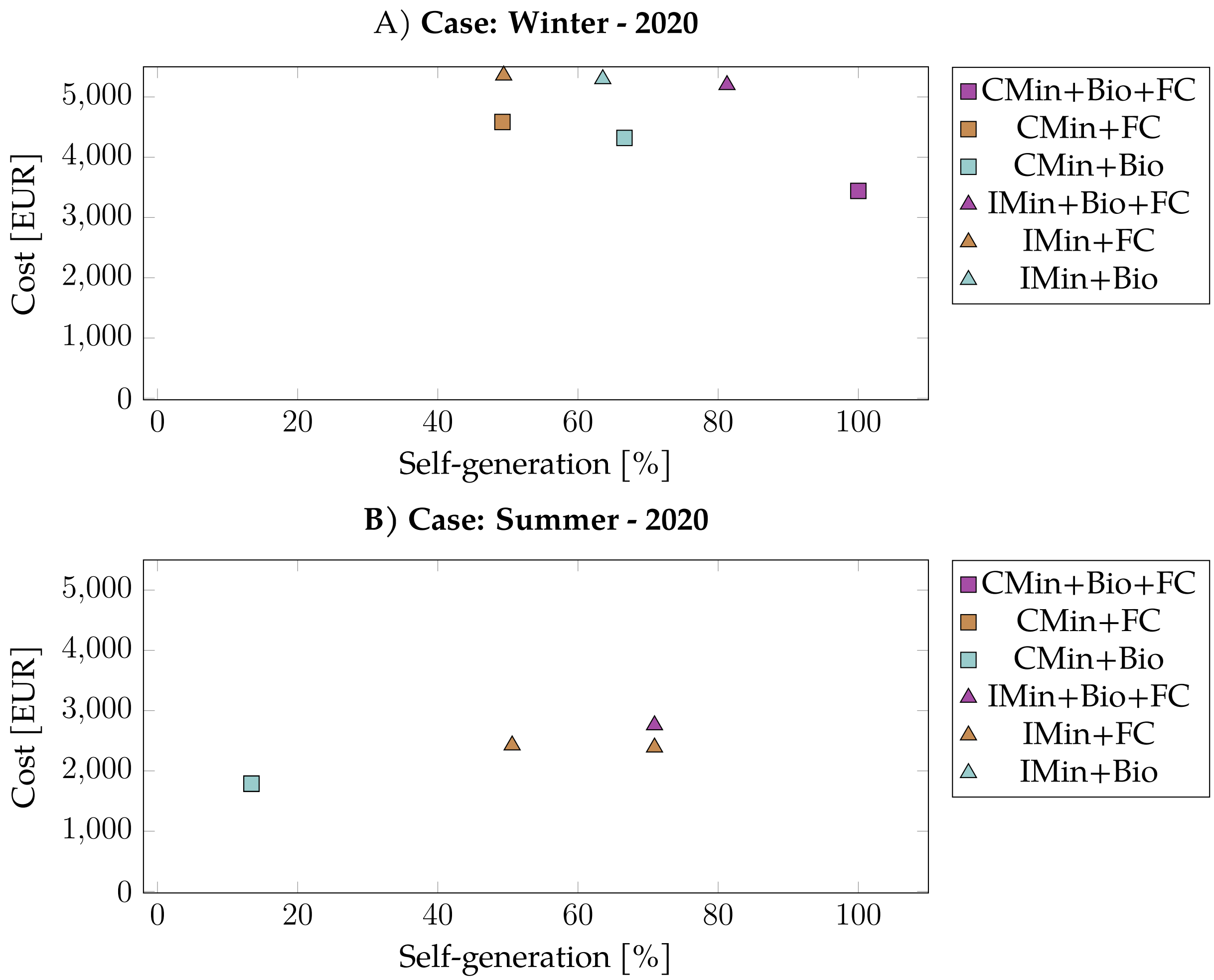


Figure 6.5: The scatter plot shows the total cost of the energy system during the simulation period on the y-axis and the degree of self-generation on the x-axis. The duration is for 7 days during a cold temperature period with mean temperature of -5.5^{o}C, A), and warm temperature period with a mean temperature of 15.4^{o}C, B).

In Figure 6.5 subplot A), all CMin cases are located in the same spot, as neither of the scenarios include investment in any of the CHP units. The relationship between total cost and self-generation is reasonably linear for the cases during summer, while the cases during winter require further examination. Due to the increased TEr and mean spot price for electricity (W: 0.051 EUR/kWh vs. S: 0.029 EUR/kWh), it becomes more profitable to include CHP units. This is reflected in the increased fuel costs and reduced import costs for the IMin cases in Figure 6.4 A).

6.3 Sensitivity analysis

To gain a better understanding of how the different economic parameters affect the profitability o the system a simple sensitivity analysis was performed. The three uncertain factors are the CAPEX of FC technologies, hydrogen fuel costs and electricity costs.

6.3.1 Hydrogen price

AS presented in Chapter 2 there are expected reductions in the cost of pure hydrogen fuel during the coming years. To examine how the system will be affected by the altering hydrogen prices, cases for one year (2020 and 2050), were simulated, altering the price of hydrogen by increments of 0.2 EUR/kgH2 from 0.6 through 3.2 EUR/kgH2. The simulations were performed by forcing investment in FC-CHP and not investing in bio-CHP. The results of this analysis can be seen in Figure 6.6.

By forcing this investment, the values determining whether the fuel cell is operational or not is the relationship between the hourly spot prices, TEr and the hydrogen cost meaning that the operation curve for the FC is similar in 2020 and 2050. Also indicated in Figure 6.6 are the critical hydrogen costs which the market will have to reach for FC-CHPs to be profitable at the given CAPEX and energy system configuration. These values are approximately 1.6 EUR/kgH2 for 2020 and 1.9 EUR/kgH2 for 2020, meaning that any values below these points could be profitable.

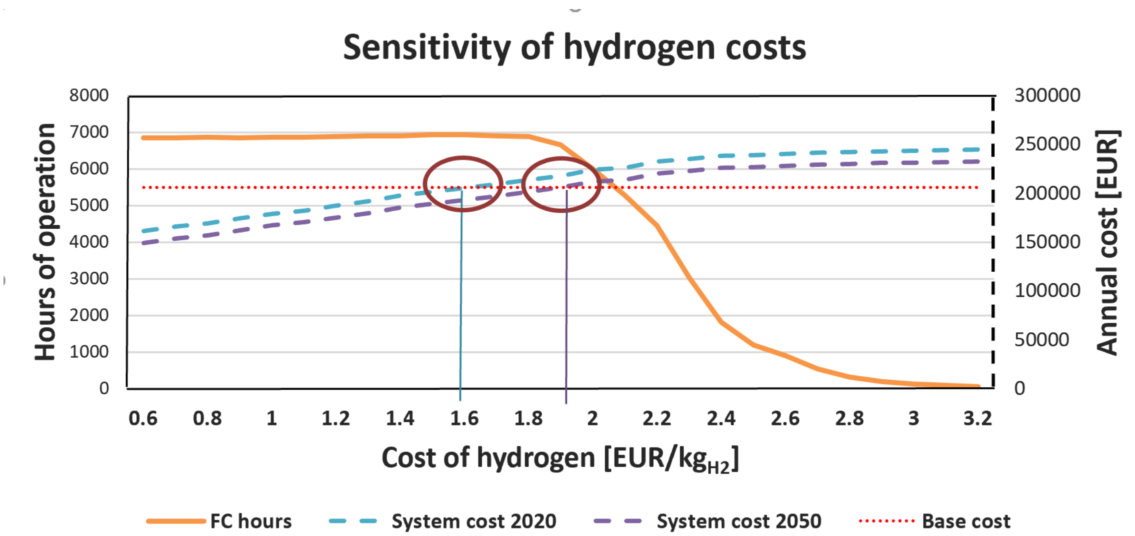


Figure 6.6: Plot showing the sensitivity of fuel cell operation and annual cost of the energy system to hydrogen costs for 2020 and 2050. The red circles indicate the critical hydrogen costs where it could be considered profitable to invest in fuel cells at 1.6 EUR/kgH2 for 2050 and 1.9 EUR/kgH2 for 2020.

