Securing a sustainable use of bioenergy by utilising hydrogen and CAES for electricity production

Master Thesis
Sustainable Energy Planning and Management
Aalborg University
June 4, 2021

AALBORG UNIVERSITY
STUDENT REPORT

Department of Planning
Sustainable Energy Planning and Management
Rendsburggade 14
9000 Aalborg
http://www.plan.aau.dk

Title:

Securing a sustainable use of bioenergy by utilising hydrogen and CAES for electricity production.

Project:

Master Thesis

Project period:

01/02 2021 - 04/06 2021

Authors:

Kristina Ifversen Espersen
Mikkel Kamp Hansen

Supervisor:

Peter Sorknæs

Pages: 86

Appendixes: 2

Finishing date: June 4, 2021

Abstract:

This study investigates how green hydrogen through the utilisation of CAES can contribute to securing a sustainable level of bioenergy use in the Danish electricity sector by substituting the biomass-based dispatchable electricity-producing units with a dispatchable electricity-producing unit consisting of a CAES unit fueled by green hydrogen.
This is investigated by utilising knowledge and theories about the dependency on bioenergy and the lock-in mechanisms that hinder the implementation of alternative sources of energy. Furthermore, an energy system analysis is applied for the investigation of the hydrogen-CAES system. This is used to investigate the amount of electricity the system can contribute with and thus the amount of bioenergy that can potentially be substituted and the revenue that can be obtained by operating the system. The simulation results show that the Green Hydrogen Hub can produce 1.04 TWh of electricity annually, based on the used assumptions. It can be argued that this electricity, or parts of it, can be used to substitute bioenergy used for electricity production and thus minimise the bioenergy dependency.

Preface

This thesis is completed by a group of two students on the MSc of *Sustainable Energy Planning and Management* at Aalborg University.

The group would especially like to thank *CEO of Hydrogen Valley, Søren Bjerregaard Pedersen* for being the initial contact person and catalyst of the GHH collaboration. The group would also like to thank the other contributing parties of the collaboration for delivering data and knowledge upon the GHH project, Chief Business Development Manager at Gas Storage Denmark, Hans-Åge Nielsen and *Senior Business Developer at Eurowind Energy Henrik Lykke Sørensen.*

The current COVID-19 pandemic has affected the thesis in different ways. First of all, there has been a high level of focus on the theories applied, and the theoretical approach has become central to the thesis. The technical perspective with the energy system analysis has been negatively affected by the pandemic because the gathering of data for the analysis has been rendered difficult, and the empirical foundation has therefore been limited. Therefore this thesis has a character of complex theoretical analyses and simple technical analyses.

Instructions for reading:
In order to gain the best understanding of the thesis, it should be read in chronological order.

The references are noted using the Harvard method [Surname, Year]. In the bibliography, the books are noted with author, title, year of publication, web link, and download date, while author, title, weblink note the web pages used and date of download.

Figures and tables are noted considering the chapters and sections they are presented in. Along with the notation of the figures and tables is an explanatory text.

The abbreviations used throughout the thesis account for both the singular- and plural form of the reference, even though they are only written in singular form.

Appendix A is attached as an external Excel file, while an email correspondence with HV verifying the assumptions is attached in Appendix B.

The source of the picture on the front page is Colourbox [n.d.].

Kristina Ifversen Espersen

Mikkel Kamp Hansen

Summary

Dette speciale har til formål at undersøge, hvordan grøn hydrogen potentielt kan anvendes i det danske energisystem til at nedbringe anvendelsen af ubæredygtig bioenergi og derved afhængigheden af bioenergi som regulerbar ressource. Specialet tager udgangspunkt i en problemanalyse, som starter med en undersøgelse af de danske politiske målsætninger; både kort- og langsigtede, hvor det langsigtede mål er klimaneutralitet i 2050. Et klimaneutralt energisystem består udelukkende af vedvarende energikilder, hvilket har resulteret i en massiv fremgang i energiproduktionen fra vindmøller og solceller, hvis produktion fluktuerer afhængigt af vejrmæssige forhold. For at opretholde fleksibilitet i systemet er det nødvendigt at anvende regulerbare ressourcer, hvilket bioenergi er tilsigtet som i fremtiden, eftersom det er et brændsel der politisk er defineret som værende CO_2-neutralt. Der er dog flere udfordringer forbundet denne skabelse af en afhængighed af bioenergi i det fremtidige energisystem, blandt andet at; ressourcen ikke er uudtømmelig, mængden er usikker samtidig med at store dele af bioenergien er importeret (dele endda fra lande der ikke har bæredygtighedskrav). Afhængigheden af bioenergi, samt de tilhørende negative eksternaliteter, har gjort det interessant at undersøge om andre ressourcer potentielt kan spille rollen som regulerbar ressource i det fremtidige danske energisystem. Power-to-X teknologien har potentiale til dette, hvor specielt grøn hydrogen kan anvendes som en kilmaneutral regulerbar ressource. Den danske virksomhed Hydrogen Valley undersøger mulighederne for grøn hydrogen som regulerbar ressource til afbalancering af udbud og efterspørgsel af el på elnettet i projektet *Green Hydrogen Hub*, som dette speciale er udarbejdet i samarbejde med. Den udarbejdede problemanalyse har dannet grundlag for følgende problemformulering:

Hvordan kan grøn hydrogen udnyttet igennem et CAES system bidrage til at sikre bæredygtigt forbrug af bioenergi i Danmarks klimaneutrale elsystem i 2050?

Derudover har dette speciale en overordnet teoretisk tilgang, hvor der tages udgangspunkt i tre teorier som i høj grad anvendes sammenhængende, idet synergieffekter opstår ved at inddrage alle tre teorier samlet. De anvendte teorier er path dependency, carbon lock-in og multi-level perspective, som tilsammen danner grund for forskningsdesignet for dette speciale. Derudover er der anvendt forskellige metoder til besvarelsen af problemformuleringen, og dette speciale bærer i høj grad præg af samarbejdet med Hydrogen Valley, som har gjort det muligt at tilgå data der ellers ville være svært at få adgang til. Derudover er litteraturstudie anvendt gennem hele specialet. Ydermere tager analysen sit udgangspunkt i en energisystemanalyse, hvilken er udarbejdet ved brug af EnergyPLAN og Excel. EnergyPLAN er anvendt til at simulere *IDA 2050 scenariet* og levere dets output, som sammen med data fra Teknologikatalogerne fra Energistyrelsen og data fra Green Hydrogen Hub har dannet datagrundlag for simuleringen i Excel.

Analysen i dette speciale indledes med en undersøgelse af potentialet for bæredygtig bioenergi i Danmark i 2050, hvor fem forskellige kilder estimerer dette niveau. De forskellige kilder har dog forskellige estimater og det understreges at potentialet i fremtiden er meget usikkert, hvorfor det i denne analyse er bestemt at det danske bioenergiforbrug skal, og derved afhængigheden, skal minimeres så meget som muligt. Som nævnt danner *IDA's 2050 scenarie* grundlag for analysen, og dette scenarie anvender mellem 45,9-75 TWh bioenergi årligt, afhængig af anvendte brændselspriser. I dette speciale er det simuleringen med høje brændselspriser der er anvendt, og derved det laveste bioenergiforbrug. For at undersøge om grøn hydrogen potentielt kan konkurrere med bioenergi i Danmark, er en analyse af grøn hydrogen udarbejdet. Denne analyse undersøger priserne forbundet med produktion af grøn hydrogen, som i fremtiden potentielt kan udkonkurrere andre hydrogenformer og produceres til blot 9,2 DKK/kg i 2025. For at undersøge om grøn hydrogen kan konkurrere med bioenergi er en komparativ analyse af de to brændsler udarbejdet, som resulterer i et resultat der viser at træbiomasse er mest konkurrencedygtigt prismæssigt. Dog forventes det, at der i slutningen af 2021 vil blive udarbejdet en specifik handleplan for PtX i Danmark, som potentielt kan indeholde afgiftsordninger og subsidier til fordel for grøn hydrogen. Det er derfor fundet, at grøn hydrogen kan konkurrere med bioenergi, såfremt man tager de negative eksternaliteter forbundet med bioenergi i betragtning, samt har for øje at en handleplan for PtX snart publiceres.

Næste skridt i analysen er en simulering of analyse af Green Hydrogen Hub systemet, som undersøger hvordan de forskellige komponenter i Green Hydrogen Hub opererer i det danske energisystem. De installerede kapaciteter for anlæggene er ligeledes anvendt til en Excel analyse af hvordan Green Hydrogen Hub vil operere på årlig basis. Idet modellen har til formål at undersøge, hvordan bioenergianvendelsen kan minimeres, er elpriser fra *IDAs 2050 scenarie* anvendt for at undersøge hvornår de forskellige komponenter skal operere. Disse budpriser priser er udregnet med formål om at producere det største årlige økonomiske overskud fra produktionen. Excel simuleringen viser at Green Hydrogen Hub under de anvendte antagelser kan producere et overskud på 25,1 M€. Ligeledes vil Green Hydrogen Hub kunne producere 1,04 TWh elektricitet årligt, hvilket potentielt kan anvendes til at erstatte bioenergi anvendt i elsektoren, og derved minimere afhængigheden. Derudover aftager Green Hydrogen Hub 1,11 TWh elektricitet årligt fra nettet, og bidrager ydermere derved til opretholdelsen af balance i systemet.

Dette speciale er forbundet med en række usikkerheder, som er diskuteret. I estimeringen af bæredygtigt bioenerginiveau foreslog flere kilder et bæredygtigt niveau højere end det *IDAs 2050 scenarie* opererer med, hvilket potentielt ville resultere i at bioenergiforbruget ikke nødvendigvis behøves minimeret. Dog findes der flere gældende årsager til at minimere denne afhængighed af bioenergi. Ydermere var flere af de anvendte antagelser i modelleringen diskutable, og alternative antagelser ville have resulteret i ændrede resultater. Dog er de anvendte antagelser blevet verificeret af Hydrogen Valley. Slutteligt er det blevet diskuteret, hvordan analysen af specialet er blevet præget af de anvendte teorier, eftersom disse danner forskningsdesignet.

List of Abbreviations

CAES compressed-air energy storage.
CCS carbon capture and storage.
CCUS carbon capture, utilisation and storage.
CEEP critical excess electricity production.
CF capacity factor.
CHP combined heat and power plant.
CO2 carbon di-oxide.

DH district heating.
DSM demand side management.

EEP excess electricity production.
EOP end-of-pipe.
EU European Union.
EV electric vehicle.

FLH full-load hours.

GHG greenhouse gas.
GHH Green Hydrogen Hub.

HP heat pump.
HV Hydrogen Valley.

IEA International Energy Agency.
IPCC Intergovernmental Panel on Climate Change.

LCOE levilized cost of energy.

MLP Multi-Level Perspective.

O&M operation and maintenance.

P2H2P power-to-hydrogen-to-power.
PP power plant.
PtX Power-to-X.
PV photovoltaic.

RD research and development.
RE renewable energy.
RES renewable energy source.

SOEC solid oxide electrolysis cell.

TIC Techno-Institutional Complex.

UN United Nations.

V2G vehicle to grid.

WT wind turbine.

Contents

Page

Introduction 1

The Earth's climate has always fluctuated and changed from ice ages to warmer periods, but during the last century, the Earth's temperature has risen unusually fast; this temperature rise is referred to as global warming, which ultimately leads to climate changes. The definition of *climate changes* is a long term change in the Earth's overall temperature with massive and permanent ramifications. [IPCC, 2014]

These changes are not favourable for the Earth's ability to sustain life. The reason for this belief lies in the explanation that the Earth's atmosphere consists of different gasses such as oxygen, nitrogen and greenhouse gasses (GHG) such as carbon dioxide and methane. GHG reflect the light onto the Earth's surface, heating it. A rise in the level of GHG can cause a temperature rise. The main human activities causing a rise in greenhouse gas emissions are the combustion of fossil fuels, agriculture, deforestation, and waste pollution. [IPCC, 2014; NASA, n.d.b]

The energy supply has been based on fossil fuels for decades, contributing to an increase in the concentration of GHGs in the atmosphere. [IRENA, 2021] Action is needed to preserve the world's ability to sustain life and avoid the most damaging effects of climate change. [NASA, n.d.a]

The Paris agreement, an international legally binding agreement on the reduction of climate changes, was signed in 2015 to limit global warming to below 2°, preferably to 1.5° relative to the pre-industrial levels. [United Nations, 2016]

To limit global warming to 1.5°, the Paris Agreement pushes the participating countries to take action and create strategies aiming to reduce their GHG emissions rapidly using the best available technologies (BAT), for example, production energy.

The agreement includes commitments from nearly 200 countries, including all major emitting countries (China, USA, Russia, India, Japan, Germany etc.). The fact that nearly all nations committed to the agreement shows a worldwide consensus that climate change is driven by human behaviour, that it is a threat to the environment and thus to humanity, and that global action is needed to reduce the causes and negative effects. [Denchak, 2021]

The Paris Agreement is, according to CAT [2020], driving climate action, but both [UNEP, 2020] and CAT [2020] present temperature estimates, which shows that the participating countries are still not on the pathway for limiting the warming to 1.5°. It is evaluated by IRENA [2021] that the expansion of renewable energy (RE) has to increase eight times faster than currently in order to achieve the ambitious goals of the agreement; therefore, an acceleration of action is needed.

Problem Analysis 2

Reducing climate change depend on both global, national, regional and individual action.

As a part of the EU, Denmark is obligated to follow the directives and regulations provided by the EU because of the binding legislative framework conditions. The regulation consists of binding legislative acts, which all participating countries have to adapt and comply to, while the directives aim for the same overall goal of climate neutrality, but can be achieved using different measures in different countries depending on, for instance, different resources. [European Commission, n.d.]

The EU influences Denmark's national action towards climate neutrality, but Denmark also has a national climate policy. The climate policy of Denmark covers several sectors such as agriculture, transportation, industry, and energy production. [Danish Energy Agency, n.d.] Looking into the Danish energy policies is interesting since Denmark has one of the most ambitious targets regarding energy policies. [Jacobsen, 2020]

2.1 The Danish Energy Policy

The energy policy of Denmark and the political goals that are issued are mainly driven by the national reduction targets specified in the Danish Climate Act (Klimaloven) adopted in 2020, and the commitments that Denmark has made to international climate targets in EU and UN [Klima-, Energi- og Forsyningsministeriet, 2019; Danish Energy Agency, n.d.].

The Climate Act is legislative and obligates Denmark to two legally binding climate targets [Klima-, Energi- og Forsyningsministeriet, 2019]:

- Short term (2030): Denmark's GHG emission must be cut by 70% compared to 1990-levels (excl. shipping and air traffic industries)
- Long term (2050): Denmark has to reach climate neutrality by not emitting more GHG than absorbed

The law is based on a framework that obligates the incumbent ministers to act according to the legally binding targets. The government is furthermore obligated to revise the sub-targets for the next ten years, every 5th year, and elaborate a specific climate action plan for the period. However, the targets can never be less ambitious than the previously made targets - the *no sliding* principle applies. [Gorrissen Federspiel, 2020; Danish Energy Agency, n.d.]

Additional to the legally binding targets set out by the Danish Climate Act and the international agreements, the government of Denmark has political goals influencing the energy sector. An overview of the Danish and European goals towards climate neutrality is presented in Table 2.1.

Agreement	Objective	Year
The Danish Climate Act	*70% reduction of GHG emissions*	2030
	Climate neutrality	2050
EU 2030 targets	*The total share of GHG emissions has to be reduced by 40%, relative to 1990*	2030
	The large emitters who subject to the EU Emissions Trading System has to reduce the GHG emissions by 43%, compared to 2005	2030
	The GHG emissions from buildings, agriculture and transportation has to be reduced by 30%, compared to 2005	2030
	At least 27% of renewable energy in the system	2030
	At least 27% energy efficiency	2030

Table 2.1. Overview of the political objectives influencing the Danish Energy Sector.

In 2019 the total GHG emission was reduced by 36%, compared to 1990 levels. [Danish Energy Agency, 2019]
To achieve the 2030 target of a 70% reduction in GHG emissions 23.8 Mton CO_2-eq. still needs to be removed, compared to the GHG emission in 1990 of 70.8 Mton CO_2-eq. This substantiates that action is needed in order to reach climate neutrality.

2.2 The path towards climate neutrality

The 36% achieved reduction of GHG emissions is primarily because of fossil fuel phase-out, which has almost entirely been replaced by RE, using bio-, wind- and solar energy. The RE *production* has increased by 288% in 2019, relative to 1990, including an increase of 6,262% of solar energy produced in the same period. Furthermore, wind energy production has increased by 2,546%, resulting in a total installed wind power capacity of 6.1 GW in 2019. [Danish Energy Agency, 2019]

It is evaluated by the independent expert organ "The Danish Council on Climate Change" (Klimarådet) that the commercialisation of new technologies is necessary to achieve the 70% GHG reduction before 2030. According to Klimarådet [2020], it is possible to achieve a 60% reduction using existing commercialised technologies, which means that to reduce the remaining 10%-points, new technologies have to be implemented. Klimarådet [2020] mentions that carbon capture storage (CCS) and carbon capture storage and utilisation (CCUS) will play a role in reducing the remaining 10%, but alternative non-commercialised technologies will have to contribute as well.

Looking at the primary energy *consumption*, in Table 2.2, it is visible that the total energy consumption has decreased by 5% since 1990 and that the RE share has significantly increased.

Fuel Equivalent [TWh]	**1990**	**2000**	**2010**	**2019**	**1990 to 2019 [%]**
Primary Energy Consumption	221	228	233	**206**	**-5%**
Oil	96	103	88	**78**	-18.6%
Natural Gas	21	52	51	**31**	39.7%
Coal and Coke	88	47	43	**19**	-85.1%
Waste, Non-renewable	2	4	5	**5**	155%
Renewable Energy	13	22	47	**74**	454%

Table 2.2. Primary energy consumption in Denmark from 1990 until 2019. Data from Danish Energy Agency [2019].

As visible in Table 2.2, a large amount of fossil fuels is, however, still consumed, with oil, coal and natural gas as the primary sources, resulting in a RE share of 35% of the final energy consumption in 2019. The remaining 65% of energy is produced from fossil fuels, which have to be entirely phased out by 2050 to achieve the long-term national goal of climate neutrality.

However, it is noticeable that the total fossil fuel usage has decreased over the last decades, and the RE consumption has increased in the same period, which is a trend that is set to continue. An illustration of the Danish energy consumption in 2019 is shown in Figure 2.1, including a further illustration of the Danish RE consumption.