6.3.2 Electricity prices

The electricity costs were varied between 50 % and 200 % compared to the spot prices for 2019. The results are presented in Figure 6.7. The price of hydrogen is constant and is set at 2.4 EUR/kgH2 during 2020 and 1.5 EUR/kgH2 during 2050.

It is obvious that at the lower hydrogen cost and CAPEX for year 2050 the profitability of FC-CHP is much more resilient to lowered spot prices. The slope of the operation curves for 2020 and 2050 are also different, mostly due to the difference in hydrogen cost for the two cases. The lower the hydrogen cost the steeper the curve.

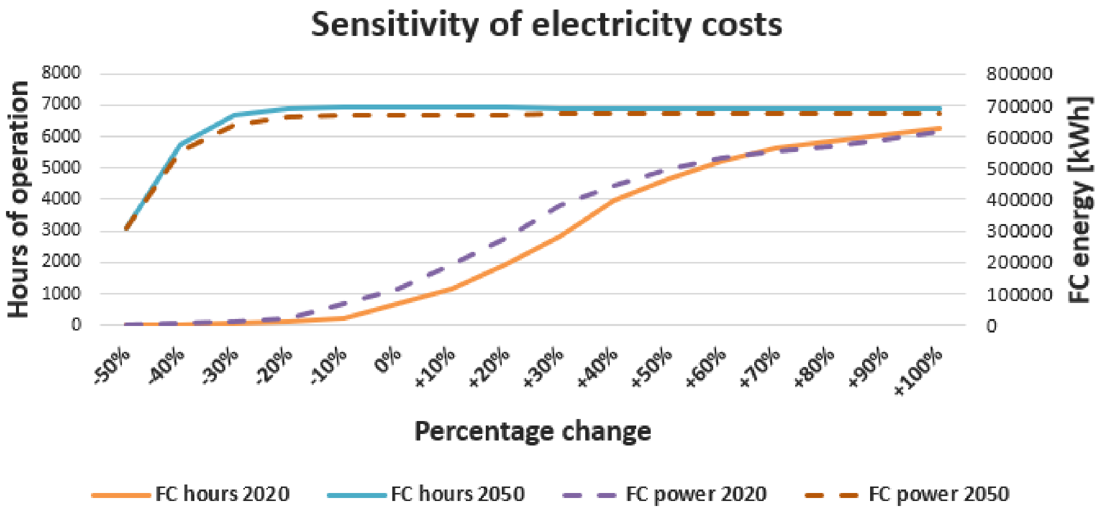


Figure 6.7: Plot showing the sensitivity of fuel cell operation to change in spot price. The spot prices are related to the values from 2019 that were used during the initial simulations.

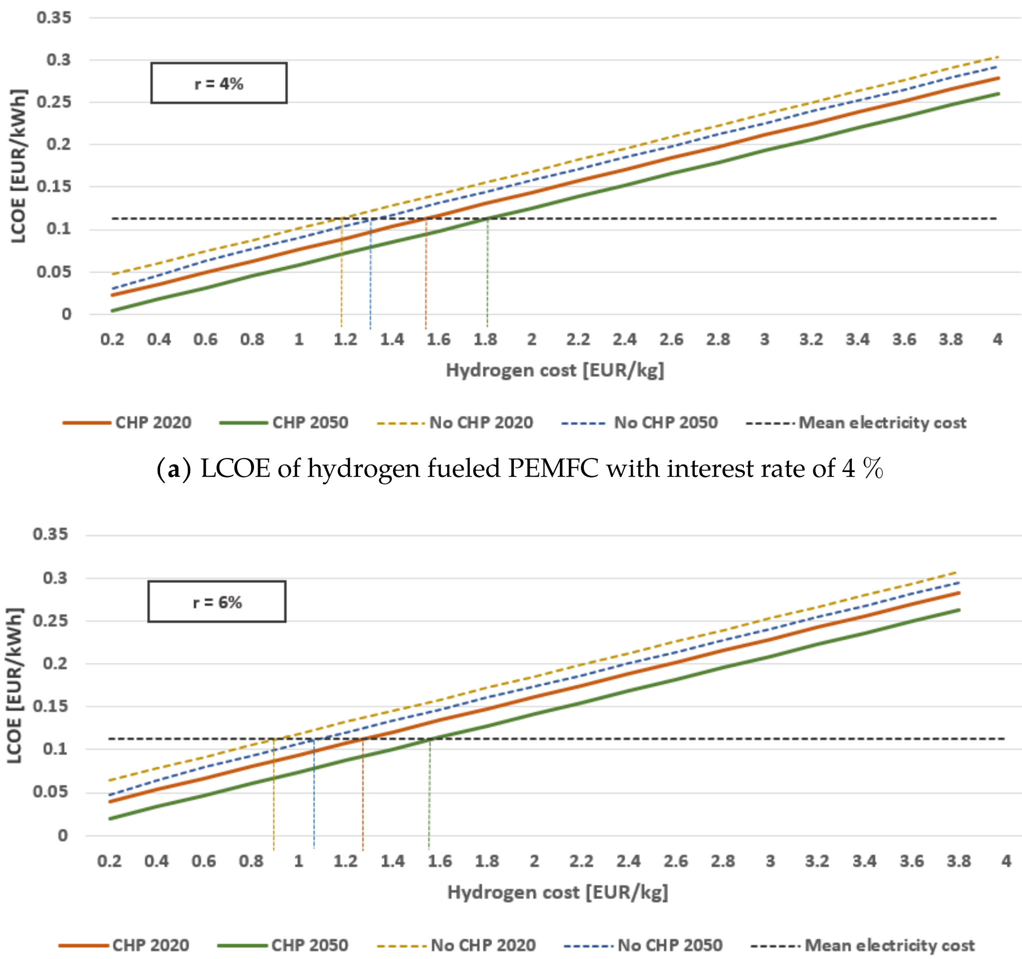
6.4 LCOE

The LCOE were calculated using Equation (5.2) and district heating was chosen as reference technology for the heat credits. The fuel reformer cost represent an additional 24.5 % increase in the investment compared to fuel cells fueled by pure hydrogen to allow the unit to reform natural gas, and similarly the heat recovery cost represent a decrease of 17.5 % when the heat recovery components are not needed, i.e. when the FC only provides electricity [72]. Figure 6.9 shows the LCOE for PEMFC as a function of the hydrogen cost for both CHP and electricity-only FCs. The LCOE were calculated for interest rates of both 4 % and 6 % the same way it is carried out in NVE's technology report [63]. The mean electricity price is the average consumer price for electricity in 2019. A common target for stationary fuel cells is to achieve 50,000 hours of operation during the lifetime. Assuming an economic lifetime of 10 years the operation is set to be 5,000 hours per year.

Table 6.5: Parameters used for calculation of LCOE.

Parameter	Value
Economic lifetime	10 yrs [71]
Discount rate	4 % & 6 %
Maintenance	5 %
Electrical, η_{fc}	45 % (LHV)
CHP fraction, ϕ_{chp}	0.9
Operational hours	5000
Investment 2020	1,600 EUR [71]
Investment 2050	900 EUR [71]
Mean electricity cost	0.1126 EUR [73]
Fuel reformer cost	24.5 % [72]
Heat recovery cost	17.5 % [72]

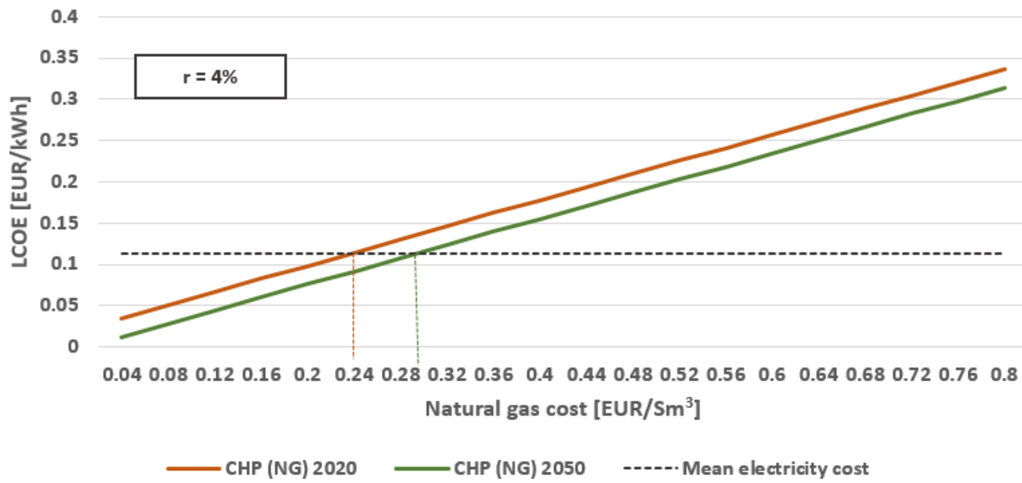
Figure 6.9 shows the LCOE of pure hydrogen fueled PEMFC both with and without providing heat in 2020 and 2050. The mean electricity price is also shown in the figure and is used to find the critical price of hydrogen below which it could be considered profitable to invest in the FC unit. Figure 6.9 similarly show the LCOE for natural gas fueled PEMFC.



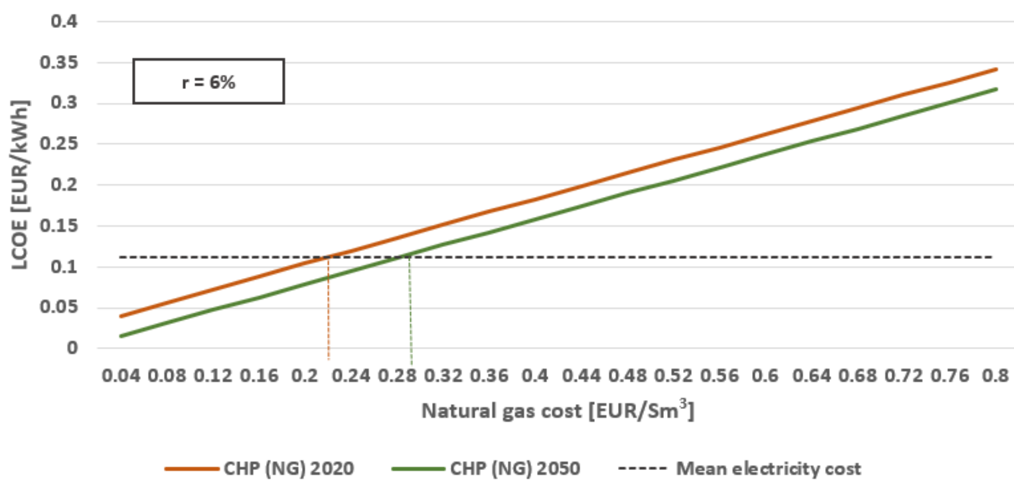
(**a**) LCOE of hydrogen fueled PEMFC with interest rate of 4 %

(**b**) LCOE of hydrogen fueled PEMFC with interest rate of 6 %

Figure 6.8: Levelized cost of energy for PEMFC assuming constant annual cost and production.



(**a**) LCOE of NG fueled PEMFC with interest rate of 4 %



(**b**) LCOE of NG fueled PEMFC with interest rate of 6 %

Figure 6.9: Levelized cost of energy for PEMFC assuming constant annual cost and production.

The LCOE calculations give similar results to the sensitivity analysis regarding the critical price of hydrogen. The main reason for the discrepancies between the two are the fact that the LCOE only references the mean electricity cost and not the optimal operation of the energy system where it is installed. This leads to the LCOE having even stricter tolerances for the hydrogen price than shown in the sensitivity analysis.

6.5 Results for different building types

Simulations were carried out for the six different building types presented in Chapter 5. The heated area for the buildings were scaled individually so the annual heating demand was equal for all cases. Table 6.6 shows the heated area along with electrical and thermal energy demand for each building.

Table 6.6: Heated area and annual energy demand for six different building types.

Building	Area [m2]	El demand [kWh]	DH demand [kWh]	TEr
Evenstad	8,592	902,783	1,054,451	1.168
Apartment	11,046	428,876	1,054,451	2.459
Hospital	4,209	951,982	1,054,451	1.108
Office	8,401	2,529,842	1,054,451	1.237
Nursing home	14,372	852,335	1,054,451	0.415
Shop	13,870	1,924,087	1,054,451	0.548
University	9,358	1,654,062	1,054,451	0.637

A base case was simulated for each building similarly to the initial cases with solar energy and battery pre-installed. Each building was subsequently simulated by forcing investment in a 100 kWe PEMFC. The resulting KPI's can be found in Table 6.7 and the relationship between TEr and reduction in annual cost of each building can be seen in Figure 6.10.

Table 6.7: Resulting KPI's for six different building types and Campus Evenstad when an FC-CHP unit is installed in 2020 and 2050.

Case	Net benefit [EUR]	Cost reduction	Capacity factor
2020			
Evenstad	-8,986	-4.4 %	0.135
Apartment	-11,391	-8.3 %	0.134
Hospital	-14,224	-6.5 %	0.141
Office	-13,901	-6.8 %	0.141
Nursing home	-13.957	-4.6 %	0.155
Shop	-15,822	-5.2 %	0.147
University	13,283	-5.0 %	0.144
2050			
Evenstad	21,924	10.7 %	0.762
Apartment	19,519	18.9 %	0.743
Hospital	32,238	15.6 %	0.814
Nursing home	33,345	17.0 %	0.863
Office	28,653	8.3 %	0.760
Shop	29,291	9.9 %	0.779
University	35,629	13.4 %	0.860

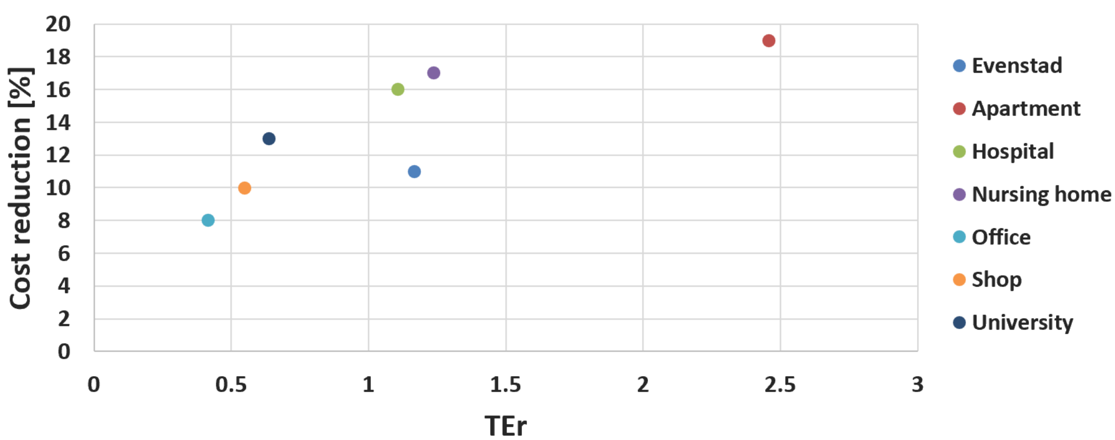


Figure 6.10: Cost reduction for six different building types and Campus Evenstad when an FC-CHP is introduced in 2050.