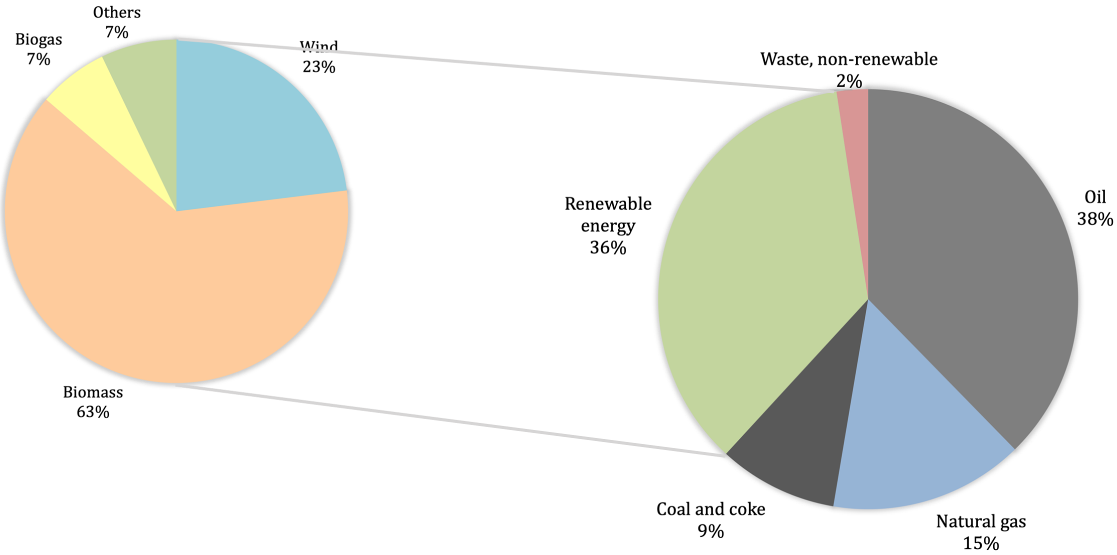

Figure 2.1. Primary energy consumption by fuel in 2019. Own production. Data from Danish Energy Agency [2019].

Bio- and wind energy are the most significant contributors to the RE in Denmark, with bio-energy representing more than 2/3 of the total renewable energy consumption in 2019, while wind turbines (WTs) accounted for around 1/4 of the total renewable energy consumption. Even though the total consumption of bioenergy is larger than wind energy consumption, wind energy accounts for more than half of the total electricity produced, while bioenergy only accounted for around 10% of the electricity. This shows that wind energy is used for electricity production to a larger extend than bioenergy, which is mainly used for heating, transportation and industry. [Danish Energy Agency, 2019]

Figure 2.1 shows a remaining dependency on fossil fuels, which according to the political targets, needs to be addressed by increasing the RE share. The primary RE sources in 2019 are bio-energy and wind. The deployment of wind power is set to increase incrementally as more capacity is expected to be operating in the future. Thus, it is expected that the future energy system in Denmark primarily will be dependant on bio-energy and fluctuating RE sources. [Danish Energy Agency, 2020a]

2.3 Solving one problem as others occur

With the ultimate national goal towards climate neutrality by 2050, the expansion of RES is increasing incrementally. Danish Energy Agency [2020c] expects that the primary heating supply will be heat pumps and, to a lesser extend, other heat-producing plants, mainly biomass boilers and solar heat, while the electricity production primarily will be wind- and solar power.

Both wind- and solar energy are fluctuating and rely on weather conditions, while bioenergy is a dispatchable energy source that can be utilised when demanded. Danish Energy Agency [2020a] expects the bioenergy usage to increase as a result of the phase-out of fossil fuels, which is illustrated in Figure 2.2.

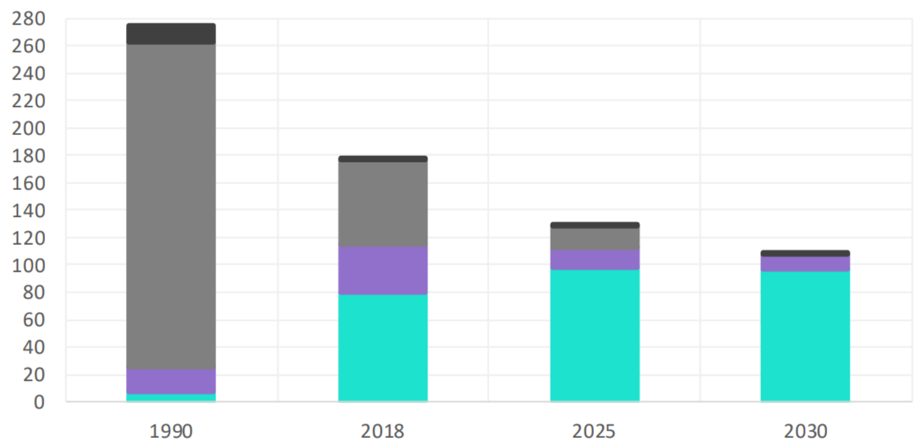

Figure 2.2. Fuel consumption for CHP in PJ. [Waste incineration not included] blue: biomass, purple: gas, grey: coal, black: oil. Data from Danish Energy Agency [2020a].

The demand and supply of electricity have to be in balance to prevent blackouts in the electricity system, which there are different ways of handling. In hours when the supply is higher than the demand, the production from the dispatchable energy sources can be turned down, the excess electricity can be exported to connected systems, and/or the surplus electricity can be stored. Furthermore, flexible electricity consuming technologies, such as EVs, HPs, electric boilers and electrolysis, can be up- and down regulated to balance the demand curve. Subsequently, when the supply is lower than the demand, the dispatchable energy sources can be utilised to meet the demand and energy from storage can be utilised, or/and electricity can be imported via the transmission lines. There are, although some determining challenges concerning the above-mentioned balancing measures. [IEA Bioenergy, 2017]

Turning down the production from, e.g. WTs in hours with too much electricity in the system is contradictory because it does not secure that the most value is made from the investment. [Wittrup, 2019] Exporting electricity from the fluctuating energy sources is likewise paradoxical - because nearby countries often have surplus production from these sources in the same hours, and therefore the export price will be low; in some cases, it can even be negative. The same mechanism happens when importing electricity when the production is too low - the nearby countries will likely also have a low production so that the import price will be high. This means that the export of electricity often has low electricity prices in a Danish context, and electricity is often imported at higher prices. A graph to illustrate this is presented in Figure 2.3, which shows the annual average correlation between the import and export price in Denmark. It is visible, that the electricity import price is higher than the export price, which is caused by the significant dependency on non-dispatchable energy sources, and the lack of ability to store the excess electricity, lack of demand-side management (DSM) and the similarity of production curves in the connected electricity markets. [Gas Storage Denmark, n.d.]

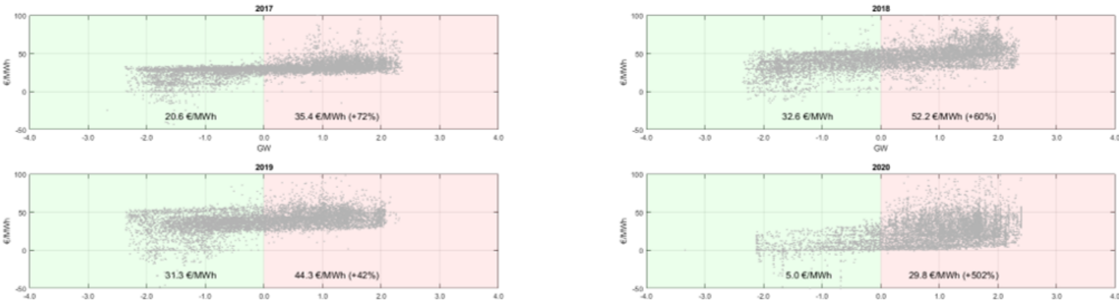

Figure 2.3. Annual difference on import and export price of electricity. Green; annual export prices. Red; annual import prices.

Storing electricity can be a solution when the supply is higher than the demand, but different barriers are related. The primary barrier is the cost-efficiency of batteries since it is quite expensive to store electricity compared to other energy storage types. [Lund et al., 2016] Additionally, batteries are not viable for long term storage. [Hargreaves and Jones, 2020] Long term storage of energy is relevant in a Danish context because of the seasonal fluctuations in supply and demand. The energy demand is generally higher in winter, which causes the electricity prices to rise, which can be seen in Figure 2.4.

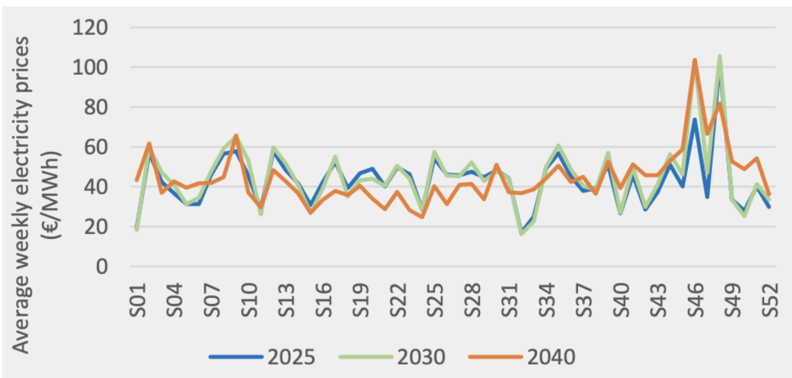

Figure 2.4. Seasonal variation in weekly electricity prices in DK1

The seasonal variations in electricity prices, seen in Figure 2.4 supports the fact that there is a need for seasonal storage in the Danish energy system, which ultimately makes the battery solution impracticable to solve this challenge.

When looking at commercialised low-cost storage alternatives in Denmark, storing energy as heat is widely used. Using heat storage is 100 times cheaper in terms of investment per unit of storage capacity, according to Lund et al. [2016]. Moreover, gas and liquid storage have substantially lower capital costs than thermal storage per unit storage capacity. Gas and liquid fuels occur primarily as natural gas and oil today, and in the RE future, these sources will be phased out, and the storage capacity can potentially contain methane or methanol instead, produced CO_2-neutrally from green biomass, green hydrogen and renewable electricity [Lund et al., 2016].

Moreover, gas and fuels are better suited for sectors that are hard to electrify, such as transportation, industry and heat. [Thollander et al., 2020] Gas and fuels have a high calorific value and are energy-dense, and are therefore best used in the sectors which are hard to electrify because of the demand for energy-dense fuels. For instance, oil has some clear advantages for the transport sector because of the energy density compared to other fuels, the weight, and most importantly, the liquidity of the source, which makes it ideal for storage, distribution, and combustion in the existing engines. [Gross, 2020] Therefore, the optimal solution for a RE system would be a design that avoids electricity storage (with the only purpose of storing energy) altogether and utilises thermal, gaseous and liquid storage. Therefore, it will be more feasible to develop storage capacity for the needed large share of fluctuating electricity production in the future. [Lund et al., 2016]

The challenges of supply and demand and the challenges of storage manifest that dispatchable technologies are critical in an energy system with a large amount of fluctuating renewable energy sources (RES). As visible in Figure 2.1, biomass is currently by far the largest renewable dispatchable energy source used.

2.3.1 The challenges of relying on bioenergy

As described, it is necessary to have dispatchable energy technologies in an energy system to secure the supply, and in the future, biomass is the primary resource aimed to contribute to this vital role. Using bioenergy as the primary dispatchable energy source is, however, associated with some severe challenges;

Firstly, basing the dispatchability of the energy system on one energy source is controversial and creates a dependence on that one source. Dependency on one source has previously been problematic in the Oil Crisis in 1973, which raised awareness of the importance of not basing the system on one fuel. [Gregg et al., 2014] According to Dincer and Bicer [2019] being dependant on different sources of energy gives better energy security because the reliability of more sources is higher. This substantiates the challenge of basing the dispatchability of the system entirely on bioenergy.

Secondly, bioenergy is not infinite, the harvest is changing from year to year, and it depends on weather conditions that are changing. The harvest is uncertain and could potentially fail, which would put the supply of energy at stake. [Eziz et al., 2020]

Thirdly, the sustainability of the used amount of bioenergy is questionable. Bioenergy is only sustainable if used and appropriately sourced. Denmark is currently using too much biomass, according to Klimarådet [2018]. Denmark used three times as much biomass per capita in 2016 than the global potential, which manifests a paradox in the sustainability of the Danish biomass use.

If the supply of bioenergy cannot come from the production in Denmark only, the bioenergy needs to be imported, which additionally creates dependence on imported fuels and foreign energy sources. [Arler et al., 2017; Danish Energy Agency, 2020b] Using imported biomass can be questionable because of different rules, regulations and declarations of the biomass. If biomass is imported from certified sustainable producers, it may be qualified as sustainable biomass; but this is not always the case. In fact, more than 1/4 of the imported biomass in Denmark in 2018 was from the USA and Russia, which are countries that do not have binding legislative climate policies and are not obligated to count the emissions related to biomass. The UN defines that the emissions related to biomass should be accounted for in the country that harvests the biomass and not the country that uses the resource. This ultimately means that the USA- and Russia imported biomass used in Denmark is not accounted for in the Danish GHG emissions. It is unclear how Russia and the USA take responsibility for the emissions, which creates a situation where no one potentially accounts for the emissions. This means that even though there is a use of biomass and thus a GHG emission, it is not accounted for under the present international regulations. Therefore there is a risk that the use of imported biomass in Denmark creates global emissions not accounted for anywhere. [Danish Energy Agency, 2020b] An increase in the Danish use of imported biomass from these countries is therefore risking that the transition towards climate neutrality is only an illusion because the actual emissions are not accounted for.

An additional challenge of relying on imported biomass is the dependence on external economies. Any problem of supply or crisis in the country of biomass' origin can negatively impact the Danish energy system and ultimately the Danish economy, as was the case in the oil crisis. [National Academy of Sciences, 2008] The oil crisis is, however, not 100% identical to a potential biomass crisis because the oil production was previously limited to a few countries. Today, biomass is produced all around the world, and a worldwide crisis is quite unlikely. However, as Denmark is dependant on imported biomass from the USA and Russia, it would influence the Danish economy if a change were to happen in the production of biomass in any of those countries. [Danish Energy Agency, 2020b]

The fact that bioenergy consumption is increasing internationally alongside the green transition adds to the uncertainty of being dependant on external economies for the supply of bioenergy because when more countries depend on the resource, the potential effect of a decrease in production in one of the large producers of bioenergy will affect more countries and can therefore evolve into a crisis. The production of biomass also varies from year to year and depends on the weather conditions; if the harvest fails or is substantially reduced in one country, there is a risk that the surrounding countries, with similar weather conditions, will experience the same challenges. This would strain the entire global supply chain of biomass because it would increase the demand from the rest of the biomass producers. [Eziz et al., 2020]

Furthermore, it is worth noticing that the national biomass potential span widely from country to country. For instance, large countries with limited energy demands can potentially have large national biomass potentials per capita, while small countries with a high energy demand can have small national biomass potentials per capita. This eventually makes it easier for the countries with a high biomass potential to become CO_2-neutral, while it becomes challenging for the countries with a low biomass potential to become CO_2-neutral. This manifests that biomass distribution from countries with high potentials might be necessary for other countries in their achievement of being CO_2-neutral. Therefore, it is necessary to adopt a global perspective when estimating the national sustainable biomass consumption.

In Denmark, the spatial aspect of the production and use of energy crops is a determining sustainability factor. The administration and management of the land use and the time horizon of the land use are determining. The opportunity costs of land use and the energy source that the energy crops are replacing determine sustainability. [Danish Energy Agency, 2020b]

When bio waste products are replacing fossil fuels, it is an advantage for the climate. In other cases, for instance, when large trees are cut for the use of energy production, it can contribute to global emissions and climate change. Ultimately, if the trees are not replanted, the use of biomass for energy production can contribute to more significant environmental impacts than the use of coal, according to the Danish Energy Agency [2020b]

The biodiversity and air- and soil quality can be affected negatively by a rise in the production and use of biomass. Danish Energy Agency [2020b] state that biomass from forestation, in general, cannot be classified as being CO_2-neutral. According to the EU commission, the CO_2 from the combustion of biomass from forestation does not equal the CO_2 captured, and the time horizon from the emission to the capturing will cause consequences for the climate. They also argue that combustion of biomass in most cases emit more CO_2 per energy unit than the fossil fuels that it substitutes because of the lower energy density per unit of carbon compared to, for example, coal and, in most cases also a lower efficiency if the conversion to for example electricity. [Danish Energy Agency, 2020b]
Additionally bioenergy is associated with air pollution including emissions from NO_x, SO_2, $PM_{2.5}$, N_20 and NH_3, which can be problematic for the air quality and the local environment. [Masson-Delmotte et al., 2019]

The essence of this is that a greater reliance on fluctuating energy sources in the future will entail that bioenergy will play a critical role in Denmark's future climate-neutral energy system because there are no commercial large-scale, long-term storage solutions for electricity yet. Therefore, bioenergy is crucial for balancing supply and demand because of its dispatchability. This section clarifies that there are several challenges concerning bioenergy use, which is a driver for reducing the dependency on bioenergy. This makes it relevant to investigate alternative solutions for dispatchable RE sources, which do not entail the same challenges as bioenergy.

2.3.2 Solving the occurred problem

The first relevant alternative for dispatchable RES is demand-side management (DSM), which is defined as management activities of adopting effective incentives and guidance measures to improve energy efficiency and reform consumer behaviour. It is evaluated that DSM should be applied to the largest extent possible, but the potential is limited, and other alternatives should be applied. [Singh and Banerjee, 2017]

Another alternative relevant to look into is energy storage in batteries, but batteries are not viable for long-term storage, which is needed in the Danish energy system, as Figure 2.4 manifests. Batteries are therefore not relevant for this thesis, as it is evaluated that other suitable alternatives for cost-efficient long term storage exist. [Hargreaves and Jones, 2020]
A potential alternative for long term storage of energy is Power-to-X (PtX), a process where electrical power is converted into either heat, hydrogen or synthetic fuels. PtX is currently a hot topic when discussing how to decarbonise the hard to abate sectors, including the heavy transport sector and industry. The PtX process covers numerous solutions which are still being investigated and tested. [Rambøll, n.d.]

In the future climate-neutral energy system, the undesirable peaks in electricity demand will most likely reduce in quantity and frequency because of DSM. This will help balance the energy system on a day to day basis. Long-term storage is needed in co-operation with the DSM because the DSM will operate to reduce peaks and balance the system fluctuations on an hourly and daily basis but does not work to balance the seasonal supply/demand imbalances.
Additionally, the security of supply in the system ultimately relies on the possibility of turning energy-producing technologies up in the case of need or drawing from the storage. This creates a window of opportunity for niche developments that can store excess electricity when supply exceeds the demand, and utilise it when demand occurs, which is an opportunity that PtX potentially can take advantage of. Therefore, it is interesting to investigate how PtX can balance the electricity system, both when demand is higher than the supply and vice versa - cost-efficiently.

A Danish company called Hydrogen Valley is looking into this window of opportunity. They are operating in a project alongside other energy companies to investigate how green hydrogen can play a role in the energy sector. *Green hydrogen* is defined as hydrogen produced through an electrolysis process powered by RE. They investigate how it is possible to produce green hydrogen and utilise it for transport, industry, and heat generation. Besides these main applications of green hydrogen, they investigate the potential of using the hydrogen to balance the electricity sector through a process called power-to-hydrogen-to-power (P2H2P), where the hydrogen is utilised for electricity production through compressed air energy storage (CAES) processes. This creates a system where hydrogen, in theory, can be produced in the case of surplus electricity in the system and utilised in the case of a deficit. This investigation is fascinating since it aims to solve the challenge of balancing the electricity system without using bioenergy unsustainably.

3 Problem Statement

Through the above mentioned, it becomes clear that in order to reach climate neutrality in 2050, action is needed. There are several challenges associated with this. First of all, fossil fuels have to be phased out, and renewable energy sources must be implemented as a substitution. With biomass representing more than 2/3 of the total renewable energy consumption in Denmark in 2019, this shift in energy supply has shown to create a significant dependence on biomass; this is partly caused by the fact that biomass has similar abilities as the existing fossil fuels and is a dispatchable resource, and with minor adjustments can be used in the existing infrastructure.

With the national goal being climate neutrality in 2050, the RE share is expected to increase, and so is the use of biomass.

The increasing use of biomass is associated with several challenges, which are mentioned in the Problem Analysis in Section 2.3.1; this causes a situation where moving away from the fossil fuel-based energy system towards a system based on RE sources creates new challenges - new problems occur while solving the initial ones.

Because of these challenges, the Problem Analysis has depicted that the use of bioenergy in Denmark should be brought to a sustainable level, and alternative solutions for dispatchable electricity production should be investigated.

This creates a window of opportunity for new technologies to develop and compete with the existing ones. *Green hydrogen* is a fuel that can potentially play a similar role as biomass in the electricity system, with the use of a developing method called P2H2P; this makes it interesting to investigate what role green hydrogen potentially can play in the electricity system to substitute and ultimately reduce the dependency on bioenergy.

Hydrogen Valley is operating a project investigating how green hydrogen stored in large salt caverns in the underground of Denmark can be utilised for electricity production through a CAES process, a so-called P2H2P method.

With the knowledge presented above, it is interesting to investigate how green hydrogen can contribute to reducing the dependency on unsustainable bioenergy in Denmark through the utilisation of P2H2P using CAES processes.

Research Question:

How can green hydrogen utilised through CAES processes contribute to securing sustainable use of bioenergy in Denmark's climate-neutral electricity system in 2050?

Sub-questions:

1. What is the potential of sustainable bioenergy consumption in Denmark in 2050?
2. What is the potential for substituting the bioenergy used for electricity production with green hydrogen through CAES processes in 2050 in the Danish electricity system?
3. How can a sustainable level of bioenergy use be secured by substituting bioenergy for electricity production with green hydrogen and CAES?

3.1 Delimitation

This section aims to describe the scope of this thesis and clarify the delimitations that have been made. The delimitations are caused by the time limit, the COVID-19 pandemic, future uncertainties and other reasons. It is worth noticing that the delimitations define the scope and substantially impact this thesis since it defines what is investigated and, therefore, ultimately the outcome. The following delimitations have been made:

- The EnergyPLAN analysis is limited to further investigation of already existing models because of the time limit of this project. Using existing models developed by experts has been evaluated as a favourable solution because it is already reviewed and tested. Another substantial reason for this approach is that it becomes possible to only focus on specific parts of the energy system while remaining the holistic approach.

- Sustainable biomass is, in this project, defined as biomass produced from waste products. Therefore, sustainable biomass does not include energy from crops or forestry, with the main focus on producing energy or blue biomass (biomass produced underwater). The main reason for not using energy from crops or forestry is the negative impacts on the spatial planning in Denmark, where land is already a sparse resource, and therefore energy from crops or forestry and blue biomass is not considered sustainable in this project. With current political plans being implemented, 140% of the Danish land will be used; this substantiates the fact that land is a sparse resource in Denmark, and therefore the land used for energy production must, as any other sector, reduce the land use to a minimum. [Arler et al., 2017] This analysis does, however, not take into consideration that some areas could be used for several things simultaneously, and the Danish spatial potential could, therefore, in theory, exceed 100%. However, it is not expected that 40% of the Danish land can be used for two or more causes, which manifests the spatial challenges. Blue biomass is particularly not considered in this project mainly due to the high production costs and the sector's underdevelopment. The lack of cost-effectiveness of the blue biomass further substantiates that the areas should be prioritised for food production rather than energy production. [Petersen et al., 2016]

- When analysing how green hydrogen can contribute to electricity production, it is only investigated by analysing a hydrogen CAES system, as stated in the research question. The hydrogen CAES system is a technology used by Hydrogen Valley in the Green Hydrogen Hub system, which is one reason for focusing on this. It is additionally based on well-known existing technology, *CAES*. Other technological approaches could have been used, using, for instance, fuel cells. However, because of the time limit and the scope of this thesis, it has been chosen not to look further into alternative solutions. The analysis of other viable solutions is left for future work.

- Only green hydrogen is investigated, as the research question focuses on the climate-neutral energy system. Other types of hydrogen are only used as references when comparing the price level of green hydrogen.

- In the definition of sustainable biomass consumption, no in-depth analyses has been made. In order to evaluate a sustainable biomass consumption level, academic articles have been analysed, which is defined as the optimal approach within the scope of this thesis and within the time limit. However, this future biomass consumption has been found to be quite uncertain, and a quantitative potential has not been identified ultimately because of this uncertainty.

Research design 4

The purpose of this section is to describe the structure of the thesis and give an overview of how the applied theories and methods are used in the pursue of answering the research question presented in the problem statement in Chapter 3.

The main aim of the research in this thesis is to investigate how green hydrogen can play a role in securing sustainable use of bioenergy in the future climate-neutral electricity system. This is investigated by analysing data in an energy system analysis, which is done through a mixed approach of both using EnergyPLAN and Excel.

The research design of this thesis is presented in Figure 4.1. This figure shows how the different themes/chapters of this thesis are correlated and used in combination to answer the research question as presented. The theories and methods used are equally contributing to answering the research question and sub-questions, and the theories are furthermore creating the basis for analyses made in this thesis, as explained in Chapter 5.

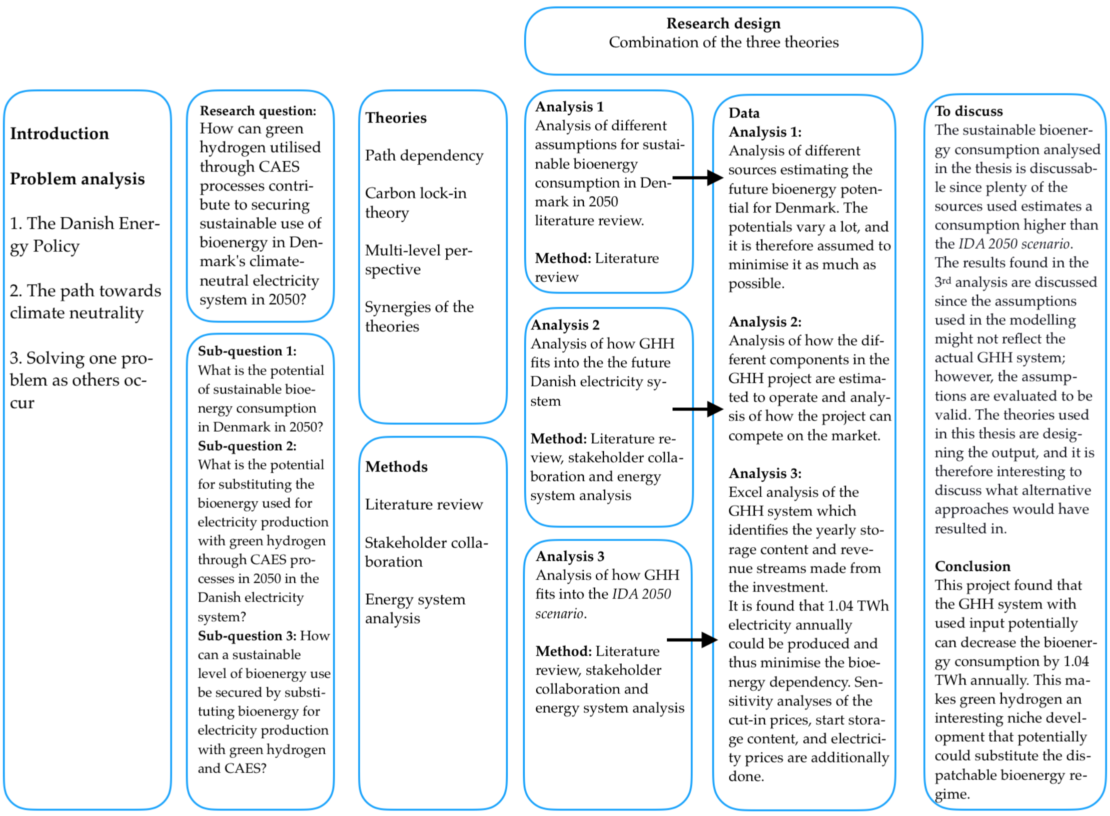

Figure 4.1. The real world being interpreted though the conceptual world using observations, modeling and predictions. [Dym, 2004]

As visible in Figure 4.1, the combination of the three theories plays an essential role as the "research design" of this thesis. The theories have been used to investigate the different aspects of the thesis, especially when answering the research question.

Theoretical Approach 5

This chapter aims to describe the theoretical approach of this master thesis. The theories contributing to the thesis are path dependency, carbon lock-in and multi-level perspective, which complement each other well and bring the analysis to a level where synergy effects occur. The theoretical approach is a description of the theories individually and an analysis of how they fit into the context of this thesis, and eventually a description of how they supplement each other and elevate the analysis. The combination of these theories creates the world view of the thesis. Combining the theories creates a theoretical approach where they benefit each other and create a direction to escape from fossil fuel path-dependant solutions taken in the past and eventually escape from the dependency on bioenergy fostered by the same lock-in mechanisms.

The development and implementation of energy technologies to accomplish the transition towards a 100% RE system face different barriers, including the intermittency of energy, the externalities, the need for transmission etc. Alongside these well-agreed barriers, the development and deployment of RE must overcome over a hundred years of technical and institutional adherence to frameworks built for the fossil fuel industry. [Stein, 2017]

As John Maynard Keynes stated in 1987:

> *"The difficulty lies, not in the new ideas, but in escaping the old ones"* [Keynes, 1987]

The real challenge is not creating new ideas but implementing them and making them predominant over the old ones.

When the existing frameworks define future choices, and the intuitions fail to break from the existing paths, even when breaking from the paths would result in better overall outcomes, that is when the path dependency dominates. This is the case when looking at how the fossil fuel infrastructures affect the path towards a 100% RE system. The fossil fuel infrastructures define the future development of the energy sector, and bioenergy is used in CHP for energy production because it has abilities similar to the before used, fossil fuels and it can adapt to the existing infrastructure. Even though other solutions do exist, these remain unused because of their lack of ability to be integrated into the existing infrastructure and contribute with the same abilities to the system, such as dispatchability and storage; this could be the case, for example, direct electrification of the heating sector as an alternative to the use of CHP. The CHP not only supplies heat when needed, but also contributes to the electricity sector by stabilising the grid and producing electricity when the supply is too low; the same form of dispatchability and grid stabilisation is not seen in the case of direct electrification of the heating sector.

5.1 Path dependency

Path dependency is a theory that can be used to explain why phenomenons evolve as they do and how past decisions affect future decisions. [Liebowitz and Margolis, 1995]

Path dependency is characterised as an accumulation of activities and competencies that create a pattern of self-reinforcing processes that can potentially lead to an inflexible system. This pattern cannot be broke without interference or external impacts, and the inflexibility of the system can lead to an irreversible state of conservation. [Bergek and Onufrey, 2013]
The path dependency can as stated, lead to situations where the most optimal solutions are not utilised. This reflects in the fossil fuel dependency seen today. According to Stein [2017], the majority will argue that investments in RE solutions will result in a better overall outcome with lower marginal fuel costs, lower emissions of CO_2 and air pollutants and less dependence on unsustainable energy sources, and still, we are dependant on fossil fuels. Although low oil and gas prices contribute to the dependency, the mechanism of path dependency plays a significant role as well. [Stein, 2017]

According to Pierson [2000], path dependency consists of three phases, starting with a *critical juncture*, which is an event that causes a move towards or away from a certain path, the second phase being the period of positive feedback where the development of the path is fortified by positive feedback mechanisms affirming the path. The last phase is another *critical juncture*.
As an example, the initial *critical juncture* that caused the oil dependency in the energy sector was the finding of oil and gas in the underground, which led to a supply of abundant and cheap oil and gas. This supply caused investments in infrastructure to carry and transport the oil and gas, which was the beginning of the second phase of path dependency; *reinforcing mechanisms*. The reinforcing mechanisms have been in play ever since, as transportation, industry etc., have been built upon these fossil fuels. Investments in projects based on fossil fuels still happen today, mainly because of the financial incentives; these investments are *critical junctures* that preserves the path dependency on fossil fuels. In contrast, investments in RE technologies represent the *critical junctures* that moves the development away from the existing path. The dependency on oil and gas is under revolution as society learns more about the negative externalities that the use of fossil fuels is associated with. This represents a *critical juncture* pushing the development away from fossil fuels and towards RE technologies, which is where bioenergy comes to play a significant role. People's minds focus on RE because they desire a shift in energy production because of the negative externalities that the fossil fuel industry is associated with. However, because of the path dependency and the existing fossil fuel infrastructure, the most obvious alternative is bioenergy because it has similar abilities and can be used to fuel existing CHP plants and create heat for the DH grid. This is, although, still path dependency because the new path towards a system based on RE is influenced by existing infrastructure and behavioural patterns. [Stein, 2017]

The carbon lock-in theory explains how to break the path dependency on fossil fuel use and force such *critical junctures* to happen. [Stein, 2017]

5.2 Carbon lock-in

The concept and term carbon lock-in, invented by Gregory C. Unruh, refers to how institutions and systems have been locked into using fossil fuel-based technologies caused by path-dependent decisions made in the past. Carbon lock-in can be used to describe the persistent market and policy failures associated with fossil-fueled technologies that inhibit the usage of more environmentally friendly technologies, even though the environmentally and economic advantages are apparent. [Unruh, 2000]

These fossil fuel-based technologies are often costly to build but relatively inexpensive to operate, reinforcing political, market and social factors, which makes it difficult to escape from the usage or "unlock" the carbon dependency. An example of a carbon extensive technology-forcing carbon lock-in is investments in coal-fired power plants since the investment costs are relatively high and the fuel price is contrasting low. [Erickson et al., 2015] The average lifetime for coal-fired power plants historically is 46 years, but it is not unusual that they can operate for 50-60 years. [Cui et al., 2019] Investments in such technologies forces a carbon-lock in, since the fuel costs are low, and to maintain the investment; it has to produce energy, which eventually lockout alternative less carbon extensive technologies. Additionally, the high level of investments in infrastructure built around fossil fuels creates a carbon lock-in. To exemplify this, the extensive gas grid and oil infrastructures have been costly to construct, and if they are not utilised for years to come, there will be a high level of sunk costs associated. Likewise, the previous technological choices, investments and developments affect the transportation industry, according to the carbon lock-in theory. Significant investments made in the transportation industry has historically been made based on fossil fuels. This has resulted in an industry encouraging fossil fuel-based transportation because of the existing infrastructure and investments aligned with the carbon lock-in theory. In addition to this, the habit of using transportation based on fossil fuels, which are accessible all over the world, plays a role in the path dependency and carbon lock-in. Using a technology with a different range of capabilities requires an alteration of the habits around transportation and ultimately a behavioural change.

These mechanisms add to the carbon lock-in and create a situation where that path is even more difficult to escape from.

The question is how the carbon lock-in theory can contribute to breaking the path dependency and secure that *critical junctures* happen to break the path that has been set. [Stein, 2017] The first step of breaking the path dependency lies in understanding the underlying mechanisms at the root of the problem. The mechanism that creates the self-reinforcing barriers to change, and thus the path dependency, is the Techno-Institutional Complex (TIC). The TIC is the culmination of the evolutionary processes that occur in the technological infrastructures, organisations, society and governing institutions due to the increasing returns of scaling the technology and institutions. [Unruh, 2002]

These barriers are defined as the carbon lock-in, where policy action is inhibited even when there is a known better alternative.

Carbon lock-in occurs from systematic interactions between technologies and infrastructures and cannot be described only as a set of general rules. The TIC contributes to describe the complex understanding of carbon lock-in. The TIC arises because large technological systems cannot be fully understood as general technological artefacts but have to be seen as complex systems embedded in a powerful social context of public and private institutions. [Unruh, 2000]

The TIC has created advantages for specific technologies and fuel sources to be used in the industry, which has been done to lower economic, social and psychological costs of the dominating technologies - lowering the inventive for non-dominant technologies to be used. This is done to create a stable, predictable and reliable system. The downside is that it can cause an absence of the ability to change in the future, which can be problematic due to foreseeing future risks. This has been seen when fossil fuels were incentivised and expanded rapidly, and the associated climate challenges were not foreseen. Additionally, to escape from these path-dependent decisions, the Danish government subsidised the use of biomass to substitute fossil fuel usage; however, the dependency on biomass is now problematic, as described in Section 2.3. [Unruh, 2002]

The negative externalities that past decisions are associated with can be mitigated using three different policy approaches, the first being the *end-of-pipe (EOP) solutions* where no alterations are made to the existing system, but the emissions are treated, the second being the *continuity solutions* where selected components or processes in the system are modified, and the third being the *discontinuity solutions* where the entire system is replaced. The EOP solutions and continuity solutions are path dependant solutions that seek to keep as much of the original systems as possible. This happens because of the lock-in mechanisms. Although, when facilitating a change towards the use of new technologies, these mechanisms can be taken advantage of by utilising the existing infrastructure as a part of the new technological solutions and using terminologies that the consumers are used to from their existing systems. Thereby, the financial and psychological expenditures of the transition towards new technologies are minimised, and the alterations are less radical, which ease the change. [Unruh, 2002]
The discontinuity solution represents the case of radical change, where a system is completely replaced. This is rarely seen in large systems or infrastructures like the gas grid; once an extensive distribution grid for gas is in place, it becomes embedded in the infrastructure and can not easily be removed or altered, for instance. [Unruh, 2002]

Technological development is not constrained by science, technical possibilities, and technologies' availability, but rather in the organisational, social and institutional structures. Different technologies can play a role in both a continuous and discontinuous solution. Looking at the technology of wind turbines, they can both play a role in a continuous solution of the energy transition by contributing to the renewable energy generation for the already existing electricity grid and energy system, and in a discontinues solution by moving away from the central energy production and towards a more distributed and isolated energy system depending on how they are used. Choosing between continuous and discontinuous solutions is often a trade-off between investment costs, performance, and behavioural changes. [Unruh, 2002]

Once the TIC is locked in, it can be difficult but necessary to replace it and utilise alternative solutions to create change. This emphasises the importance of the organisational, social and institutional structures and their impact on the possibility of change. The policymakers should seek to create flexible TIC that allow for future development and evolution, and new policy regimes or technologies should, in general, not be seen as the optimal solution to the climate challenges but instead another step in the development towards the solution. [Unruh, 2002]

The first step towards breaking the path dependency and carbon lock-in is to accept that they exist. Secondly, securing that a shift in the logic around energy production can be achieved and pushing for new paths to happen. This includes the cultivation of positive feedback mechanisms for RE which can happen through tools such as legislation, subsidies, policy etc. One might argue that one of the dynamics that need to change for achieving a shift in logic is a shift from supply-side thinking towards more demand-focused thinking. This includes energy savings and DSM and the fact that the demand side can contribute with energy from their energy production from solar PV, etc. Another dynamic changing the logic is the increasing awareness of the climate challenges and the negative externalities associated with the use of fossil fuels; this awareness creates a *window of opportunity* and can act as the critical juncture pushing the transition towards a RE based system. A change in the generation is also one of the dynamics that might change the logic, both because the dependence on investments made upon fossil fuels in the past might not be as dominant and because the strength of investing in RE has now surpassed new investments in fossil fuels, as well as the political focus, has shifted. The younger generation might not be as locked into the path of fossil fuel energy dependence, and the change in the logic around the use of fossil fuels and RE might already be a reality for them. Reducing the positive feedback mechanisms for fossil fuels is just as important as creating them for the RE alternatives. This can be done by using policies, acts, taxes, etc., and as the amount of fossil fuel use decreases, so should the value of the system. There is a vital determination for the fossil fuel developers to keep their plants running to secure the investments they made; this determination can affect the development of the RE sector, which one should be aware of. [Stein, 2017]

As Albert Einstein once said:

> "The problems that exist in the world today cannot be solved by the level of thinking that created them" [Einstein and Prensky, n.d.]