As can be seen from Figure 6.10 there is a present correlation between the thermal-to-elecitricty ratio of the building and the reduction in annual cost of the system. The three most suitable building types are apartments, hospitals and nursing homes which all have a higher heating demand than electricity demand and are commonly buildings that facilitate people during all hours of the day ensuring fairly stable demand profiles throughout the day.

6.6 Research questions based on results

This section will raise some questions about the potential of implementing FC-CHP units that are not addressed directly by the results found throughout this chapter. Most of the questions regards FCs in energy systems and the practical applicability of such systems in Norway. The answers can be found in the subsequent chapter.

6.6.1 Operation of fuel cell

Is there a more optimal way of operating the fuel cell unit in energy systems than that provided by the MILP model?

Results from the initial simulations show that it could be profitable to include FC-CHP units en energy system. The optimization model chose to operate the fuel cell on an hourly basis whenever the cost of operating the FC is less expensive than importing electricity and heat from the grid. PEMFC have both quick start-up times and dynamic response but the operation of the unit will have a direct input on the durability of the technology as described in Chapter 3.3.

6.6.2 Delivery of pure hydrogen to FC-CHP

Which methods could best be utilized for delivery of hydrogen to an FC-CHP, and at what locations could it be beneficial to establish such systems?

It was assumed that the FC in the energy system model received a continuous supply of hydrogen fuel. This meant that there were no limitations on the operating hours for the FC based on input of fuel, nor were any costs related to transport and storage of hydrogen considered in the economic analysis of the energy system. The profitability of FC systems will however depend on these factors among other factors.

6.6.3 Low quality heat from low temperature fuel cells

Is it plausible for an LT-PEMFC unit to provide the necessary heat for a system of the size used during the simulations in this thesis?

A low temperature FC was chosen for the energy system in this model, and While small-scale PEM units have been proven able to provide DHW in the sub 1 kWe segment, some researchers remain uncertain of the potential for these units to provide CHP in larger systems. NVE emphasized that due to the low quality nature of the heat in LT-PEMs, these are not suitable for industrial CHP systems [63].

7 Answers to research questions

7.1 Operation of FC-CHP

In this section operation of the Fuel Cell (FC)-unit will be examined in more detail. There were no investment in FC for any cases during 2020, so the focus will be on the operation of FC-Combined Heat and Power (CHP) with investment in 2050. As can be seen from the summer and winter cases in Table 6.4 the model will not invest in FC-CHP during summer. In the initial cases for 2050, the resulting FC-CHP unit was run for 6,929 hours. Figure 7.1 shows a scatter plot of the electrical output of the FC as a function of outside temperature. Figure 7.2a similarly shows the operation of the FC-unit and the outdoor temperature through the year.

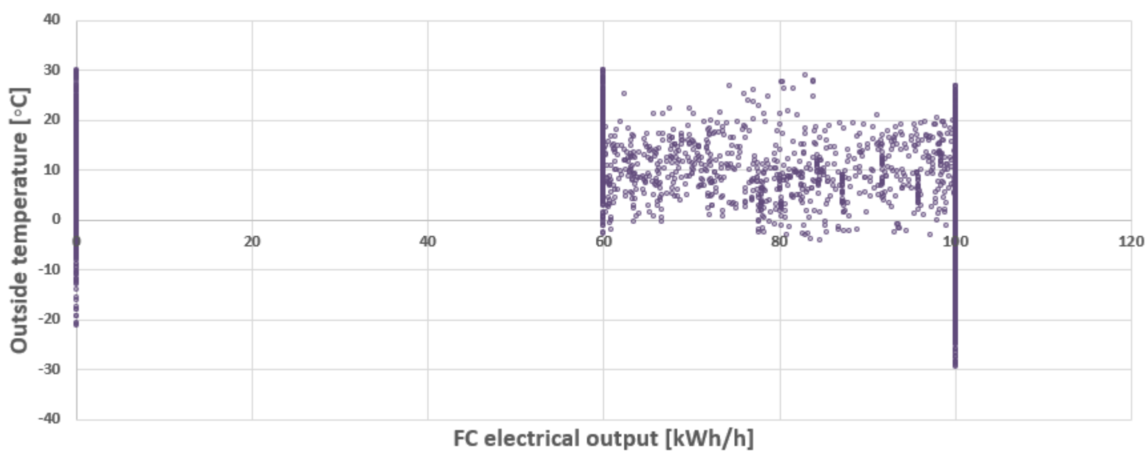
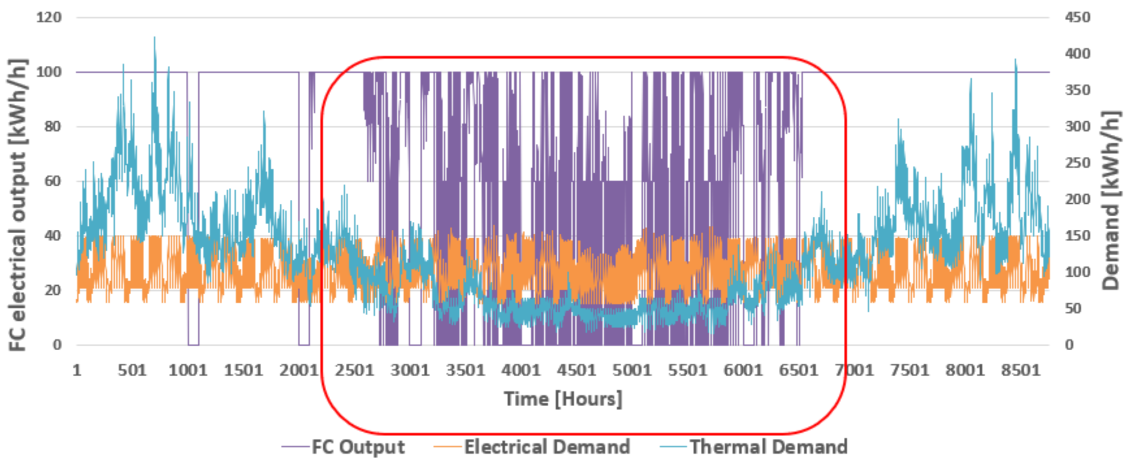
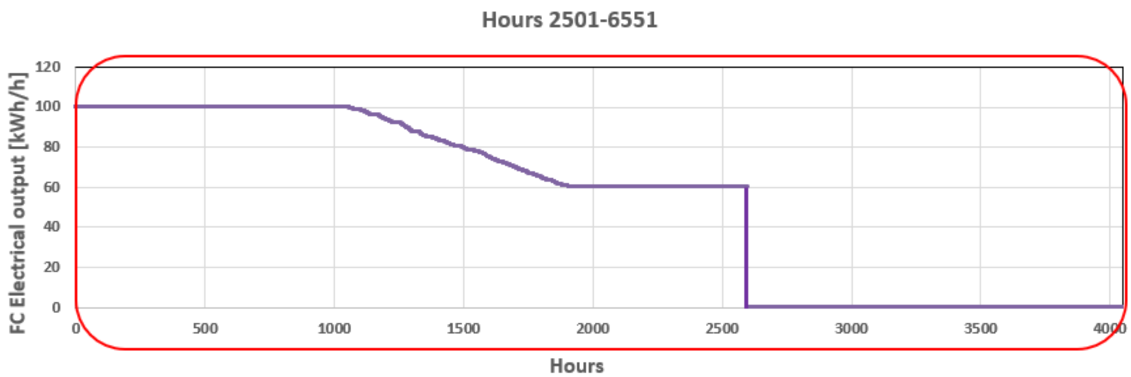


Figure 7.1: T-curve for the electrical output of FC as a function of the outside ambient temperature in 2050.