This quote manifests that a shift in the way of thinking is needed to create the most optimal solutions - also in the future. As awareness of technologies not being optimal within their aim/field is raised, it becomes possible for niche technologies to take advantage of other technologies' disadvantages, creating a window of opportunity for the niches. This phenomenon is explained through the transition theory multi-level perspective.

5.3 Multi-level perspective

The multi level-perspective (MLP) framework is a theory describing how regimes or stabilised solutions can change. The idea behind MLP is to describe how transitions happen through interactions between three analytical levels; *niches, socio-technical regime* and *the socio-technical landscape.* In the MLP theory, a focus area is how existing systems can change from one regime to another. This is interesting because it can contribute to solving the before-mentioned challenges of the development and evolution of the energy system being locked in. In this section, the different analytical levels are described individually and eventually illustrated together as a system in Figure 5.1. The main reason for illustrating this through a figure is to show how the different transition levels impact each other and are dependent on each other. Finally, to see how the theory works in a real-world context, an example of how MLP has influenced transitions earlier is presented.

The analytical levels of MLP

This section describes the three analytical levels of the MLP framework theory. [Geels, 2011]

Socio-technical regime

The regime can be described as a business as usual scenario or a set of rules in a socio-technical system. The regime has been present for a long time and is locked-in, path-dependant and resistant to change. Lock-in mechanisms make it difficult to escape from the path-dependant regime, even though innovative alternative solutions can replace the regime with less negative impact. [Geels, 2011] Lock-in mechanisms can, as stated earlier, be the sunk costs related to the system, the cognitive routines which make the people used to a particular system - or even subsidies applied for the regime. These lock-in mechanisms make the playing field uneven because alternatives lack to compete in these terms. It is difficult to escape from these path-dependent carbon locked-in regimes, and the changes, therefore, often happen incrementally with minor adjustments accumulating into stable paths. The changes do not occur radically; however, Geels states that societal "shocks" can be stepping stones for radical changes in a regime, referring to shocks as financial crises or the COVID-19 pandemic, for instance. [Geels, 2020] Radical innovative solutions are struggling to break through, even though they might be proven as a better alternative than what exists in the regime. Therefore, radical innovative solutions need artificial structures to break through, which the landscape could create. These radical innovative solutions are in the MLP theory known as niches.

Niches

Niches occur in the periphery in protected spaces where new technology is developed, which could be research and development (R&D) labs, subsidised demonstration projects or small market niches, where users have a special demand and are willing to support innovative initiatives. Niches are radical innovation ideas and technologies which deviate from the mainstream society and regime. The goal for the inventors of the niche is that the idea or technology will influence the existing regime or ultimately replace it. [Geels, 2011]

This goal is not easy to achieve since the existing regime is often very resistant to change due to different lock-in mechanisms, and the niche may therefore lack to compete with the existing regime, referred by Geels as the "unfair playing field". Therefore, the niches cannot directly compete with the mainstream markets because of the price-performance, which are much lower in the existing technology, and niches are therefore called "hopeful monstrosities" by Mokyr. [Geels, 2020; Mokyr, 1990]

It is interesting how these hopeful monstrosities, niches, emerge and develop over time and gain momentum to overthrow the existing regime, which is the core puzzle of transition studies. [Geels, 2020]
Niches are essential for society because they are stepping stones towards societal changes, which potentially can be changed from a conventional and outdated system towards an updated and modern system. If the niches replace the existing regime, the niche will eventually influence the socio-technical landscape, as exemplified later on.

Socio-technical landscape

The socio-technical landscape is the exogenous context influencing the regime. Exogenous contexts can be slow-changing secular trends as demography, macro-economy, ideology or climate change. Additionally, it can also be shocks as the oil crisis, rescission, wars or pandemics, according to Geels [2020]. The socio-technical landscape can change and shape the way regimes and niches interact with each other. [Geels, 2020]
The socio-technical landscape is, therefore, the broader context that influences the regimes and niches. The landscape can be described as ongoing global trends, which pressurise the existing regimes, creating a window of opportunity for the niche to support or ultimately replace the regime. [Geels, 2011]

A figure illustrating how these analytical framework levels interact with each other is presented in Figure 5.1.

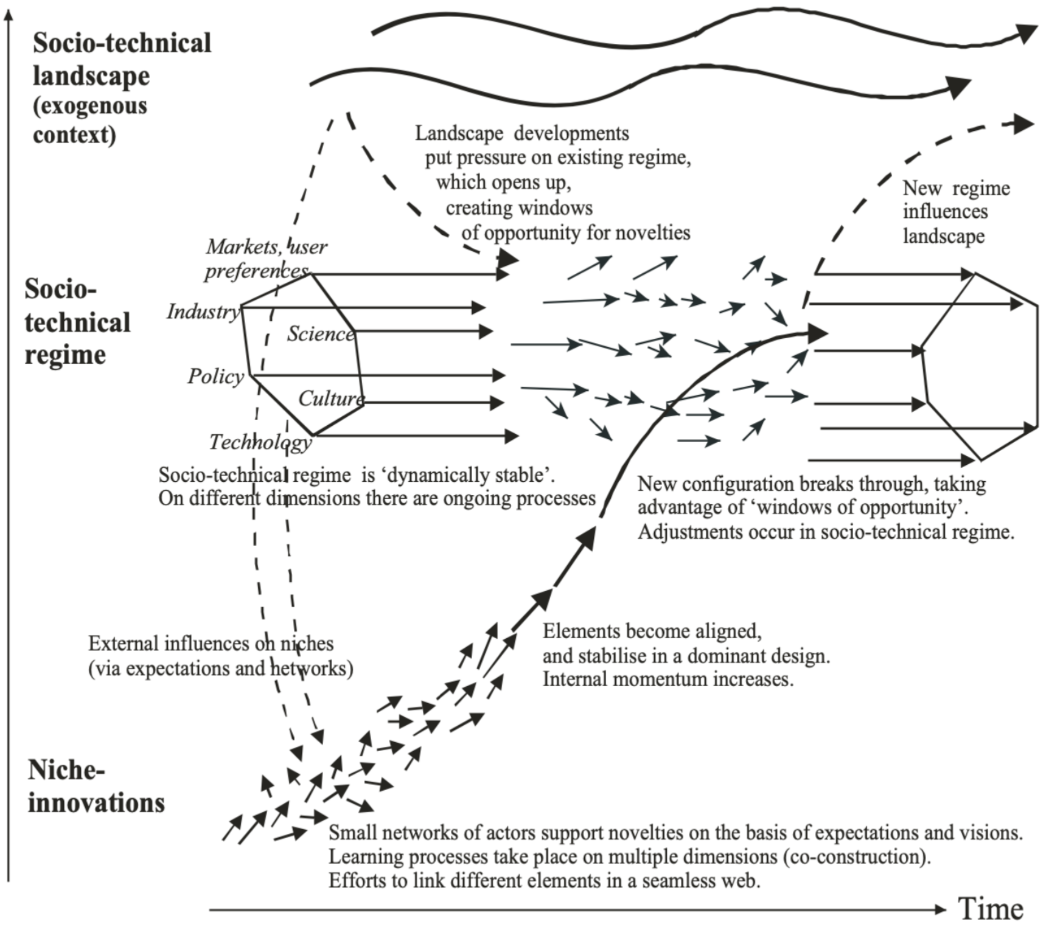

Figure 5.1. MLP structure model [Geels, 2011]

The MLP transition theory can describe the background of many shifts in paradigms and regimes previously. An example of how the MLP transition theory has influenced the development of WTs from being a niche technology to being the future electricity technology is here presented. The example furthermore shows how new regimes potentially can foster new landscapes or challenges.

WTs have not always played a role in the energy systems globally. The conventional energy systems were almost entirely relying on fossil fuels, with coal and oil as the primary sources used in both the electricity and heating sectors. When fossil fuels are burned for energy production, GHG is emitted into the atmosphere, which strongly links to global warming. As more and more energy was demanded because of industrialisation, rise in the world population etc., more GHG was emitted into the atmosphere, causing awareness of global warming. Global warming has already had a significant impact on the planet and will eventually cause further catastrophes if it is not controlled. Global warming then becomes the landscape, which puts pressure on the existing regime; the conventional energy system (i.e. coal and oil dependency). With a landscape pressuring the regime, a window of opportunity occurs for niche developments, which can replace or support the existing regime and avoid being pressured by the landscape. WT were then developed as a technology that produced electricity like fossil fuels but did not emit GHG. This transition has caused a significant expansion of WT and other fluctuating RES, which have less negative externalities connected than compared to the conventional energy system. Eventually, this reliance on such a large share of fluctuating RES in an energy system has fostered a new challenge since the energy system is less flexible than compared to the conventional energy system. Therefore, it aims to find alternatives that can equalise the lack of flexibility, which is fossil-free. This thesis is investigating how green hydrogen can contribute to solving this challenge in Denmark.

5.4 Synergistic effects of the theories

The synergies of these theories are contributing to the analysis in a way that elevates the outcome. Several similarities and connections between the path dependency and carbon lock-in theory are caused by the carbon lock-in being derived from path dependency mechanisms. The self-reinforcing mechanisms and critical junctures characterising the path dependency theory creates the carbon lock-in. The inflexibility of the systems, thought patterns, and institutions is a consequence of the path dependency and carbon lock-in, and the awareness of what creates these mechanisms can lead to the solution to how to escape from them. The carbon lock-in theory explains what mechanisms makes the carbon lock-in (and potentially bioenergy lock-in) persist and thus what measures are needed to break the lock-in - which is very simply put, a shift in thinking. As the awareness of the need for new solutions is created and the path-dependent decisions and lock-in mechanisms are sought to be left, a window of opportunity is created, which is where the multi-level perspective theory plays a role. The MLP theory focuses on how to change from one regime to another, which contributes to solving the path dependency and carbon (and bioenergy) lock-in. It is essential to understand what mechanisms cause the lock-in mechanisms, which is explained by using all three theories. The carbon lock-in theory is the connecting bridge between the path dependency and the MLP theory, and it explains how being dependent on something can lead to being a situation where the development of the system is locked-in, which is where the MLP theory contributes by explaining how to create a shift away.

In this thesis, the theories are used to understand what mechanisms play a role in persisting the fossil fuel-based energy systems and how new developments can evolve to play a role in the energy system. The motivation for investigating the potential for integrating green hydrogen in the Danish electricity system is the current and future bioenergy lock-in. The supply of bioenergy is evaluated to be very uncertain and unsustainable. Bioenergy is intended to play a significant role in the future Danish energy system as a balancing measure because it is built upon existing infrastructure and has similar abilities to fossil fuels, which create the lock-in. However, bioenergy sustainability is uncertain, which eventually creates a window of opportunity for niche developments that can overcome some of these challenges without fostering new challenges. Green hydrogen has similar abilities as bioenergy, such as storability, dispatchability and the ability to use similar infrastructure, but without the challenges of bioenergy as mentioned in Section 2.3.1.

These theories have affected the choice of methods and analyses by raising awareness of the problems and challenges of following the path of fossil fuels and later bioenergy. This awareness, alongside other negative aspects of bioenergy dependency, has caused a desire to escape from the energy system's bioenergy dependency.

Methods 6

Based on the theories presented, it is chosen to collaborate with a niche development company focusing on P2H2P to break the path dependency and lock-in mechanisms that ultimately create a dependency on bioenergy and make it the dominant dispatchable energy resource of the system. The Danish bioenergy consumption should be sustainable in the future, as mentioned in the Problem Analysis in Section 2.3, which creates a window of opportunity that green hydrogen and the P2H2P technology has the potential of advantaging from. In addition to the stakeholder collaboration, the literature study method is used, where information and data from existing research are collected, and new findings are made. An energy system analysis is made to simulate the energy system and the P2H2P technology using existing data.

6.1 Stakeholder collaboration

This thesis is based on stakeholder collaboration. The reason for choosing this is that it gives access to expert knowledge in the field of study when conducting the analyses. Additionally, the collaboration is chosen to create an analysis with an outcome that can be valuable for a company in a current situation. Therefore meetings and discussions have been conducted in the initial phase of the thesis to secure that the thesis's interest matched with something that would be valuable for the specific company.

6.1.1 Collaboration with Hydrogen Valley and GHH

This thesis is carried out in collaboration with the Danish company Hydrogen Valley (HV), a non-profit organisation mainly financed by Mariager Fjord municipality and external aids. HV is primarily focusing on investigating the potential for PtX, mainly hydrogen. The company is located in CEMTEC Business Park in Hobro in the northern part of Jutland. Currently, HV is involved in different projects to contribute to the investigation of PtX. One of the projects they are involved with is Green Hydrogen Hub (GHH), contributing with their knowledge and skills. The project partners of the GHH are; Eurowind Energy, Corre Energy and Gas Storage Denmark (Energinet), and Everfuel as a strategic partner. This thesis investigates how green hydrogen produced through electrolysis can be stored cost-efficiently in large salt caverns underground and be utilised to produce electricity through a CAES process, in a so-called P2H2P process. [Hydrogen Valley, n.d.]

This section aims to describe the collaboration with HV during the thesis period. The collaboration is made based on a shared interest, but with the authors of the thesis being the project managers. The collaboration was initiated on the 9th of February 2021 when the authors reached out to the *CEO of HV, Søren Bjerregaard Pedersen* who suggested setting up a meeting to identify any ongoing projects. In collaboration, the GHH project was found to be exciting to investigate through the thesis. It was of shared interest that the collaboration aimed to share knowledge and possible findings.

The actors of GHH, Eurowind Energy and Gas Storage Denmark, has been part of the collaboration by contributing knowledge and data through meetings and email correspondences. [Green Hydrogen Hub, n.d.]

Even though the thesis is carried out in collaboration with HV and GHH, it should be noted that the problem formulation and research question is made without interference, and therefore the research has not been biased by the collaboration; the collaboration is as mentioned exclusively based on academic collaboration with shared knowledge and findings. When working in collaboration with external companies, it can be essential to mitigate the risks of bias and influence. There is, of course, a risk that the participating companies' interests affect the way the problem is handled and, thereby, the research. This mechanism has, for instance, happened when choosing which technological solutions to investigate in this thesis. It is important to note that the technological solutions to investigate have been made because of the interest of HV and GHH and because of interest from the authors of the thesis. The choice of technological solutions to investigate has been made to get relevant data and has thus been beneficial for both parties.

A potential risk to manage when collaborating with external partners is the reliance on data deliveries from these partners. These deliveries can affect the time management of the thesis. For instance, if data provided from the external partners required for the analysis is received later than expected, it can delay the time schedule. It can be necessary to mitigate such implications, which in this thesis has been done by using fictional data for the analysis and altering it when the delayed data has been received. When collaborating with other companies, the time management perspective is essential, as more parties' plans have to be considered, and more parties are affected by delays since they have additional deliverables and deadlines. The parties should have similar interests in delivering on deadlines and doing the work agreed on time. The perspective of interest and deliveries adds to the necessity of the analysis being interesting for all parties because it makes the stakes higher and thus the interest in delivering on time.

The analyses and results are presented for the GHH stakeholders to validate the work and clarify any wonders. The reason for presenting the results for the stakeholders is creating results that reflect the real world and its complexities the most.

The collaboration with HV and GHH is chosen because it makes it possible to analyse real-life problems and contribute to an existing industry, elevating the analysis. Furthermore, the collaboration makes it possible to gather real-world information and data, which could have been challenging to gather otherwise. It has been of shared interest that no confidential material should be used in this thesis since the authors want to have the opportunity of publishing it after the defend, and HV might want to use or publish some of the findings within this work.

6.2 Literature study

The research question aims to secure sustainable use of bioenergy in the electricity sector by utilising green hydrogen and CAES is analysed through the use of primary data and knowledge collected through the collaboration with HV and GHH and secondary data. The literature study is used to create a good foundation of data for the analyses.

6.2.1 Data collection

It is chosen to base the analysis in this thesis primarily on secondary data. Secondary data is data that was initially collected for other purposes. It is evaluated that the already excising data on, for example, energy demand, energy consumption, technology efficiencies, is sufficient for the research and that better data can not be obtained during the time frame of this study.
Secondary data can be utilised to create new knowledge by combining existing data from different sources and setting it up in new systems and contexts - this is the purpose of the energy system analysis in this research - identifying applicable existing empirical data, collecting it, evaluating it, putting it into new contexts, analysing it in the context and ultimately creating new knowledge. [Johnston, 2014]

For the collection of the secondary data, different methods are used. The collaboration with GHH, explained in Section 6.1.1, is utilised in the data collection by accessing new unpublished data from Energinet, the Danish TSO. General literature research is used in addition to secondary data from the collaborative partners. The literature research is done chiefly using chain search, where the research of new information and data is based on keywords in the found literature. Additionally, literature research is used for the collection of data from energy data portals like Energinet's *EnergiDataPortal*. [Rienecker et al., 2012]

6.2.2 Validation of sources

The validity of the used literature is assessed on behalf of the chosen inclusion criteria [University of Bedfordshire, 2018]:

- **Topicality** - The literature is evaluated based on the age of the information and data. The research used is, in general, as recent as possible, and the older data is used with cautiousness.

- **Reliability** - The reliability of the author and publisher is of vital importance when evaluating the validity of existing literature. Acknowledged publishers and authors are in general favoured and preferred. Peer-reviewed articles are used to the furthest extent possible, and where relevant peer-reviewed articles could not be found, academic journals and reports have been prioritised.

- **Application** - Evaluation of what different sources of literature can be used for in the research is crucial; this evaluation of application can include awareness of bias and different geographical settings.

An example of where these inclusion criteria are used in collecting data for the Energy System Analysis can be seen in Section 6.3, as an existing model is used as the basis for the Energy System Analysis in this thesis. As stated in the section, the model used is a model simulating the Danish energy system, created and validated by reliable sources. The topicality is evaluated by looking into the model's age and the data that constitute the model.

6.3 Energy System Analysis

In this thesis, the energy system analysis seeks to imitate the future energy system of Denmark, focusing on bioenergy use and the potential for P2H2P through mathematical modelling of the hourly energy balances throughout one year. The purpose of the simulation is to secure a sustainable level of bioenergy in the electricity sector of Denmark; this is done by introducing the niche technology of P2H2P, where electrolysis and CAES are utilised to transform electricity into hydrogen and back to electricity when needed; this system is what is utilised in GHH. It is simulated through an energy system model to analyse the actual production and the economic impacts.

In science, one will distinguish between the real world and the conceptual world. The real world is the world that we live in, and the conceptual world is the world that exists in our minds and imagination based on the cognitive understanding that we have of the real world. [Dym, 2004]

An energy system analysis seeks to imitate real-world phenomena through the conceptual world, using observations modelled and used for some form of prediction. This dynamic is illustrated in Figure 6.1 [Dym, 2004].