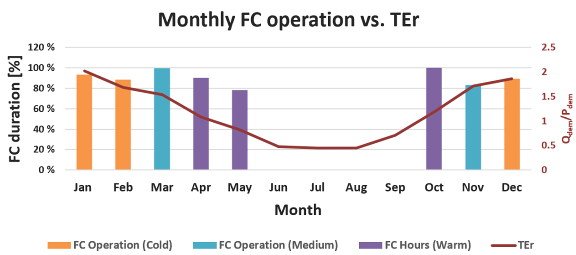
(**a**) [Duration curve for FC (left axis), and the electrical power and heating demands (right axis) during 2050.



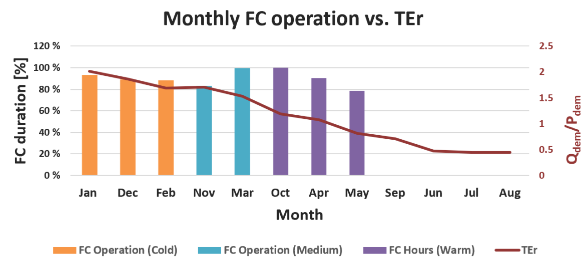
(**b**) Duration curve for FC during period between hours 2501 and 6551 during 2050.

Figure 7.2: Hourly operation of FC for the entire year 2050 (a) and duration curve for FC operation between hours 2501 and 6551 (April 14th through September 30th) (b).

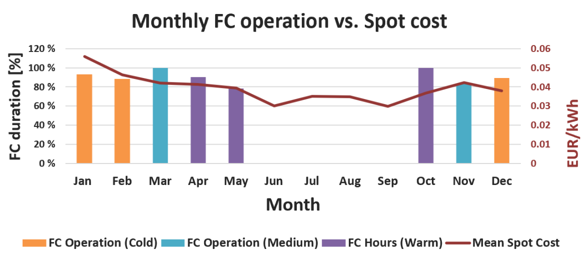
The fact that the lifetime of an FC is degrading at different rates depending on the operating conditions indicates that it could be beneficial to utilize the FC unit more selectively. This was examined by parsing the year into shorter periods, either monthly or weekly. In these simulations the model is given the choice to invest in FCs for each of the given periods. Figure 7.3 and 7.4 shows the results from the monthly and weekly cases during 2050.



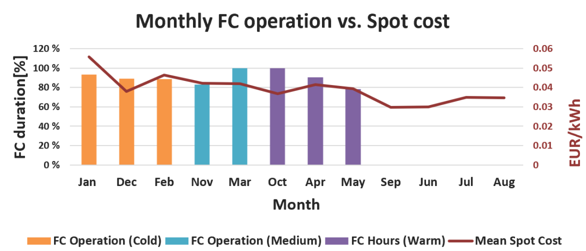
(**a**) Monthly FC opertaion and TEr - chronologically



(**b**) Monthly FC opertaion and TEr - Sorted by TEr and temperature class

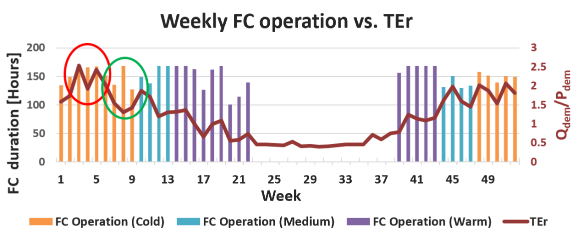


(**c**) Monthly FC opertaion and mean spot price - chronologically

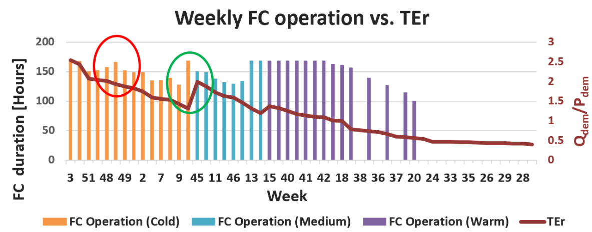


(**d**) Monthly FC opertaion and mean spot price - Sorted by TEr and temperature class

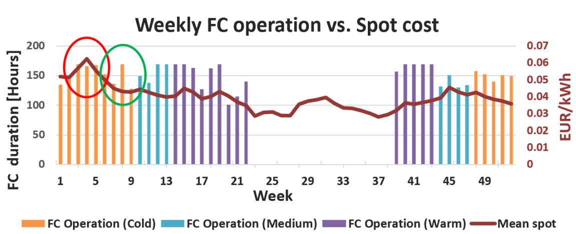
Figure 7.3: Monthly fuel cell operation. The months are sorted in outside temperature groupings, indicated by the color of the bar plots.



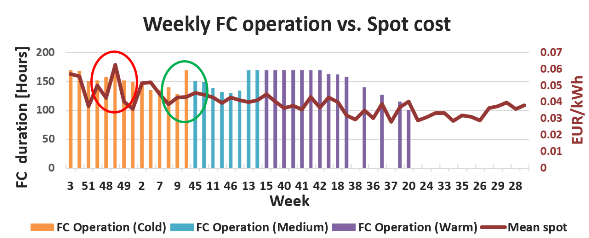
(**a**) Weekly FC opertaion and TEr - chronologically



(**b**) Weekly FC opertaion and TEr - Sorted by TEr and temperature class



(**c**) Weekly FC opertaion and mean spot price - chronologically



(**d**) Weekly FC opertaion and mean spot price - Sorted by TEr and temperature class

Figure 7.4: Weekly fuel cell operation for the entire year of 2050. The weeks are sorted in outside temperature groupings, indicated by the color of the bar plots.

As can be seen from both Figures 7.3 and 7.4, there is a clear correlation between the Thermal-to-Electricity ratio (TEr) and the investment in and operation of FC. By arranging the plots from highest to lowest TEr, as well as by outside temperature grouping (cold, medium, warm), Subfigure 7.4b indicates that a higher TEr will result in higher energy output of the FC. The outside temperature groupings are mainly presented to indicate an expected cost of District Heating (DH), as the cost of heat is generally higher during winter. As indicated by the red and green circles in Figure 7.4, there are some exemptions to the general correlation between TEr and FC output that that can be explained by the relationship between TEr and mean spot price. The red circles highlight week 4 which was an increase in spot price coinciding with a decrease in TEr compared with weeks 3 and 5, resulting in a scenario where it is particularly beneficial to utilize FC. A similar situation is indicated for week 8 in the green circles. The same correlation can be seen from the monthly cases in 7.3.

7.2 Strategic control of FC-CHP

By implementing a periodic FC control strategy it is possible to extend the economic lifetime of the unit. As proposed in Chapter 7.1 an alternative strategy could be to shut the FC-unit totally down during the month of May through September. By implementing this solution for a scenario with investment in only FC, the total cost of the system increased by approximately 3%, while the self-generation dropped by 0.14 points to 0.59. On the other hand the number of hours operating below rated power is reduced by 1,200 hours, and the number of full start/stop-cycles is reduced from 274 to 45.

Table 7.1: Key parameters for year 2050 with and without operating the fuel cells during May-August.

	Operate FC during summer	**Stop FC during summer**
Total cost [kEUR]	184	187
FC operation [h]	7,116	5,390
Self-generation	69.8	56.5
Start/stop-cycles	219	39
Part load hours	1,561	406

7.3 Delivery of pure hydrogen to FC-CHP

As of 2020 there are only three hydrogen refueling station that are currently being operated: ASKO Midt-Norge in Trondheim, hydrogen bus refueling sation at Rosenholm south-east of Oslo, and Hynion in Bærum. These along with scheduled and potential locations for future hydrogen stations and ferry docs are outline in Figure 7.5.