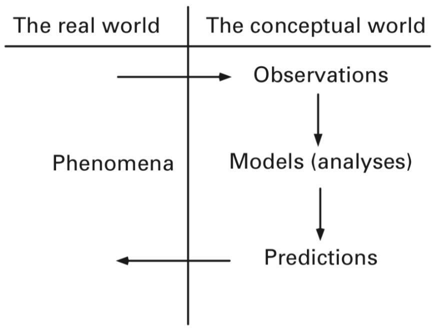

Figure 6.1. The real world being interpreted though the conceptual world using observations, modeling and predictions. [Dym, 2004]

When a problem in the real world is investigated, it can be analysed through the conceptual world using models. Models are simplified descriptions of, e.g. phenomenons, structures, or patterns. The modelling used in this analysis is based on mathematical language, which means it seeks to illustrate real-world phenomena using equations and logical operations. [Dym, 2004]

When doing mathematical modelling, computers and modelling tools can calculate the complex numerical calculations and simulations that make up the model. These tools can be spreadsheets like Excel, where models and strategies are created from scratch, or it can be simulation programs that already have built-in strategies and pre-programmed sub-

models that describe how specific technologies act. These sub-models can be put together into a more extensive collected system, called the dynamic system model. [Marion and Lawson, 2008]
This is what is seen in the EnergyPlan simulation tool. [Lund, 2014]

The modelling tool EnergyPLAN is used in this thesis since it is a deterministic input-output tool that has pre-programmed sub-models of most of the technologies needed for this analysis, which can be seen in Figure 6.2. It includes different sectors within the energy sector; the electricity sector, the heating- and cooling sector, industry and transport, which is relevant for this study since a holistic approach to the energy system is desired while focusing on the electricity sector.

Figure 6.2 gives an overview of the structure of the EnergyPLAN tool. It is visible that there are different input variables and distribution data needed for analysis through EnergyPLAN. These are simulated through a chosen simulation strategy, either a technical focus or an electricity market focus. It is furthermore possible to implement costs in the form of both financial costs and emissions. The model's output is dependant on the input variables, the distributions, the costs, and the chosen simulation- and regulation strategies.

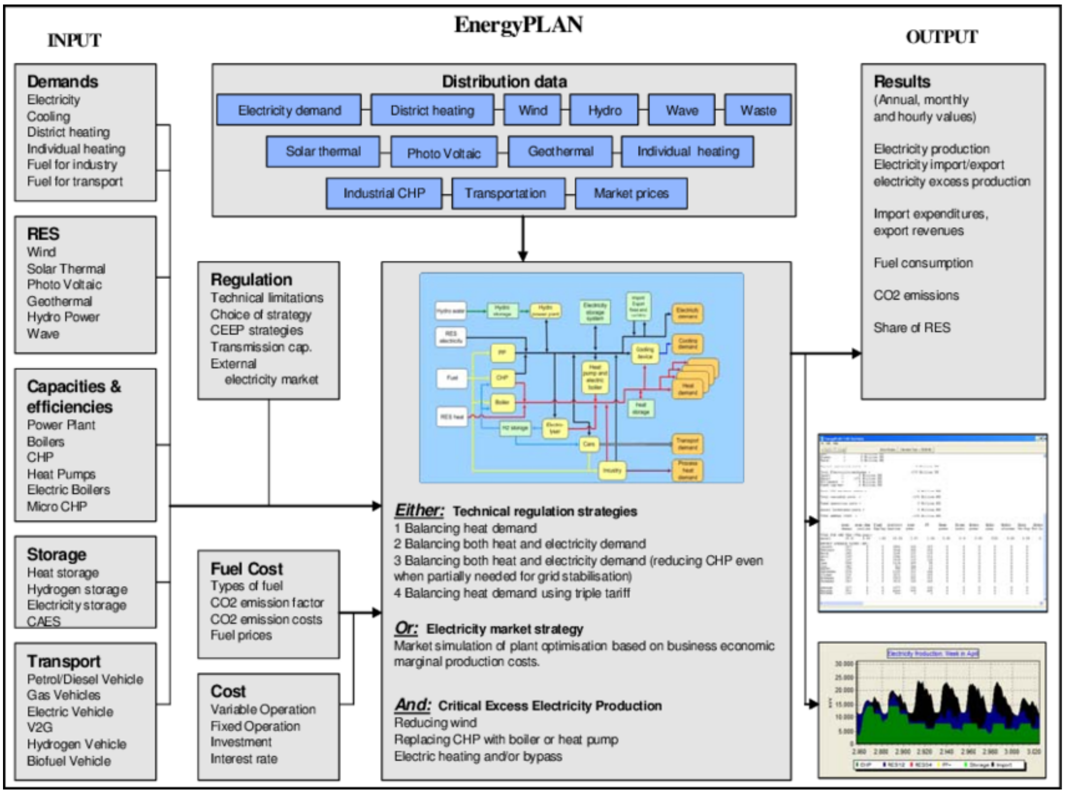

Figure 6.2. The structure of the EnergyPLAN tool [Connolly et al., 2014]

When using a specific simulation tool, it is necessary to be aware of potential disadvantages. As mentioned, the EnergyPLAN model is a deterministic simulation tool which means that a specific input will create the same results in each iteration, meaning no "random occurrences" affect the result. A stochastic simulation tool will conversely consider "random occurrences" and create different results for each iteration even though the same input is used. In reality, there will be more wind and solar resources or drought in some

years, which the EnergyPLAN does not consider. [Lund, 2014]
In order to overcome or mitigate this disadvantage, it is possible to make sensitivity analyses of different input variables. The sensitivity analysis can be used to look into how important the accuracy of certain data is for the simulation results by altering certain data to check the impact an uncertainty in the specific data has on the result. [Marion and Lawson, 2008]

Existing energy system models representing different countries, counties, and regions are available for the EnergyPLAN tool through their database. [EnergyPLAN, n.d.] It is possible to investigate parts of the system more in detail while the holistic approach remains by using existing holistic energy system models.

How simple or complex a model should be is a fine balance; if it is too simple, it can leave out important details, and if it is too complex, it can be too resourceful to create and simulate. [Marion and Lawson, 2008]
It is chosen to use a modelling approach that simulates all energy sectors of the Danish national energy system by 2050; this is chosen because a holistic approach is desired. This desire creates a system where the focus can be kept on the modelling of the GHH while comparing it to the use of bioenergy in the EnergyPLAN simulation remains possible. When integrating electrolyser capacity for the GHH system, the system produces waste heat besides producing hydrogen, which potentially can be utilised in the DH grid. Because the GHH system is modelled outside of the EnergyPLAN tool, these aspects are, however, only discussed. Furthermore, this scenario already has a bioenergy consumption which is aimed to be reduced. The model's reliability is dependant on the assumptions and the data that creates the basis for the model. Therefore, when analysing the results, it is important to be aware of the impact the assumptions and data implies - this applies regardless of which tool is used for the modelling. [Marion and Lawson, 2008]

Most of the needed sub-models are already programmed, making the modelling time-efficient, but it is still essential to be aware that the operation of the different technologies in the model is based on. EnergyPLAN is designed to simulate national and regional energy systems on an hourly basis, including all sectors; heating, electricity, transport and industry. Furthermore, most of the data available are based on hourly values that fit into this tool's input criteria. In the real world, the energy system will act continuously over time, not necessarily hourly; this is simplified because of data availability, the calculation time and the computing power needed for running the simulation. An advantage of using this tool for the analysis is that the demand and distribution profiles available are area-specific, and it is possible to implement other profiles in the EnergyPLAN model if the existing profiles are not useful. [Lund et al., 2009]

As mentioned, an already existing EnergyPLAN model has been used to investigate how P2H2P can reduce the dependency on bioenergy in the electricity sector. Using an already existing model has some clear advantages, described in the delimitation in Section 3.1. For instance, the time used on the modelling is optimised since it can be very time consuming to create a national energy system from scratch. By using an existing model, the time can be used otherwise. Furthermore, the model used is created by researchers with expertise within the EnergyPLAN field, and it is therefore reliable and verified. Therefore, it is evaluated that using an already existing model built by experts is the optimal solution, and it makes it possible to look into the bioenergy use from a holistic perspective while focusing on reducing the use only in the electricity sector the time perspective taken into consideration.

6.3.1 Basis model: IDA 2050 scenario

The *IDA 2050 energy scenario* (with high fuel prices) has been chosen for the analysis based on its holistic approach, which makes it possible to investigate the potential synergy effects of integrating the GHH system in the Danish energy system. The fact that the *IDA 2050 scenario* already has simulations of the different sectors of the energy system: electricity, heat, transportation and industry, makes the scenario relevant as the basis model for this analysis because it makes it possible to implement the GHH system while focusing on the electricity sector, while still considering and discussing the use of excess heat from the GHH and the use of green hydrogen for the transport sector. The high fuel price version of the scenario has been chosen because of the lower biomass consumption relative to the other versions of *the IDA 2050 scenario*.

6.3.2 Distribution profiles from 2013

The IDA 2050 scenario is mainly based on distribution profiles from 2013, which is essential to be aware of because it adds to the uncertainty when simulating a scenario for 2050. For instance, the distribution profiles for the RES are made based on 2013 data. To optimise the technologies towards 2050, a correction factor has been added to the distribution resulting in a distribution profile more optimised for 2050. A distribution profile that plays a significant role in the results of the energy system analysis in this thesis is the spot market price distribution, which is also based on 2013 data. A factor of 1.2 has, like earlier, been added to the 2013 spot market prices from 2013 in order to make appropriate price assumptions for 2050. This spot market price distribution plays a role in determining when the pump and turbine will be utilised in the GHH system since cut-in prices determine their operation. A simple price strategy is applied where only the spot price is accounted for, for both the purchase and sales of electricity. Tariffs like system- and grid tariffs and taxes are not considered. [Energinet, 2019]

The spot market prices in 2013 are, in general, relatively high; therefore, to investigate how much the spot market prices from 2013 (including the correction factor) differs from other years, a figure showing the duration curve for the spot market price for both 2013 and 2020 is presented. The spot market prices in 2013 are gathered from the *IDA 2050 scenario*, while the electricity prices from 2020 are gathered from Energinet [n.d.].

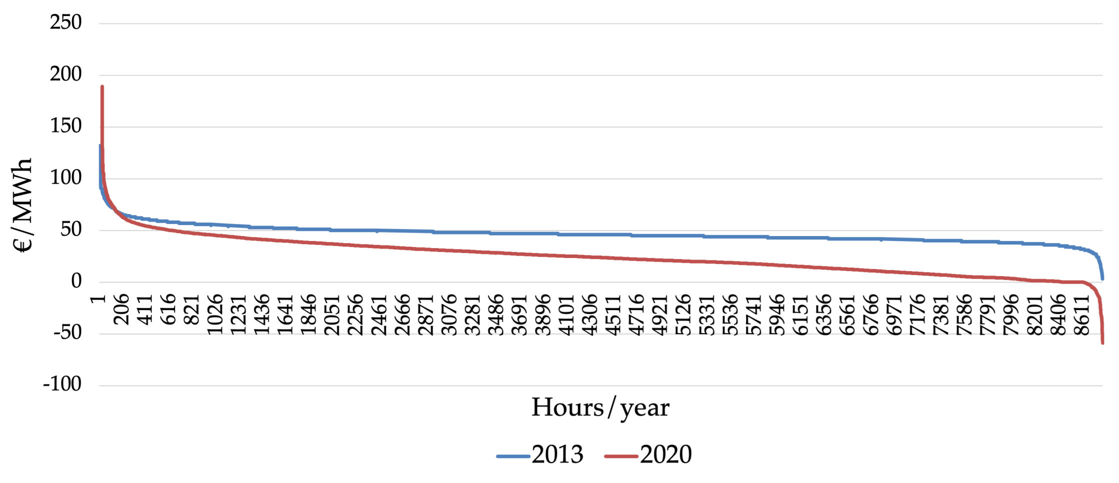

Figure 6.3. Duration curves for both 2013. Data from EnergyPLAN and Energinet [n.d.].

It is by Figure 6.3 visible that even though the corrected spot market prices from 2013, in general, are higher than in 2020, the latter one has higher peaks. This shows that if the spot market price distribution is changed to another year, other opportunities for the GHH system and their business case would be created. If spot market prices from 2020 were used, it would be possible to lower the cut-in price for the pump. However, it has been chosen to use the corrected spot market price distribution profile from 2013, since the *IDA 2050 scenario* is based on this profile and other parameters in the model, such as the bioenergy use, is based on numbers from 2013 as well, which makes it possible to compare them on the same terms considering conditions like weather and demand.

6.3.3 Modelling of the GHH hydrogen-CAES system

The GHH hydrogen-CAES system is not pre-programmed in the EnergyPLAN tool, and it is not possible to simulate the GHH system through the use of EnergyPLAN, which means alternative solutions for simulating this sub-model are needed. The solution in this thesis is to simulate the GHH system by using the hourly output data from the simulation of the *IDA 2050 scenario* in EnergyPLAN and modelling the GHH system from scratch using Excel modelling.

The GHH unit is modelled as a combined system looking at the electrolyser unit and CAES unit as combined units. In the model, it is assumed that the electrolyser and air compressor is a single component, namely ***the pump***. Furthermore, when energy from the storage has is utilised for electricity production, this happens through a CAES and hydrogen-based turbine, which is referred to as ***the turbine***. The storage units of the GHH system is referred to as ***the storage***.

Data used for the modelling of GHH

The modelling of the GHH system is based on capacities of the units from Hethey et al. [2020], which can be seen in Figure 7.1.
The technical data concerning the efficiency of the units and the economic data used is

calculated based on data from [The Danish Energy Agency, 2021] and [The Danish Energy Agency, 2020]. The calculations in the model and data used are attached in Appendix A.

The efficiency of the pump is calculated by using the efficiency of a SOEC electrolyser for 2050 from The Danish Energy Agency [2021], which is 83.5%. The efficiency of the air compressor is assumed to be the charge efficiency of the CAES storage, which is 85% according to The Danish Energy Agency [2020]. The efficiency of the turbine is assumed to be the discharge efficiency of the CAES storage, 85%. [The Danish Energy Agency, 2020] The efficiency of the pump and turbine is taken into account in the analysis. The efficiency of the storage is assumed to be ≈ 100% relating to the estimation of the hydrogen cavern storage data from The Danish Energy Agency [2020]. The technical lifetime potentials for the units are used for assessing the yearly revenue. The efficiencies and technical lifetime potentials are summed up in Table 6.1.

Energy/technical data	
	2050
SOEC electrolyser	
- Efficiency [%]	83.5
- Technical lifetime [years]	20
CAES	
- Charge efficiency [%]	85
- Discharge efficiency [%]	85
- Technical lifetime [years]	40
Hydrogen cavern storage	
- Efficiency [%]	100
- Technical lifetime [years]	100

Table 6.1. The energy- and technical data that creates the basis for the modelling of the GHH system. [The Danish Energy Agency, 2021, 2020]

The investment costs, operation and maintenance costs (O&M), and technical lifetime data are found in The Danish Energy Agency [2021] and The Danish Energy Agency [2020] as well. When looking further into the costs, the data is split into CAES, accounting for the pump, turbine and storage unit of the CAES system; and electrolyser, accounting for the electrolyser unit and the hydrogen storage. The data can be seen in Table 6.2.

Financial data	
	2050
CAES	
Specific investment [M€2015 per MWh]	0.025*
Fixed O&M [€2016/MW/year]	2460
Variable O&M [€2016/MWh]	2.46
Electrolyser	
Specific investment [M€/MW]	0.738
Fixed O&M [% of specific investment/year]	12
Variable O&M	-
Hydrogen cavern storage	
Specific investment [M€2015 per MWh]	0.0012
	*from table 3 in the source

Table 6.2. The financial data that creates the basis for the financial calculations of the GHH system. [The Danish Energy Agency, 2021, 2020]

The operation of the GHH system additionally takes into account the hourly spot market prices from the *IDA 2050 scenario*.

Finding the optimal cut-in prices for the pump and turbine

Through the Excel add-in tool *solver* the optimal cut-in prices for the turbine and pump in the GHH system are calculated. The optimal cut-in prices seek to maximise the yearly revenue made from the investment, and the cut-in prices are 42.38 €/MWh and 46.72 €/MWh for the pump and turbine, respectively. The unit does not consider the operation of the other units in the system and solely operates based on the spot market price, storage capacity, and yearly revenue; this ultimately means that the yearly revenue will decrease if the cut-in prices are changed.

The reason for EEP and CEEP not being considered in the model

The GHH system does not take EEP or CEEP into consideration, even though it, in reality, would create an opportunity for charging the storage. The main reason for this is that the CEEP rarely occur in the *IDA 2050 scenario* however it is expected that the model will operate when CEEP occurs. EEP is not considered because the system is optimised based on revenue, and in cases where the most prominent revenue can be created by utilising the electricity, it will occur in the operation anyway. This way, the GHH system avoids using electricity in the case of high prices when it can be exported.

FLH of the pump, turbine and storage

As mentioned previously, the Excel model is a simplified version of the actual GHH. The electrolyser has an installed capacity of 150 MW, while the air compressor has an installed capacity of 160 MW, resulting in the pump having an installed capacity of 310 MW in the modelling. The turbine has a total installed capacity of 300 MW. Additionally, there are both CAES storage and hydrogen storage in the GHH system. The CAES storage will, in reality, be located in an underground chamber with a storage capacity of 3.2 GWh, while the hydrogen will be stored in a large salt cavern with a total installed capacity of 200

GWh. These storage facilities are combined into a single storage facility with a storage capacity of 203.2 GWh in the modelling of the GHH system, except when looking into the economy. The model assumes that the GHH system can only operate using full load hours (FLH), which simplifies the real world, which does not exhaustively illustrate the system's flexibility.

Choosing the start storage content

In the modelling of the GHH system, it is estimated that the start content of storage is 100 GWh, which is almost half of the maximum capacity, this is assumed to be the most realistic solution since the simulation of the GHH system is based on a single year, and it is therefore not known at what storage content the system ended the previous year. If the start storage content is changed to either 0 or maximum, the simulation will change, which is explained and analysed in a sensitivity analysis in Section 7.3.2.

Production of excess heat from GHH

The GHH system can potentially produce excess heat to the DH grid because it is expected that excess heat from at least the electrolyser will be available. It is not assumed that excess heat from the air compressor, or the turbine will be available, even though it might be in reality. It has not been possible to receive specific data of the waste heat from the single components, and it has been decided to assume that no excess heat will be available from these components. There is, therefore, only a 20% excess heat potential from the electrolyser available in this simulation. As the electrolyser has an installed capacity of 150 MW out of the 310 MW, it is assumed that the total excess heat from the combined electrolyser and air compressor, namely *the pump*, is 10%, even though this estimation might be a little conservative. However, the revenue made from excess heat is not calculated, even though it potentially could be created.

Modelling GHH as a closed system

The GHH system is modelled as a closed system, which means that the hydrogen produced cannot be used for other purposes than for operating the CAES turbine and producing electricity; this creates some disadvantages to be aware of, since the utilisation of the hydrogen, in reality, could be optimised by using it for other purposes when feasible. If, for instance, the GHH system was connected to a hydrogen grid, the cut-in prices of the units and the business case could have changed. In reality, the GHH system can use the produced hydrogen for producing electricity when the spot market prices are high and use the hydrogen for other purposes such as transport and industry when that is feasible.

Reducing the bioenergy use by implementing the GHH system

The production of electricity from the GHH system is intended to substitute the bioenergy use in Denmark. The bioenergy use for electricity production is assessed by investigating the *IDA 2050 scenario* focusing on the parts of the energy system where the GHH system can substitute the bioenergy use; this is investigated by looking into the production of electricity from the GHH turbine and putting it into the context of the power production from PP and CHP. This is done with the knowledge that the system, in 2050, is 100% climate neutral, and therefore these units are fueled by the use of bioenergy.

Analysis 7

In order to answer the Research Question "How can green hydrogen utilised through CAES processes contribute to securing sustainable use of bioenergy in Denmark's climate-neutral electricity system in 2050?" an assessment of the challenges concerning balancing the electricity system in a climate-neutral energy system is needed.

Energy scenarios from Mathiesen et al. [2015], and Lund et al. [2011] (*the IDA 2050 energy vision* and *CEESA research project*) shows that bioenergy is the primary dispatchable resource balancing the future climate-neutral electricity system alongside balancing mechanisms such as demand-side management, vehicle-to-grid (V2G), storage and import/export of electricity. As mentioned in the problem analysis in Chapter 2, this creates a critical dependence on bioenergy, which is problematic for several reasons.

7.1 Analysing the potential of sustainable bioenergy

In order to analyse how green hydrogen can contribute to securing sustainable use of bioenergy in Denmark's future climate-neutral electricity system, the sustainable level of bioenergy use must be defined.

This section answers the second sub-question of the problem statement, which can be found in Chapter 3.

The maximum biomass potential is uncertain since it is in the future. In order to estimate this maximum optimally, different reports and academic articles have been analysed. Some sources calculate the worldwide biomass potential using biomass consumption per capita. Therefore, to calculate the Danish sustainable biomass potential, it is necessary to convert the consumption to a national potential. In 2050 the population of Denmark is expected to extrapolate to 6.3 million. [Statistics Denmark, n.d.]

Assessing the global sustainable biomass consumption by 2050, it is interesting to look into an IPCC released report. This report analyses the global maximum biomass consumption by 2050. Masson-Delmotte et al. [2019] mentions that there is a high level of agreement on the annual potential worldwide being restricted to a maximum of 100 EJ in 2050 and that a biomass consumption above this level will be associated with negative externalities and put significant pressure on land, food production and prices, biodiversity and ecosystems, and potential water and nutrient constraints appear. Therefore, it is expected that the average sustainable biomass consumption per capita is 10 GJ/year (with a global population of 10 billion people in 2050), resulting in a total potential in Denmark of 63 PJ in 2050. This calculation is associated with uncertainties since adapting a global average to a Danish context might not be optimal because some countries have more land available and a higher potential for biomass than others. However, it is relevant to have a global perspective when estimating the national sustainable biomass consumption because global warming should be solved globally.

A climate plan released by IDA in 2009 states that the sustainable bioenergy potential in Denmark in 2050 is 155 PJ/year without energy crops and blue biomass [IDA, 2009]. This report was released in 2009, and it should therefore be noticed that newer reports do exist.

Another source identifying a sustainable biomass potential in 2050 is the CEESA research project, predominantly carried out by researchers from Aalborg University in 2011. However, this report is built upon the earlier released report, the IDA energy vision for 2050 released in 2009, which uses the biomass consumption as described in the IDA climate plan from 2009. [IDA, 2009]
However, the CEESA project presents four different scenarios; a business-as-usual scenario, a conservative scenario, an ideal scenario and a recommendable scenario. The recommendable scenario estimates a potential of 237 PJ biomass in Denmark in 2050, which is higher than the ideal scenario and lower than the conservative. However, if energy crops and blue biomass is removed from the calculation, only 170 PJ of biomass is available, which is the part of the biomass that is defined as sustainable in this report according to the delimitations in Section 3.1. [Lund et al., 2011]
By investigating the two reports (the IDA climate plan from 2009 and the CEESA report from 2011), it becomes clear that an exact estimation of the sustainable bioenergy consumption in 2050 is difficult to evaluate. As mentioned, it should be considered that the research was released in 2011 and that more recent sources are analysed in addition.

The Danish Energy Agency released a report called "Biomasseanalyse" (i.e. biomass analysis) in 2020 with the aim of analysing the Danish biomass potential. This report estimates that the Danish sustainable biomass potential is somewhere between 160-180 PJ in 2050, produced domestically and without energy crops and blue biomass. [Danish Energy Agency, 2020b]

Additionally, a report released by Wenzel et al. [2014] from SDU (University of Southern Denmark) estimates a future worldwide bioenergy potential of 220 EJ/year, which calculated per capita, and upscaled to the Danish population in 2050 results in a Danish potential of 138.6 PJ/year (38.5 TWh/year). The report additionally estimates the bioenergy consumption worldwide in different 100% RE based scenarios. By investigating the report deeper, it can be concluded that the scenarios made by Wenzel et al. [2014] have a higher bioenergy demand than the potential when converted to the Danish conditions. It is, in this report, estimated that the Danish biomass consumption in 2050 will be between 45-120 GJ/person/year, depending on the scenario. If a more "conventional", nonetheless 100% renewable energy system, is used, a higher biomass consumption will be used since existing technologies will be used with minor adaptions. Oppositely, if a more modern 100% RE system is implemented with more synergy effects, types of storage, carbon capture etc., less biomass is demanded. If the numbers estimated in the report released by Wenzel et al. [2014] are converted into a Danish demand, the scenarios span from 283.5-756 PJ/year (78.75-210 TWh/year). These calculations supply evidence to the fact that the bioenergy demand in Denmark in the future 100% renewable energy system is high relative to the bioenergy potential in Denmark.

An overview of the different estimations of biomass potentials in Denmark by 2050 is presented in Table 7.1.

Data source	**Bioenergy potential [*PJ*]**	**Bioenergy potential [*TWh*]**
IPCC	63	17.5
IDA's climate plan 2050	155	43
CEESA	170	47.2
Danish Energy Agency	160-180	44.4-50
SDU	283.5-756	78.75-210

Table 7.1. The sustainable biomass potential in 2050 from various sources. Conversion: 1 PJ = 0.2778 TWh

As visible in Table 7.1 the biomass potential varies in the different sources; this is, in part, caused by the fact that the IPCC report is based on global estimates and in part due to the fact that the biomass potential is very uncertain in the future. It has been assessed, in the problem analysis in Section 2.3.1, that being dependant on biomass is associated with some issues such as; dependency on one dispatchable resource, biomass being an exhaustible resource, the sustainability of biomass can be questionable, biomass can result in spatial planning controversies, local air pollution, loss of biodiversity and plenty others. As analysed, it is difficult to predict the Danish sustainable bioenergy consumption by 2050, and ***it is, therefore, in this thesis, aimed to minimise the bioenergy use and thereby dependency***.

7.1.1 Relating the sustainable bioenergy potential to the consumption in IDAs Energy Vision 2050

With the assumption that the bioenergy use should be minimised as much as possible, the bioenergy use in the *IDA 2050 scenario* is analysed. The authors of the *IDA energy vision 2050* have created different scenarios and different EnergyPLAN simulations corresponding to the scenarios. These scenarios are based on different assumptions and simulation strategies. The biomass consumption in the *IDA 2050 scenarios* spans from 45.9-75 TWh/year (with CORE v15.1 as the lowest and the low fuel price scenario as the highest) [Mathiesen et al., 2015]. It is chosen to use the *IDA 2050 scenario* as the basis for the simulations made in this analysis, as mentioned in the Method in Section 6.3 since it is a model that is sector coupled and it has a bioenergy consumption, which potentially can be reduced and substituted by the implementation of the GHH system. The reason for choosing an already existing model is elaborated on page 34 in the method section.

The bioenergy consumption in the IDA scenario 2050 is 45.8 TWh.

With the sustainable bioenergy potential being difficult to predict for 2050, it is not aimed to quantify it, but it is only aimed to minimise it.

The need for minimising the bioenergy used in the system eventually creates a window of opportunity for niche developments that can cover the same demand and services, which for instance, could be green PtX and CAES.

7.2 The window of opportunity for PtX development

PtX is intended to play a vital role in escaping carbon-locked technologies, especially in the hard-to-abate sectors. Different types of PtX can contribute to the transition in Denmark because of the significant wind resources and the stable electricity transmission grid, which are vital operating characteristics for a well-integrated PtX infrastructure. [Rambøll, n.d.] Furthermore, Denmark already has a well-integrated gas grid which potentially can be retrofitted into a hydrogen grid if desired; and eventually, be connected to the European Hydrogen Backbone; this would, however, create a situation where biogas should be transported in an alternative way. [Energinet and Danish Energy, n.d.; Wang et al., 2020] However, the main driver for not utilising PtX production on a higher level than currently is the high costs related to production. The highest costs in the PtX value chain is within the electrolysis process and in the purchase of electricity. Electrolysers are currently evolving in efficiency, and the prices related are decreasing. Bloomberg estimates that the investment costs of an electrolyser in 2030 will decrease to less than 1 MDKK/MW, while IEA (the International Energy Agency) estimates an investment cost of around 2.7 MDKK/MW [Energinet and Danish Energy, n.d.]. The uncertainty of the investment costs in the future is substantial, and it is primarily dependant on economies of scale and thereby the momentum of the roll-out of large scale electrolysers.

For PtX to become price-competitive, an upscale in production is needed, which only happens when there is a market and consumers. However, most potential consumers do not invest in PtX driven technologies yet because of the high prices and its incompetitiveness to fossil fuels. This creates a situation where the development is stuck, and the discussion lies in what should be pushed first, referred to as the "PtX paradox". [Danish Energy, 2020]

7.2.1 The development of the price-competitiveness of the PtX

The price of the costs of PtX is developing. Norwegian hydrogen producer Nel has planned to cut the costs of producing green hydrogen. They plan to build a 2 GW electrolyser facility in Norway, starting with a 500 MW plant. Jon André Løkke, chief executive at Nel, states that with the installation of the 500 MW electrolyser facility, the costs of producing green hydrogen will be reduced by 50%; and subsequently, when the plant is scaled to 2 GW, it will again be reduced by 50%; resulting in a total reduction of 75%. Collins [2021] estimates that the price for green hydrogen in 2025 will be \$1.5/kg, based on a Nel electrolyser facility of 2 GW. This price is estimated, by Collins [2021], to be obtainable with an average electricity price of \$20/MWh. [Collins, 2021]

It is worth noticing that the electricity price is by far the most crucial price component when producing green hydrogen, as it accounts for between 70-80% of the total price when calculating the Levelized costs of energy (LCOE). [Collins, 2021] Therefore, it is essential to obtain low electricity prices for the production of green hydrogen to secure a competitive price. However, \$20/MWh might be optimistic. Lazard [2020] estimates the LCOE for wind energy to be between \$26-54/MWh and the LCOE for PV to be \$29-42/MWh in 2020, and it is, therefore, essential that the costs related to wind and solar drop significantly before 2025, to make it realistic to produce green hydrogen at \$1.5/kg. If it is possible to produce green hydrogen at this price by 2025, it has the potential to outplay both blue, grey and black hydrogen and become the cheapest type of hydrogen if it is assumed that these will not decrease in price. In Table 7.2, the estimated price of different types of hydrogen production in 2025 is shown.

Source	Price [DKK/kg]	Data source
Green hydrogen in DK	19	Energinet and Danish Energy [n.d.]
Import from North Africa	19	Energinet and Danish Energy [n.d.]
Blue hydrogen	14.8	Energinet and Danish Energy [n.d.]
Black hydrogen	11	Energinet and Danish Energy [n.d.]
Green hydrogen by Nel	9.2	Collins [2021]

Table 7.2. Overview of the cost of different types of hydrogen produced in 2025. The import from North Africa is green or yellow hydrogen, because it most likely will be produced from solar PV. Blue- and black hydrogen are based on international averages and are not as dependant on location as green hydrogen. $1 = 6.16 DKK

The prices in Table 7.2 are used in the analysis with cautiousness since different data sources are used, and the prices are applicable for different countries. It is, however, contributing to the understanding of the economic outlook of hydrogen production in 2025. Energinet and Danish Energy [n.d.] expect the price of green hydrogen to drop even more by 2030 and ultimately by 2035. The green hydrogen production in Denmark in 2030 is estimated to 13.5 DKK/kg and ultimately 12 DKK/kg in 2035, which will place the price between blue hydrogen and black hydrogen as visible in Table 7.2. It should be noted that Energinet and Danish Energy [n.d.] do not estimate a price development within the blue and black hydrogen production.

When estimating the price of hydrogen per weight unit, it should be noted that hydrogen is an excellent energy carrier since 1 kg hydrogen contains 33.33 kWh of energy, relative to diesel and petrol, which contains approx. 12 kWh/kg. [Ideahy, n.d.] Solid biomass (wood) is evaluated to contain around 5.3 kWh/kg, meaning that hydrogen contains 6.3 times as much energy per kilogram as solid biomass. [Clarke and Preto, 2019] Biomass in Europe is, however, cheaper than hydrogen and has a cost of 1.02 DKK/kg, according to IRENA [2012].

When relating the cost per weight unit to the energy density, it is necessary to spend around 6.5 DKK to buy the biomass to equalise the consumption of energy by using 1 kg green hydrogen. This means that even though the price of green energy drops to 9.2 DKK/kg in 2025, which it eventually will according to Collins [2021], biomass is still set to be the cheaper fuel since only 6.5 DKK has to be spent in order to gain the same amount of energy. A comparison of the costs, energy density and energy per cost of green hydrogen produced by Nel and European industrial wood pellets is presented in Table 7.3. The efficiencies when combusting/utilising the fuels are not considered for either biomass or green hydrogen, which in reality is an essential factor when calculating the energy output. However, this calculation is quite extensive and complex since many factors should be considered, and it is therefore left out of the scope.

	Cost [DKK/kg]	Energy density [kWh/kg]	Energy per cost [kWh/DKK]
Green hydrogen (from Nel)	9.2	33.33	0.27
Solid biomass (wood)	1.02	5.3	0.19

Table 7.3. Comparison of the costs, energy density and energy per cost of green hydrogen produced by Nel and European industrial wood pellets.

Table 7.3 shows that biomass has a lower cost per energy density and is, therefore, cheaper to utilise than green hydrogen. There are, however, various error sources when making this assumption. This could, for instance, be that the biomass price is not considered for 2025 but for current prices, which is applicable for the green hydrogen price. Furthermore, the price of 9.2 DKK/kg green hydrogen is questionable, as mentioned earlier, as well as the biomass price could be questionable since it depends on the origin, and the applied data is based on a source using the European biomass price. Denmark is, as mentioned earlier, importing large shares of the solid biomass from Russia and the USA, which potentially can affect the prices. Therefore, the result of this analysis is not that solid biomass is cheaper than green hydrogen but that the two resources could potentially be competing in the future, especially if subsidies regarding either of the resources get added or removed. Table 7.3 should therefore not be understood as an end result of the prices of either hydrogen or biomass but as an illustration of the price difference being lower when the energy density is taken into consideration.

With an assumption that green hydrogen has the potential of competing economically with biomass in the future, depending on the applied subsidies, taxes etc., it is interesting to investigate how the GHH project fits into the Danish national energy system and how it can contribute to minimising the use of bioenergy. However, to investigate this, it is necessary to understand the GHH project, which is described in the following section.

7.2.2 Analysis of Green Hydrogen Hub (GHH)

The Green Hydrogen Hub (GHH) project consists of three production components; electrolyser, air compressor, and gas turbine. Additionally, two storage units are included in the project; a hydrogen storage and a compressed air energy storage (CAES). In general, it is expected that the electrolyser will produce hydrogen when the electricity prices are low, which occurs when the RES dominates the production and when there is excess production. The green hydrogen can then potentially be utilised directly for electricity production through the CAES turbine or other purposes such as transportation, or it can be stored in the hydrogen storage. Likewise, it is expected that the air compressor will be utilised to fill the CAES when the electricity prices are low. When the electricity prices are high, the GHH has the potential to produce electricity for the grid through the utilisation of the potential energy in the CAES. [Hethey et al., 2020]

As visible in Table 7.4, the electrolysers has a total installed capacity of 150 MW.
The hydrogen is compressed and stored in an ample underground hydrogen cavern storage in a salt cavern. The storage capacity of the hydrogen storage is 200 GWh, which potentially can store hydrogen from 1,300 hours of production, which makes seasonal storage possible.

The air compressors have a total installed capacity of 160 MW.
Compressed air is stored in an underground chamber. The storage capacity of the CAES storage is 3.2 GWh, which potentially can store 20 hours of compressed air at full capacity. During electricity production, hydrogen and compressed air are released from their respective storage and drive a gas turbine, with a maximum generation capacity of 300 MW. [Hethey et al., 2020]

The different capacities of the units in the GHH are shown in Table 7.4.

Technology	Capacity
Electrolyser	150 MW
Hydrogen storage	200 GWh
Air compressor	160 MW
Air storage	3.2 GWh
Gas turbine (CAES process)	300 MW

Table 7.4. Capacities of the different components of the GHH, data from Hethey et al. [2020]

An overview of the electricity flows of the GHH project is shown in Figure 7.1, including the installed capacities of the different components.

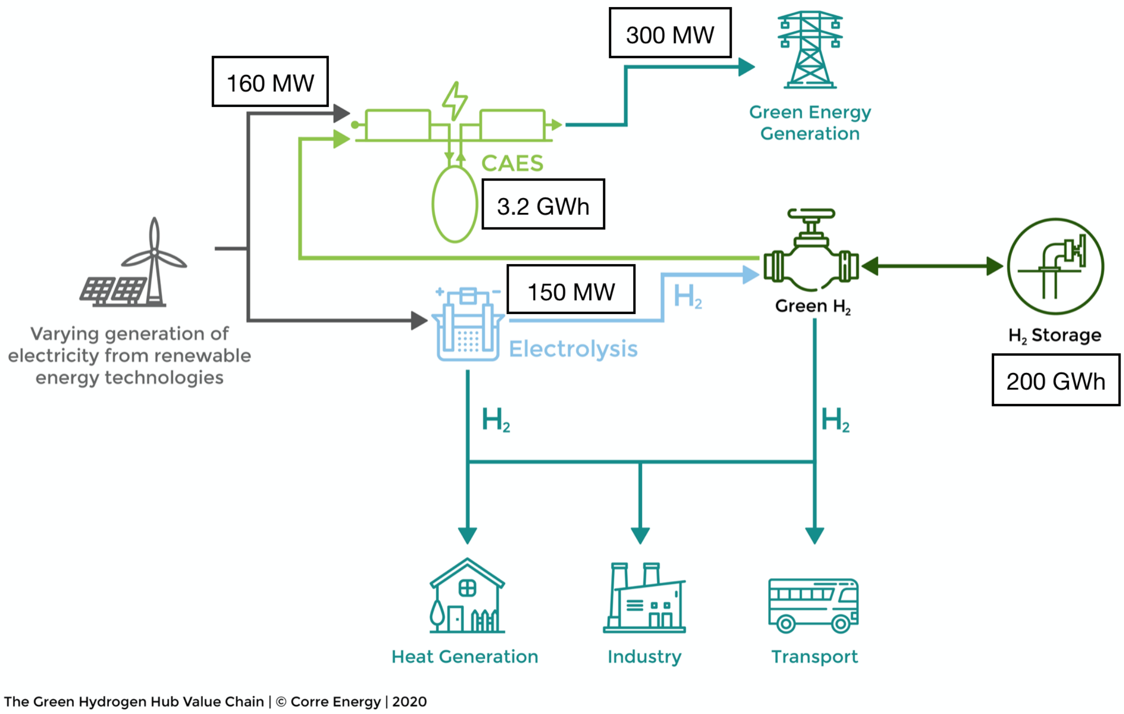

Figure 7.1. Illustration of the energy flows of the Green Hydrogen Hub system and the installed capacities. Data and model are obtained from Hethey et al. [2020]

As visible in Figure 7.1, the GHH system consists of interconnected individual components. It is estimated that the three production components in the GHH: the CAES turbine, air compressor and electrolyser, will be activated at different times and different electricity prices in the market. Hethey et al. [2020] estimates that the electrolyser will have the largest amount of full-load-hours (FLH), with 2,961 FLH in 2025; almost three times the amount of the FLH for the air compressor, with 1,082.