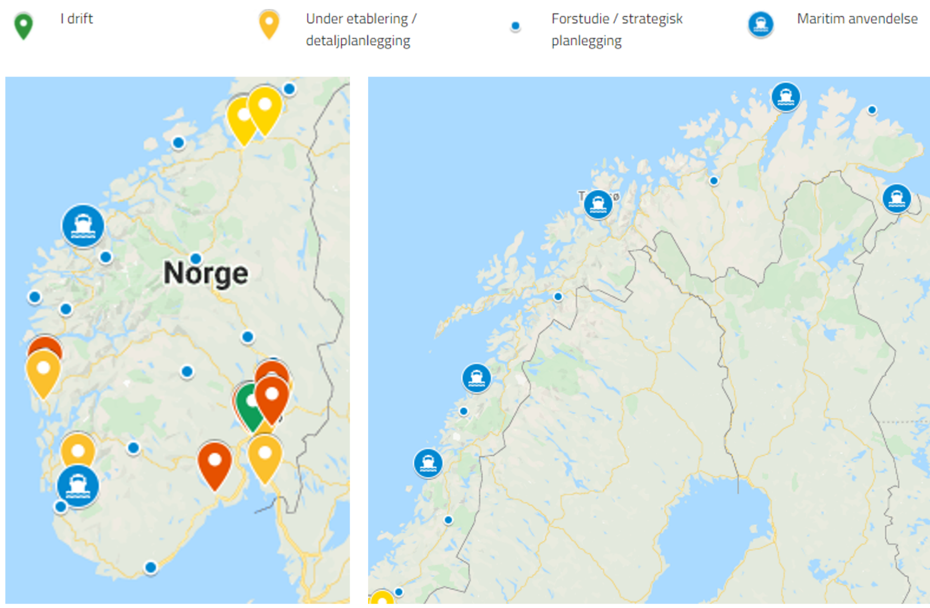


Figure 7.5: Map of current, scheduled and future hydrogen fuel stations in Norway. The red markers indicate stations with unknown status, where some are closed test stations or under investigation in the wake of the incident at Kjørbo of June 2019 [74]

One of the assumptions made during the simulations was a continuous supply of hydrogen. Assuming constant operation at rated power level of 100 kWe the FC consumes approximately 6.7 kg of hydrogen per hour. This emphasises the importance of choosing a location able to provide the FC unit with the needed hydrogen. One possible solution could be to utilize and existing, or scheduled hydrogen refueling station for supply. Another strategy could be to aim for an industrial symbiosis with hydrogen intensive production lines. Some examples are Herøya, where Yara produces Ammonia, or Equinors methanol plant at Tjeldbergodden near the island of Hitra.

The use of natural gas as a fuel could mitigate some of the infrastructure cost but at the expense of zero-emission operation and for Polymer Electrolyte Membrane Fuel Cells (PEMFC) a drop in 5-10 % drop in efficiency will be expected when a fuel reformer is introduced into the system. Solide-Oxide Fuel Cells (SOFC) could be a promising alternative if it is desirable to use natural gas. Due to the slower response of SOFC this could be suitable for energy systems where the load is fairly constant or it could be used as a base load unit for covering mainly heating and inflexible loads.

7.4 Carbon emissions from operation of fuel cells

Most energy system analysis only consider Well-to-Wheel (WTW) emissions, so emissions from e.g. extraction of minerals and construction of the system components are not considered. Even though hydrogen in itself is a carbon neutral energy carrier, the footprint related to the fuel used will depend on the means of production, transportation and storage. This holds particularly true if the FC unit is supposed to assist in decarbonization. In a WTW analysis a decentralized water electrolysis system likely mitigates both emissions from production and transportation, but could still have indirect emissions due to the electricity used by the electrolyzer. DNV estimates these indirect emission at 0.8 kgCO2/kgH2 or 0.024 kgCO2/kWh of stored energy in Norway, based on NVE's green certificate declarations [65]. Hydrogen produced through Steam Methane Reforming (SMR) will have emissions in the range of 8-10 kgCO2/kgH2 or 0.240-0.300 kgCO2/kWh. Compressed hydrogen will have an efficiency of ≈94 % [75], while liquefied hydrogen will achieve ≈87 % [76], resulting in additional indirect emissions depending on the energy utilized during the process.

7.5 Low quality heat from low temperature fuel cells

For simplicity in this thesis all the Domestic Hot Water (DHW) solutions were viewed as one cumulative energy storage unit. There are in reality different thermal demands and characteristics for the different water tanks in the system as well as different use cases. FHI[12] advises that all stored hot water should ideally remain at temperatures above 60$^\circ C$ to prevent contamination of legionella bacteria [77]. Suitable temperatures for indoor water outlets are approximately 40$^\circ C$ for bath, shower and hand washing water, and 45$^\circ C$ for the kitchen wash. Low-temperature-Polymer Electrolyte Membrane (PEM)FC operate at temperatures between 50-80$^\circ C$. While even 50$^\circ C$ will suffice to cover most space heating demand, it will be desirable to opt for units operating at the higher end of this spectrum to be able to provide the necessary heat for DHW.

It is worth noting that the DH inlet providing heat to Campus Evenstad is approximately 80/60, meaning that the supply pipe provides water at 80$^\circ C$ and leaves the return pipe at 60$^\circ C$. In this case, the DH is not used to heat DHW directly, but pro-

[12]Folkehelseinstituttet - https://www.fhi.no/

vides preheating of water in two of the largest buildings: apartments and administration building. This serves a case proving the possibility of a Low-Temperature (LT)-FCs to perform the same function in a similar energy system. The required temperature levels for the different thermal demands could be considered during the planning phase of the local heating grid to first supply heat to DHW tanks, then cover space heating demand. If given the specific conditions regarding the local heating grid, the energy loss during transportation of heat could be computed using Equation (3.21). Heat loss for a typical pipe system with cross-section below 150 mm will be less than 1 W/m [78] which become negligible in a local heating grid with less than 1 km of piping, equivalent to an energy loss of $\approx 1kWh/h$.

8 Discussion

Chapter 8 analyzes and discusses the results from Chapter 6 further, and starts with a summary of the key findings. The chapter starts by attempting to answer some of the research questions posed during Chapter 6, and continues by examining some broader aspects in relation to the implementation of Fuel Cell (FC)-Combined Heat and Power (CHP) in Norway.

8.1 Comparing with similar studies

The 'Plusskunde' agreement is currently being revised to avoid curtailment and dumping from producers exceeding 100 kW of electricity transfer. At the current iteration of the agreement it is not surprising that the results form simulations in this thesis show little to no export of power to the grid. This is in line with the conclusion given by FME ZEN in their ZEN-memo No.17 [59], as it is be more valuable to utilized the produced electricity on-site. As long as the Variable Renewable Energy (VRE) production is lower than the current demand, it will in most cases not be beneficial to export power from CHP units, as mitigating import is more valuable than adding export.

A study performed by Petkov Gabrielli focused on Power-to-Gas (P2G) for seasonal energy storage [79]. They utilized a Mixed Integer Linear Programming (MILP) framework with the objective of minimizing the annual cost and total emission from the energy system. Although their objective is to compare differing storage technologies, they highlight the fact that Power-to-Power (P2P) solutions with CHP capabilities are better suited for geographical locations with higher Thermal-to-Electricity ratio (TEr)s. This will both help in shifting renewable power by storing hydrogen through seasonal changes, and allow the system to self-utilize more of the FCs generated thermal power. They also highlight air source heat pumps as a potential competitors to FC implementation, emphasizing that the efficiency of the heat pumps were one of the most influential factors in the deployment of hydrogen technologies.

8.2 Additional benefits from hydrogen energy systems

In addition to providing on-site delivery of both heat and electricity distributed generation technologies like FCs have the potential to provide added benefits in the form of flexibility. Particularly when combining the technology with VRE and electrolysis to provide hydrogen energy storage and local hydrogen production.