The GHH system will contribute to the flexibility of the electricity system by filling the hydrogen- and compressed air storage for at least 2,961 FLH in a year (since it is assumed that the air compressor will be running simultaneously with the electrolyser). However, it is expected that the turbine will contribute with electricity production in 1,323 FLH in 2025. It is expected that the largest production from the GHH will happen in 2030, and then the production will decrease towards 2040. This decrease can be due to the expected increase of DSM features (especially because of the roll-out of smart-charging and EVs) in the future since more capacity will be able to act flexibly. A bar chart to visualise the development estimated by Hethey et al. [2020] is shown in Figure 7.2.

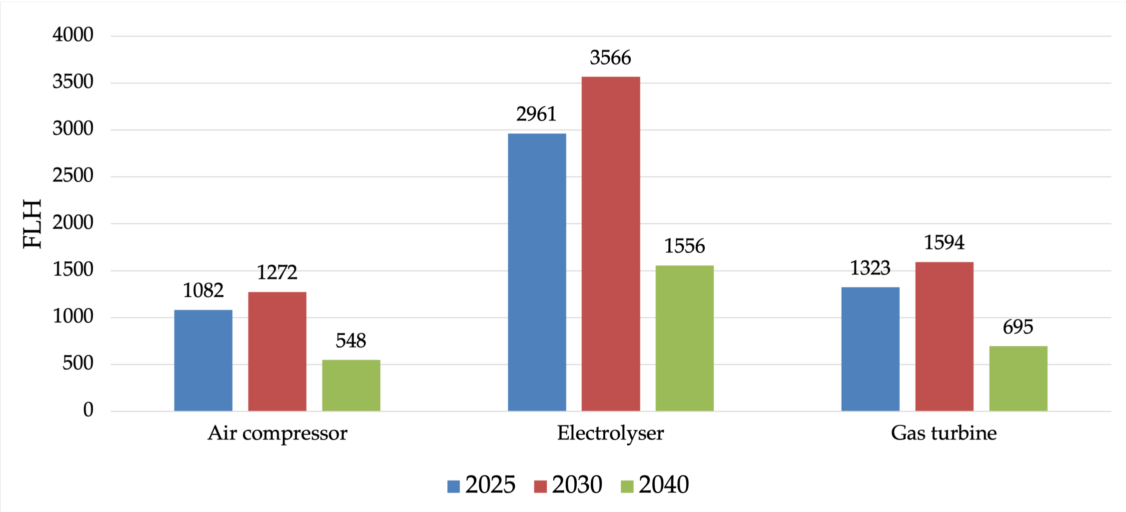

Figure 7.2. Illustration of the FLH for the GHH production components according to Hethey et al. [2020]

As visible in Figure 7.2, the different technical components is expected to have different amounts of FLH. The electrolyser and air compressor use electricity from the grid, while the turbine delivers electricity to the grid. It is in these processes interesting at what costs the different technical components are operating. It is estimated that the average cut-in price for the electrolyser in 2025 is 17 €/MWh, while the cut-in price for the air compressor is estimated to 26 €/MWh. When the hydrogen and compressed air have been stored, and the electricity price rise, an opportunity for producing electricity through the turbine is created. It is expected that the average cut-in price the gas turbine will operate under in 2025 is 81 €/MWh. A bar chart of the estimated average cut-in prices from Hethey et al. [2020] is presented in Figure 7.3.

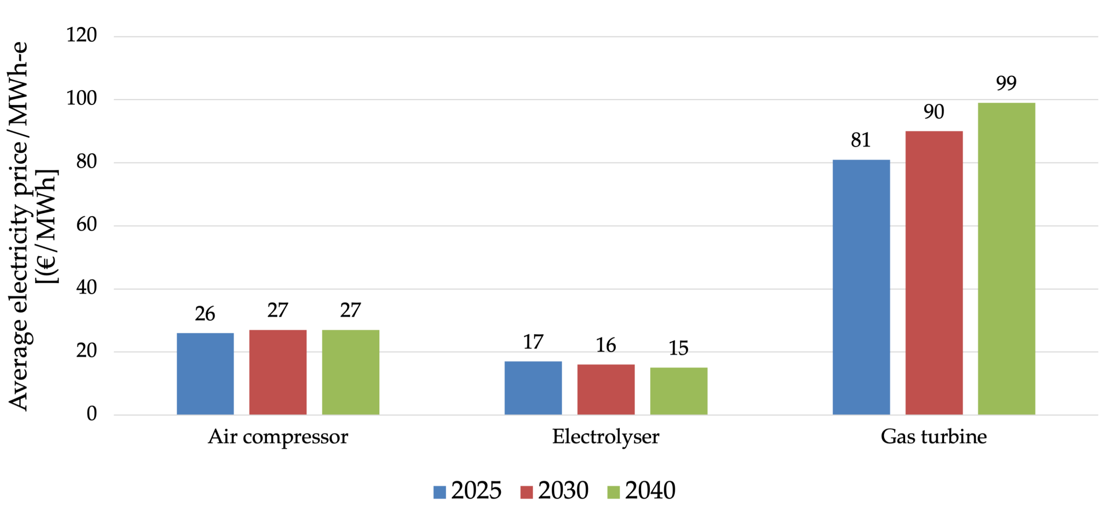

Figure 7.3. Illustration of the average electricity prices that the different production components will operate under, with numbers from 2025, 2030 and 2040, according to Hethey et al. [2020]

Hethey et al. [2020] has additionally calculated an estimation of the annual revenue from the GHH project, which span from 15-25 M€/year. This revenue made from electricity purchase and sales depends on the electricity price, which fluctuates, as mentioned in Chapter 2. The GHH aims to harvest the most lucrative electricity prices for their production. The pump has the greatest potential for creating revenue when harvesting low electricity prices. The lowest prices happens in the summer period, according to Figure 2.4 on page 9. The opposite accounts for the gas turbine, which has the largest potential of creating revenue when the electricity prices are higher, which according to Figure 2.4 often happens in the winter. However, this seasonal variation in the price distribution is not seen in the spot market price distribution used in the energy system analysis in this thesis.

In order to illustrate the proportion of hours where the price of electricity is respectively low and high on a yearly basis, a duration curve of the hourly electricity prices is made. The duration curve is illustrated in Figure 7.4 made upon data gathered from Energinet [n.d.].

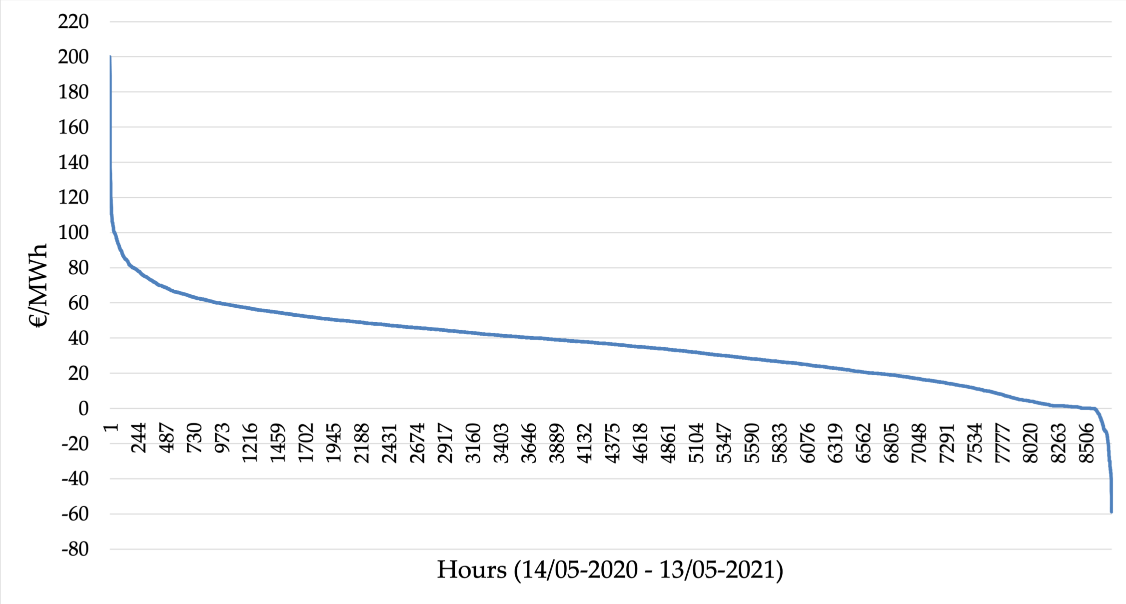

Figure 7.4. Duration curve of the hourly electricity price in DK1 from 01/01-2020 to 31/12-2020. Data from Energinet [n.d.]

GHH has the potential to contribute to the flexibility of the Danish electricity system since the electrolyser, and CAES pump potentially harvests low electricity prices when there is a large production from RES. When the RES are not operating, the turbine has the potential to contribute with renewable electricity to the grid. Therefore, using the GHH system, it is possible to utilise renewable electricity in a dispatchable way by using green hydrogen as an energy carrier that can be used to produce renewable electricity when the fluctuating RES are not meeting demand. [Hethey et al., 2020] This dispatchable RES, green hydrogen, can potentially substitute and minimise the biomass consumption, which, as stated, is playing an essential role as a dispatchable energy resource in the future electricity system. There are many reasons for minimising the biomass consumption and dependency as investigated in Section 2.3.1, and using a system like GHH creates a potential for replacing biomass with green hydrogen as a dispatchable electricity resource.

According to Hethey et al. [2020] the GHH system will be operating at 4,284 FLH in 2025, which equals 49% of the whole year. The high amount of FLH is substantial for the business case of the GHH since more hours of operation (during hours with feasible electricity prices) creates more revenue. [Hethey et al., 2020] The GHH can furthermore contribute to curve out fluctuations in the electricity prices by producing electricity when the prices are high and consuming when the prices are low because it helps balance supply and demand. Furthermore, the operation of GHH means that excess electricity sold cheaply to external energy systems will be reduced since GHH potentially can utilise electricity when the electricity price is lucratively low. This, in general means, that the GHH system has the potential to make the Danish electricity system more flexible. Furthermore, as mentioned previously, it has the potential to compete economically with biomass as a dispatchable electricity resource in a Danish context in the future, especially if subsidies are added or changed in favour of green hydrogen. As mentioned, it should be noted that the Danish government will publish a strategic plan for the development of PtX in Denmark by the end of 2021, which potentially involves subsidies in favour of green hydrogen and electrolysis. The coming subsidies and regulations in the future are, however, difficult to predict and will therefore not be considered in depth in this thesis, even though it is a very important factor when estimating the potential for PtX technologies in a Danish context.

7.3 Energy System Analysis of the GHH

In order to model the GHH system, data from the *IDA 2050 scenario* is gathered on an hourly basis and inserted into the Excel tool, as described in the method. This makes it possible to investigate how the GHH system works under the applied assumptions. A description of how the assumptions are implemented in the Excel model is presented in the method in Section 6.3. The assumptions used for the Excel modelling of the GHH system is shown in Table 7.5.

Input values for the modelling of GHH	
Turbine cut-in price	46.72 €/MWh
Pump cut-in price	42.38 €/MWh
Turbine capacity	300 MW
Pump capacity	310 MW
Storage capacity	203.2 GWh
Storage content (beginning of the year)	100 GWh
Roundtrip efficiency of the GHH system	72%
Excess heat for district heating	10%

Table 7.5. The data that the energy system model of the GHH system is based on. Note that the cut-in prices are calculated based on creating the largest revenue.

When the listed assumptions and the distribution profile for the hourly spot market prices from the *IDA 2050 scenario* is used as the basis for creating an hourly Excel model of the GHH system, it is visible from the results how the storage develops during the year. In figure 7.5 it is visible how the yearly simulation begins with 100 GWh of energy stored, which eventually decrease when the spot market price is high, and vice versa when it is low, caused by the cut-in prices for the turbine and the pump.

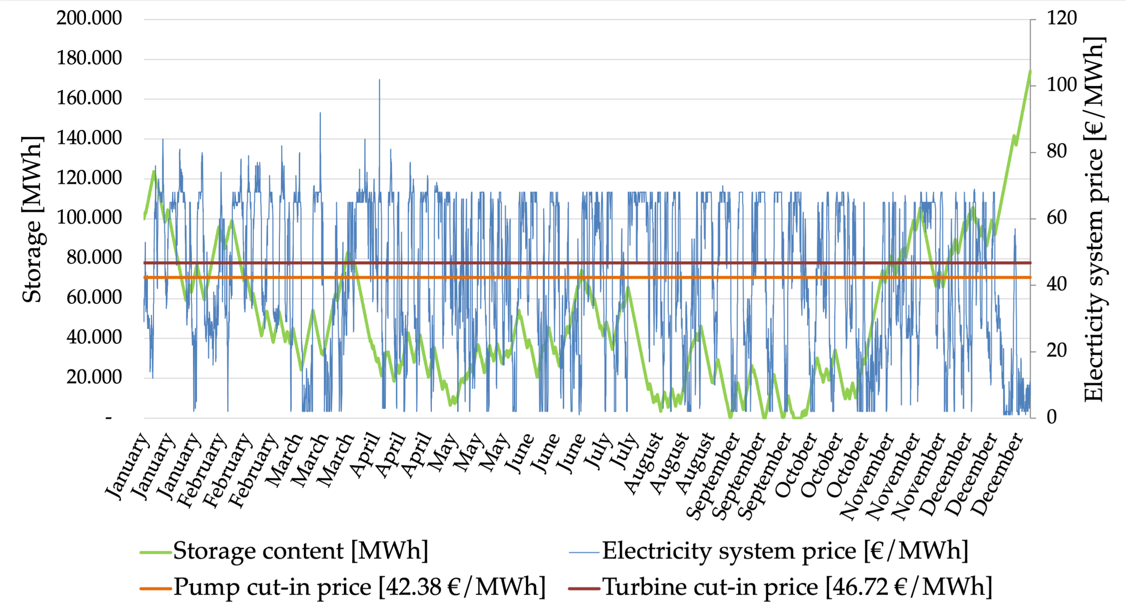

Figure 7.5. The annual operation of the storage in the simulation compared to the fluctuations in spot market prices and cut-in prices of the GHH system's pump and turbine.

It is furthermore visible from figure 7.5 how the storage content ends at 174 GWh, which potentially will be the start storage capacity of the next simulated year. It is visible that the storage gets charged quickly in December, caused by the low spot market prices. The cut-in prices are, as mentioned in Section 6.3, calculated through an Excel add-in tool called "Solver", which optimises the two variables (the cut-in prices) in order to get the highest yearly revenue. The cut-in prices used are therefore based on securing the highest yearly revenue.

An illustration of the revenue stream from the GHH investment is shown in Figure 7.6.

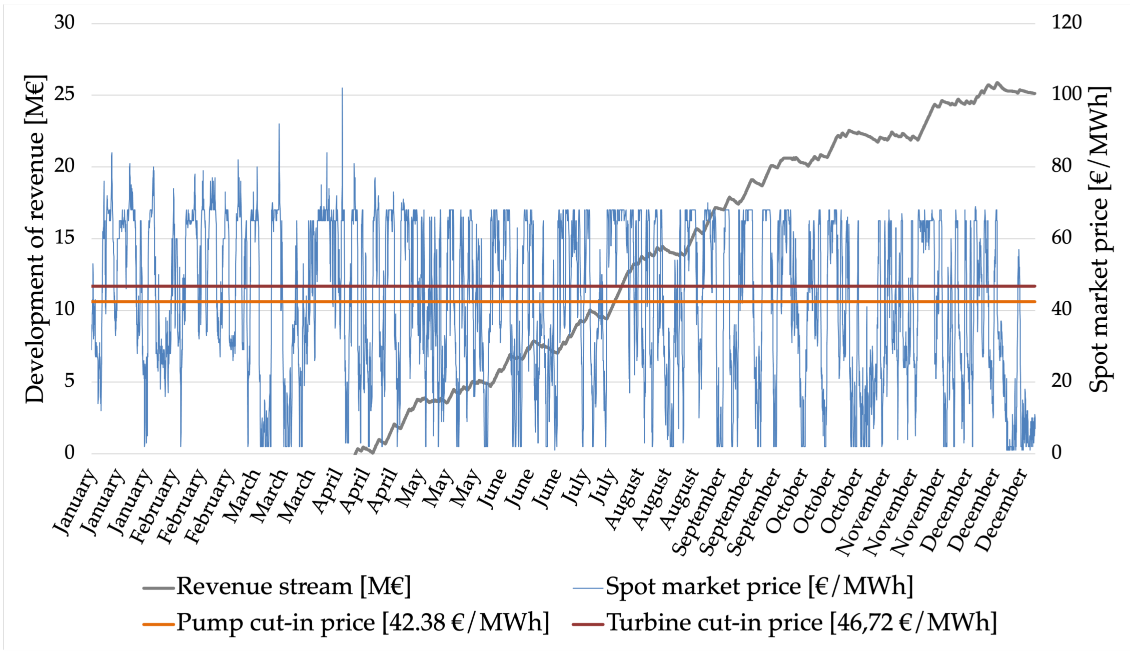

Figure 7.6. The annual development of revenue in the simulation compared to the fluctuations in spot market prices and cut-in prices of the GHH system's pump and turbine.

The hourly revenue seen in Figure 7.6 results in a yearly revenue of 25.1 M€. The grey graph shows the revenue stream in million Euros [M€]. This figure shows how the GHH successfully harvests the low spot market prices to store energy in the storage and harvests the high spot market prices to produce electricity again. Even though the storage content ends with 174 GWh, which is 74 GWh higher than the start storage content, a high revenue is made. The revenue calculation takes the investment costs, fixed costs, variable costs and technical lifetime of the components into consideration. The yearly costs related to the operation and investment of the GHH system results in a yearly cost of 15.36 M€, which result in the revenue starting the year as a negative value in the figure. The revenue stream shows that whenever the spot market price is above 46.72 €/MWh, the system creates revenue, and since the spot market prices often reach 70 €/MWh, the creation of a high revenue is possible, and the revenue stream increases fast. On the other hand, when the spot market price is below 42.38 €/MWh, a cost is related, but since GHH often harvests spot market prices below 10 €/MWh, the revenue stream decreases only slightly. The high revenue is predominantly made from the large fluctuations in spot market prices, since the average electricity price the turbine is operating under is 62.9 €/MWh, while the average electricity price the pump is operating under is 22.5 €/MWh. The average operation prices for the pump (consisting of the air compressor and the electrolyser) are pretty similar to the prices estimated by Hethey et al. [2020], while the estimated average electricity prices for the turbine is higher, as visible in Figure 7.3. The amount of FLH hours is, however, not similar to the ones estimated by Hethey et al. [2020], who estimate a total annual operation of all components at 4,284 FLH in 2025, while this simulation has 8,370 FLH. The remaining hours of the year have either spot market prices between the two cut-in prices, or the storage is either empty or full, with the latter one not being applicable for this yearly simulation. These calculations are visible in Appendix A.

It is in this analysis furthermore calculated that the pump will produce 10% excess heat, which potentially could be utilised in the DH grid. The 10% excess heat is found in the electrolysis process, where it is expected that 20% excess heat is possible to utilise. The electrolyser accounts for almost half the capacity of the pump, which is why only 10% excess heat is expected from the pump. This excess heat production follows the distribution profile of the pump (because it is produced in the electrolysis) and is therefore producing excess heat all year; it does therefore follow the DH demand profile well.

With the knowledge regarding the modelling of the GHH system, it is interesting to investigate how it potentially can contribute to minimising bioenergy consumption. The following subsection is therefore investigating how the GHH system potentially can minimise the bioenergy consumption found in the *IDA 2050 scenario*.