As presented in Chapter 7 it could be beneficial to operate FC-CHPs seasonally. By turning the FC off during May through August the CHP unit could be operated as a base load provider for the remainder of the year with approximately 5,000 full-load hours.

Peak shaving due to distributed generation could thus be a huge benefit to system operators. Investment in new power transfer infrastructure is expensive, so by lowering the necessary transmission capacity in the grid the system operators could possibly save large sums on infrastructure costs. Although the Greenhouse Gas (GHG) emissions associated with the power produced in Norway is relatively low due to the high fraction of hydro power production, it could still be environmentally beneficial to increase investment in renewable energy sources in Norway. By increasing the amount of distributed generation, the hydro electric power producers gain more flexibility, allowing for a larger degree of export to neighboring countries with higher GHG emissions.

Much like VRE, hydro electric power plants have a low marginal cost associated with production of power. However unlike solar or wind power, hydro electric power is flexible when it comes to production. In the European power market the electricity prices varies by time of day and demand, among other factors, and is commonly lower during night time or weekends. Due to the inherent flexibility in dispatch of hydro electric, these power plants often only operate during daytime, or hours with high electricity cost, to maximize the revenue per unit of water. By lowering the domestic demand for hydro electric power, distributed renewable generation in Norway can thus in some regards be viewed as a means of lowering the emissions from the European power sector.

Both voltage drops and power loss in centralized power transfer are directly related to the current through the lines. By reducing the current transfer it is possible to reduce voltage drops proportionally to the current reduction, and power losses by the square of the reduced current level as seen in Equation (3.24) and (3.25) respectively.

As part of an effort to decarbonize the energy sector, there has been a push towards electrification in Norway during the past three decades. Although not directly related the shift from using fuel based boilers to electric space heaters and heat pumps for thermal power has coincided with an increase in electricity consumption of 28.3 % within Norway from 1990 to 2018 [80]. A similar increase is expected from 2018 to 2040, meaning that decentralized CHP units in general have an added potential to mitigate some of the transmission losses that will result from increased electrification of the heating sector.

8.3 Governmental policies

The Norwegian Government opted in 2018 to develop a strategy for research and development of hydrogen as an energy carrier [81]. As evidenced by the synthesis report developed for the government by DNV [4], much of the focus has been on hydrogen in the transportation and industrial sectors. This could indicate that there will probably not be any substantial subsidy programs for FC energy systems within the next couple of years. Within the revised national budget[13] presented in 2021, there are provision of 200 MNOK to support the advancement of hydrogen technologies and construction of important hydrogen infrastructure [82]. Although no part of the press statement addresses hydrogen in the energy sector, it could still be considered a good step in the direction towards Norway as an international player in the hydrogen economy.

8.4 Limitation in method

This section will present some key limitations of the method used during this thesis. Some of the key assumptions will be stated firstly, then the choice of economic factors will be discussed.

8.4.1 Assumptions and simplifications

Similar electricity market conditions and energy demands for the year 2020 and 2050. With a shift towards renewable energy sources as well as increased carbon taxes and electrification, it is however estimated that the future electricity prices will increase slightly towards 2040 [83]. With additional reliance on VRE the electricity prices are also expected to become more weather dependent and volatile. Due to the many uncertainties tied to the future prices in the power market, the same values were chosen for 2020 and 2050.

The electricity prices were assumed equal in 2020 and 2050 and this could be problematic due to the uncertainties of the energy market composition towards 2050. With a shift towards renewable energy sources as well as increased carbon taxes and electrification, NVE estimates that the future electricity prices will increase slightly towards 2040 [83]. With additional reliance on VRE the electricity prices

[13] Revidert nasjonalbudsjett 2021 - https://www.regjeringen.no/no/statsbudsjett/2021/

are also expected to become more weather dependent and volatile. Due however to the fact that the focus during the optimization phase was on assessing the economic and operational performance of the fuel cell unit this was suitable assumption to make. The effects of plausible change in electricity prices were however also addressed during the sensitivity analysis.

8.4.2 Choice of economic factors

All future estimates for cost reduction of the generator technologies were gathered from the Danish Energy Agency's report on Technology Data. The estimates for fuel cells in particular are subject to a large degree of uncertainty due to the early market phase of the technology. The DEA projections are based in large part on on technology roadmaps given by Ea Energy Analyses DK and IEA. The nominal investment costs for fuel cells were given with upper and lower limits within a 90 % confidence interval. The costs were given in MEUR/MWh for a nominal system of 1 MWe capacity, so the upper values were chosen to account to a reasonable degree for the cost increase due to sub-nominal installation capacity.

A discount rate of 5 % was chosen for the economic analysis in this thesis. In their long term analysis of energy technologies NVE utilizes a discount rate of 4 % by governmental recommendations [63]. The Norwegian Climate Agency also recommends a 4 % discount rate, however, due to the degree of uncertainty in hydrogen fuel costs the rate was set slightly higher.

9 Conclusion

From the research presented in this thesis it can be concluded that utilizing fuel cells to provide heat and power for buildings in Norway is considered profitable by the year 2050. Based on the operation of the fuel cell unit found in the initial simulations, a periodic operation scheme of the fuel cell combined heat and power unit was recommended to mitigate the degradation caused by frequent start/stop-cycles during periods with lower thermal energy demand. By turning the fuel cell unit off during the months of May through August it was found that the number of start/stop-cycles were reduced from 274 to 45, potentially mitigating a permanent open-circuit voltage loss of -45.8 mV. Although the relationship is not linear, this would result in increased operational lifetime. By performing an Levelized Cost of Electricity (LCOE) analysis it was found that the price of hydrogen fuel would have to fall below 1.47 EUR/kgH2 for an Fuel Cell (FC)-Combined Heat and Power (CHP) to become profitable today. If the FC provides only electricity it would have to be as low as 1.11 EUR/kgH2. By accounting for estimated investment cost reduction towards 2050 it was found that the critical hydrogen price for a FC-CHP unit in 2050 increased by 20.1 % to 1.77 EUR/kgH2. This price of hydrogen is well within the expected price range for green hydrogen by the year 2050.

9.1 Summary of contributions

This thesis was written with the attempt at achieving a number of objectives as stated in Chapter 1.2. For simplicity of comparison, the contributions will here be restated along with a summary of whether each objective goal was reached or not.

C1 - Literature review By reviewing a selection of reports, articles and research papers there was established a context in which this thesis could be viewed. The findings were presented in Chapter 2 and gave a brief summary of the expected growth and future cost estimates for both utilization and production of hydrogen. Although a majority of hydrogen today fits in the industrial market segment, as well as future estimates for hydrogen demand in Norway focusing on the maritime and transportation sectors, there are enough interest in implementing FCs in the energy sector of countries like Japan, Germany, USA and South Korea to warrant an examination of topic within Norway as well.

C2 - Techno economic analysis With the current costs of manufacturing of fuel cell modules and production of hydrogen fuel, the economic potential for investing in FCs for medium sized energy systems is limited. It was however determined that with future estimates for cost reduction in production of both fuel cell technologies and hydrogen fuels, FC-CHP systems could be profitably included in micro grid systems.

Through mixed integer optimization modelling of a microgrid energy system it was found that it could be profitable to invest in fuel cell combine heat and power solutions by the year 2050. The results show that hydrogen costs would have to fall below 1.8 EUR/kg to make FC-CHP solutions profitable in 2020, while an expected 38.5 % reduction in CAPEX will make the system profitable in 2050. Much like with the electricity mix, the environmental impacts of using hydrogen depends on what means were used to produce the hydrogen. By using green hydrogen in 2050, it was found that the emissions could be reduced by 61.9 % compared to the base case.

In addition to the energy system at Campus Evenstad, six different building types were examined. Through these simulations it was found that apartment buildings, hospitals and nursing homes had the best potential cost reductions when investing in the FC-CHP with 18.9, 15.6 and 17.0 % respectively.

C3 - Practical aspects of implementing fuel cells in Norway During the discussion in Chapter 7 and 8 some of the practical considerations required for implementation of FC-CHP in energy systems was addressed. To allow for continuous supply of hydrogen for the FC, the geographical location of the energy system should be considered. Ideally the hydrogen could be produced onsite through water electrolysis if this is found profitable, but other alternatives include direct supply through pipeline from either a hydrogen refueling station or hydrogen intensive industry like Yaras ammonia plant at Herøya in Porsgrunn. The quality of heat from low temperature FCs were briefly discussed, emphasizing that it is not unusual for sub-grids within a District Heating (DH) network to receive supply water at the temperature levels commonly seen in Polymer Electrolyte Membrane Fuel Cells (PEMFC).

9.2 Further work

Based on the work presented during this thesis there are a number of possible courses of actions to further assess the potential for FC-CHP in Norwegian Buildings. This is separated into three main categories, being improvements to the methodology, suggestion for real life test cases and additional topics related to the subject of hydrogen technologies in the energy sector.

9.2.1 Improvements

The first major improvement would be to examine the system performance over the entire lifetime of the microgrid. As the operation of the fuel cell is based on the relationship between fuel costs and electricity costs, a year with different electricity costs could yield very different results. This was proven during the sensitivity analysis, so electricity costs for multiple years should be considered.

One possible improvement that could be made to is to account for peak shaving caused by locally produced power. The optimization model could include a factor representing the power part of the electricity grid cost. As the power part of the grid costs are dependent on the maximum of a set of variables it was not optimized during the course of this thesis.

9.2.2 Test study of real case

One interesting case study could be to retrofit an existing FC test system or project with heat recovery components or at least take measurements of the inlet and outlet of the cooling circuit. As mentioned previously, there have been a handful of hydrogen fuel cell pilot projects in Norway, yet none of these have examined the potential for making the spill heat useful. Quantifying the benefits of seasonal operation of fuel cells compared to continuous operation.

9.2.3 Aspects of interest

Although the direct economic potential for including FC-CHP units in commercially sized buildings today is limited it could be interesting to assess the non-monetary value of including the technology. This includes quantifying the benefit of combining fuel cells with hydrogen energy storage and the potential for peak shaving. It could also be beneficial to compare FCs more directly with alternative technologies like heat pumps.

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A Appendix A - Energy system components

A.1 Power system model parameters

Tables A.1 and A.2 shows the economic parameters used during the simulations. Maintenance costs (O&M) are given in percentages of the investment cost. Estimated costs for 2050 are calculated form Danish Energy Agency's Technology Report [71].

Table A.1: Economic lifetime, efficiency, and maximum and minimum power output of energy system components used in the optimization model.

Source	Lifetime [years]	Efficiency	Installed capacity [kW]	Min [kW]	Max [kW]
Fuel Cell [71]	10	0.45	100	60	100
CHP Bio [59]	25	0.25	40	12	40
Boiler Bio [59]	20	0.85	330	99	330
ST [59]	20	-	100 [m2]	-	-
PV [59]	20	-	60 [kWp]	-	-

Table A.2: Investment cost, annual maintenance cost, fuel cost and carbon dioxide emissions of energy system components used in the optimization model.

Source	Invest 2020 [EUR/kW]	Invest 2050 [EUR/kW]	O&M	Fuel Cost [EUR/kWh]	Emmisions [kgCO2/kWh]
Fuel Cell	1600 [71]	985 [71]	4% [71]	0.045/0.073	0
CHP Bio	4500 [59]	4142 [71]	4.5% [71]	0.041	7
Boiler Bio	690 [71]	590 [71]	5% [71]	0.041	7
ST	700 [84]	636 [71]	6% [71]	-	0
PV	730 [79]	450 [71]	3% [71]	-	0

A.2 PVsyst parameters

Figure A.1 and A.2 shows the basic parameters used for the solar energy system used in the optimization model. The PVsyst model outputs the hourly electrical output from the PV modules and the local irradiance. The irradiance was used to calculate the heat delivered by solar thermal collectors.

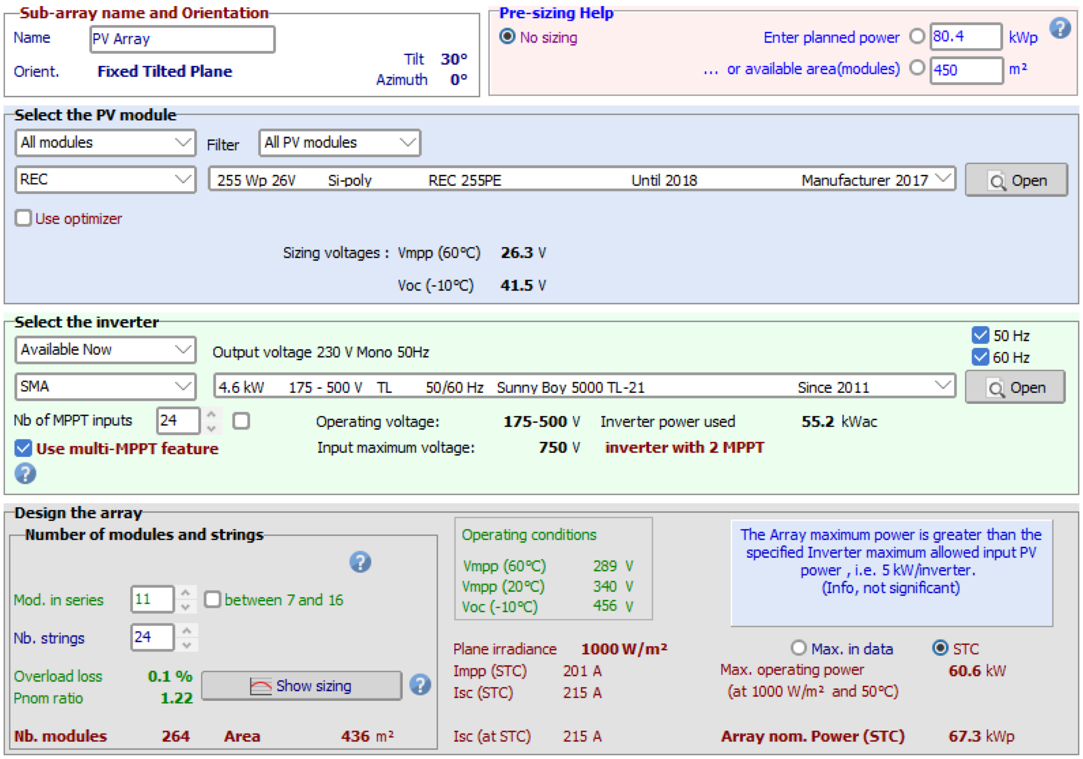

Figure A.1: Screen-cap of the system configuration for the PVsyst model used during this master thesis.

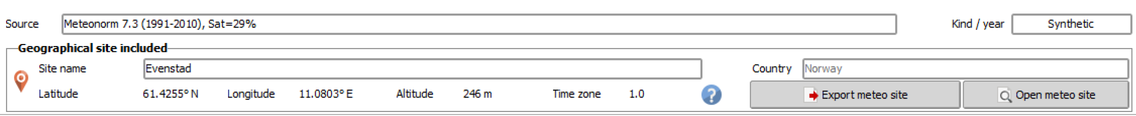

Figure A.2: Screen-cap of the location for the PVsyst model used during this master thesis.

B Appendix B - Optimization model code repository

The code and software used for the optimization modelling throughout this thesis can be found in the repository at:

https://github.com/even-glad-sorhaug/master.git

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