7.3.1 GHH contribution to minimising the use of bioenergy

To answer the research question, the potential for P2H2P from the GHH system has to be put into the context of reducing bioenergy use. According to the previous research of the potential for sustainable bioenergy in Section 7.1, the bioenergy use should be minimised because of the uncertainty of the actual and future potential as well as being associated with different negative externalities as mentioned in Section 2.3.1 and 7.1.

When analysing the potential for minimising the bioenergy use by utilising P2H2P processes, it is essential to note that the GHH system is only one production site, and it is not inconceivable that several of these sites can be constructed in Denmark in the future, if desired. Additionally, it is estimated by Green Hydrogen Hub [n.d.] that the electrolyser capacity will be expanded to 1 GW towards 2030, while the hydrogen storage will have a total installed storage capacity of 400 GWh. The analysis of the GHH system, in this thesis, is investigating the currently planned capacities and the planned 1 GW electrolyser and 400 GWh hydrogen storage capacity is therefore not investigated. The main reason for this approach is the research design of this thesis. It aims to investigate how the GHH system can develop as a niche development and take advantage of a window of opportunity to substitute and minimise bioenergy as a dispatchable electricity-producing resource in the existing regime. Therefore, this should be understood as an initial analysis investigating the potential for substituting bioenergy in the electricity sector with P2H2P.

According to the analysis, the GHH system can contribute with 1.04 TWh of electricity annually, which equals approx. 13.9% of the electricity produced from bioenergy based power plants (PP) and combined heat and power plants (CHP) in the *IDA 2050 scenario*. This means that the GHH system alone can reduce bioenergy use by 1.04 TWh through the electricity created. If the capacity of the GHH system in the future increases, this reduction can potentially be higher. To utilise the GHH system for electricity production instead of the PP and CHP, there must be content in the storage when the power is needed. Therefore, it would be interesting for further analysis to look into how the GHH system's storage content and electricity production fits the bioenergy use in the CHP and PP on an hourly basis.

Besides potentially substituting bioenergy for electricity production, the GHH can contribute to the purchase of electricity to fill the CAES and hydrogen storage. It is with the known assumptions estimated that the GHH system can utilise 1.12 TWh of electricity annually. It should be noted that the GHH takes advantage of low spot market prices, which often occurs when there is a large share of RE in the grid. Denmark has in the previous years sold this electricity for low prices to connected countries, as shown in Figure 2.3, or has been forced to stop wind turbines from producing, which the GHH system potentially can take advantage of and contribute to avoiding [Wittrup, 2019]. The GHH can also contribute to the DH grid in Denmark with 0.11 TWh of heat annually, representing 0.3% of the total Danish DH demand. According to Figure 7.5, the storage is filled the most in November/December where the pump is producing; the pump is what the excess heat potential of 10% is calculated from, which means that the highest amount of excess heat produced from the system is in November/December. In general, these months are known as months that have a high heating demand compared to most other months. This creates an opportunity to utilise the excess heat from the electrolyser in these months.

When making such an analysis, it is interesting to investigate how sensitive the outcome is to changes in the data. This sheds light on how important the accuracy of the data is for the validity of the model. The following sub-section is therefore introducing different kinds of sensitivity analyses.

7.3.2 Sensitivity Analysis of the energy system analysis

The purpose of the sensitivity analysis is to investigate how sensitive the simulation of the model is to alterations in different parameters. The parameters chosen to do the sensitivity analysis upon are the spot market price of electricity, the cut-in price for the pump and turbine in the GHH system and storage start content. The reason for choosing these parameters is that these parameters are very defining for the analysis, and they are pretty likely to change in reality.

It is chosen to look into the sensitivity based on the yearly operation of the system and the revenue streams.

In figure 7.7, it is shown that an alteration of +/- 10% of the spot market prices affects the yearly operation of the storage. The storage will charge substantially more in the scenario with low spot market prices. It is visible that the difference between the operation of the storage in the original scenario and the scenario with high spot market prices are more similar. Furthermore, the low spot market price scenario is the only scenario where the storage is filled to the maximum capacity of 200 GWh at some point.

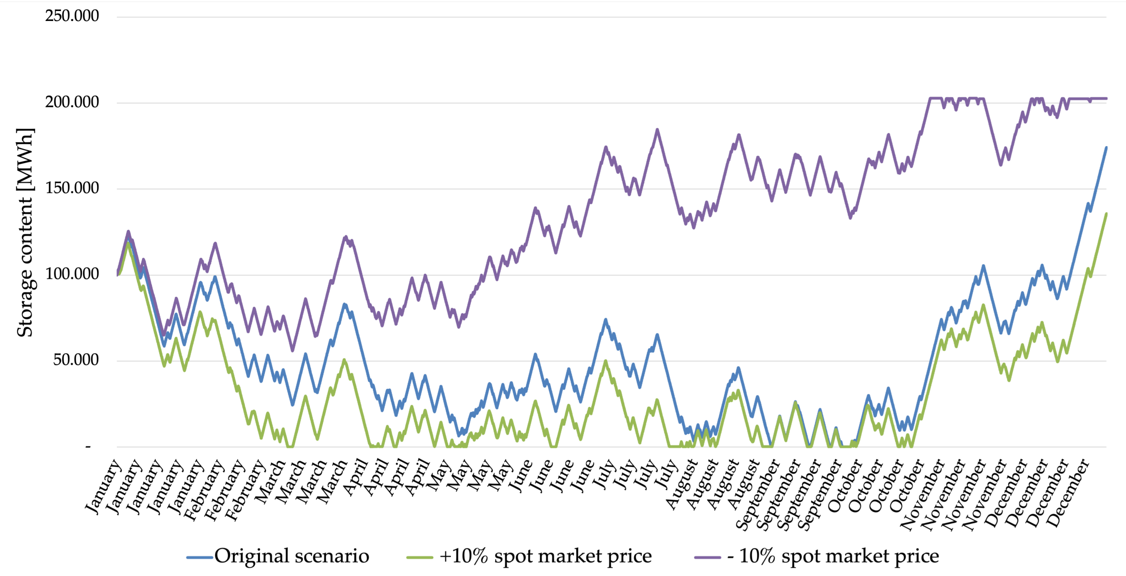

Figure 7.7. The sensitivity of the operation of the storage in the GHH system when altering the spot market prices of electricity.

In figure 7.8, the development of revenue for the three scenarios, the original, +10% spot market price and -10% spot market price, is shown. It is visible that the high spot market price scenario and the original scenario creates the highest revenues of the three, even though the low spot market price scenario utilise the storage capacity the most, according to figure 7.7. The total annual revenue from the three scenarios is 25.1 M€ for the original scenario, 27.8 M€ for the high spot market prices and 15.8 M€ for the low spot market prices. This can be caused by the fact that the model only simulates one year, and therefore the low spot market price scenario, which fills the storage towards the end of the year, does not get to profit from the energy stored, which in reality would not be accurate.

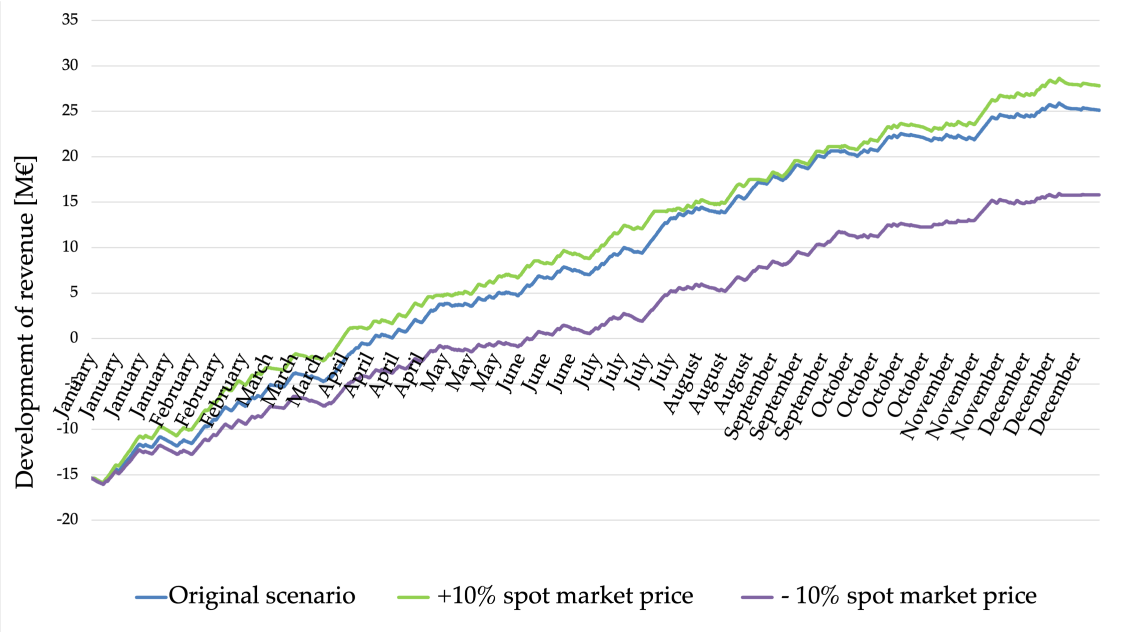

Figure 7.8. The sensitivity of the development of revenue from the GHH system when altering the spot market prices of electricity.

The sensitivity analysis also analyses the operation of the storage for the three scenarios, the original scenario, the scenario with +2€ cut-in price, and -2€ cut-in price. The calculated cut-in prices are listed in Table 7.6 below.

Original scenario	
Turbine cut-in price	46.72 €/MWh
Pump cut-in price	42.38 €/MWh
+2 € cut-in price	
Turbine cut-in price	48.72 €/MWh
Pump cut-in price	44.38 €/MWh
-2 € cut-in price	
Turbine cut-in price	44.72 €/MWh
Pump cut-in price	40.38 €/MWh

Table 7.6. The cut-in prices for the GHH system's pump and turbine in thr three scenarios, original, +2 €/MWh and -2 €/MWh.

It is visible in figure 7.9 that the storage fills the most in the scenario with the high cut-in prices and that the operation of the storage for the original cut-in prices and the low cut-in prices is quite similar. The scenario with high cut-in prices is the only scenario where the storage is filled to the maximum capacity.

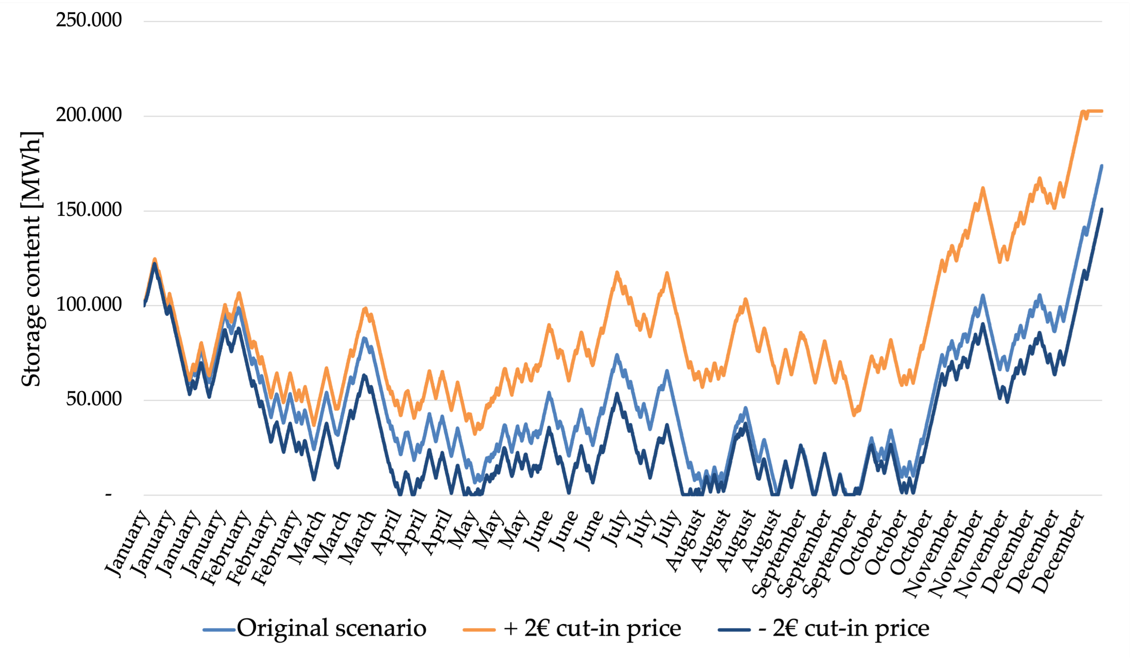

Figure 7.9. The sensitivity of the operation of the storage in the GHH system when altering the cut-in prices for the pump and turbine.

Figure 7.10 illustrates how sensitive the revenue stream is to changes in the cut-in prices. The revenue stream is not remarkably sensitive to the changes in cut-in prices tested in this analysis—the scenario with high cut-in prices does have a marginally lower total annual revenue. The total annual revenue from the three scenarios is 25.1 M€ for the original scenario, 22.8 M€ for the +2€ cut-in price, and 24.8 M€ for the -2€ cut-in price. These results verify that the optimal cut-in prices are found in the Excel modelling since any changes in the prices result in lower yearly revenue.

Similar to the previous Figures 7.7 and 7.8, the fact that the storage of the scenario with high cut-in prices is more filled by the end of the year can be contributing to the fact that it has a lower revenue.

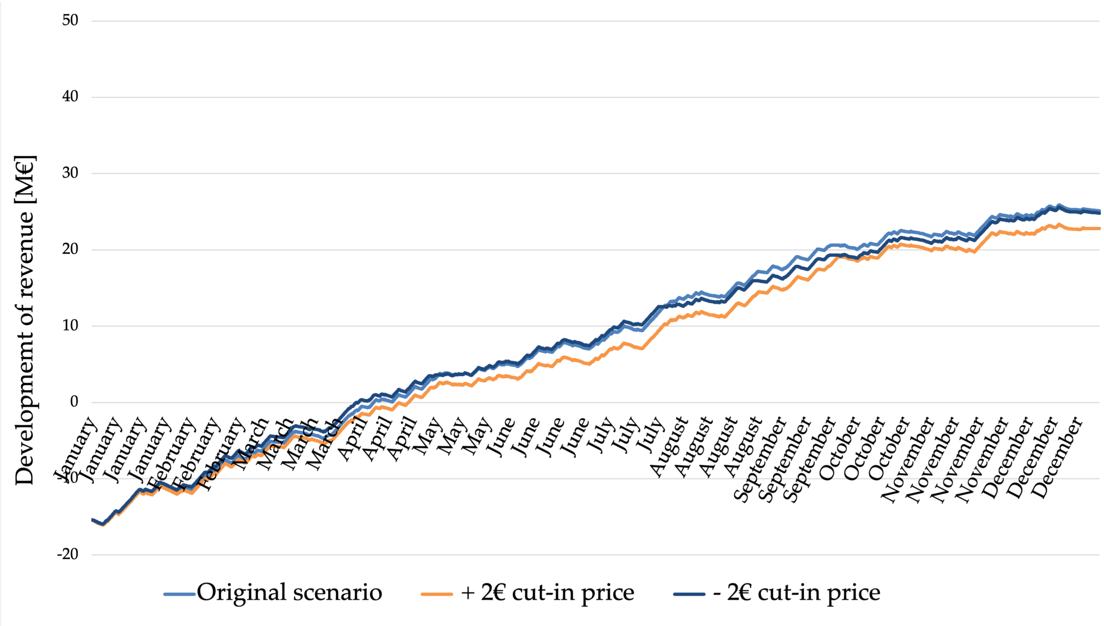

Figure 7.10. The sensitivity of the development of revenue from the GHH system when altering the cut-in prices for the pump and turbine.

In figure 7.11 the operation of the original scenario, with a storage start content of 100 GWh, is shown alongside scenarios where the storage content starts the year with respectively 0 GWh and 200 GWh. This shows that the original scenario and the scenario with a start content of 0 GWh operates uniformly at the end of the year and ultimately ends with the same storage content. They do never fill the storage fully. In the scenario where the storage content is 200 GWh at the beginning of the year, the storage does never empty, neither does it fill besides in the beginning and end of the year. In order to make the sensitivity relying on the same assumptions, the solver tool in Excel should be reused to optimise the cut-in prices that create the most significant revenue for the different start storage contents, which is not done.

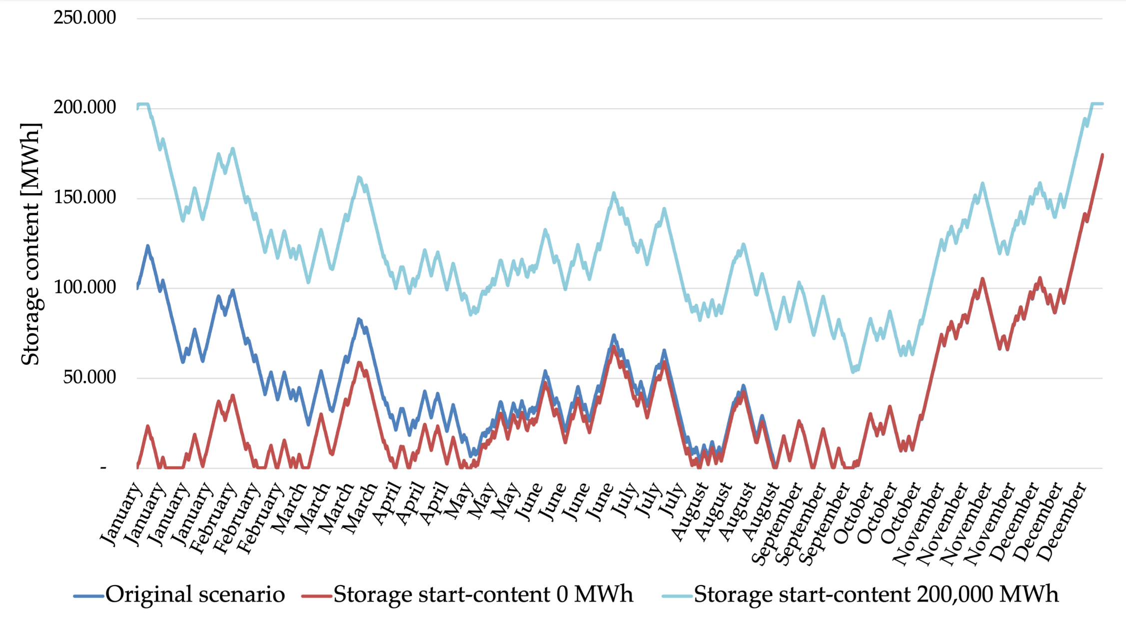

Figure 7.11. The sensitivity of the operation of the storage in the GHH system when altering the storage content in the beginning of the simulation.

Looking into the revenue of the three scenarios, the original, the 0 GWh storage content, and the 200 GWh storage content on figure 7.12, it is worth noting that the three scenarios begin from different starting points concerning making revenue. The high storage content will naturally be able to earn more without paying for the energy used by the pump because there is already energy in the storage from the beginning. The scenario with 0 GWh in the storage results in the lowest revenue with a total annual revenue of 18.5 M€. Interestingly, the original scenario with 100 GWh stored at the beginning of the year almost makes the same revenue as the scenario with 200 GWh stored. The annual revenue from the original scenario is 25.1 M€, while the scenario with 200 GWh stored is 27.5 M€. Like in the other analyses, it shall be noted that the scenario with a start content of 200 GWh ends the year with more energy stored, which in reality would affect the revenue in the coming year.

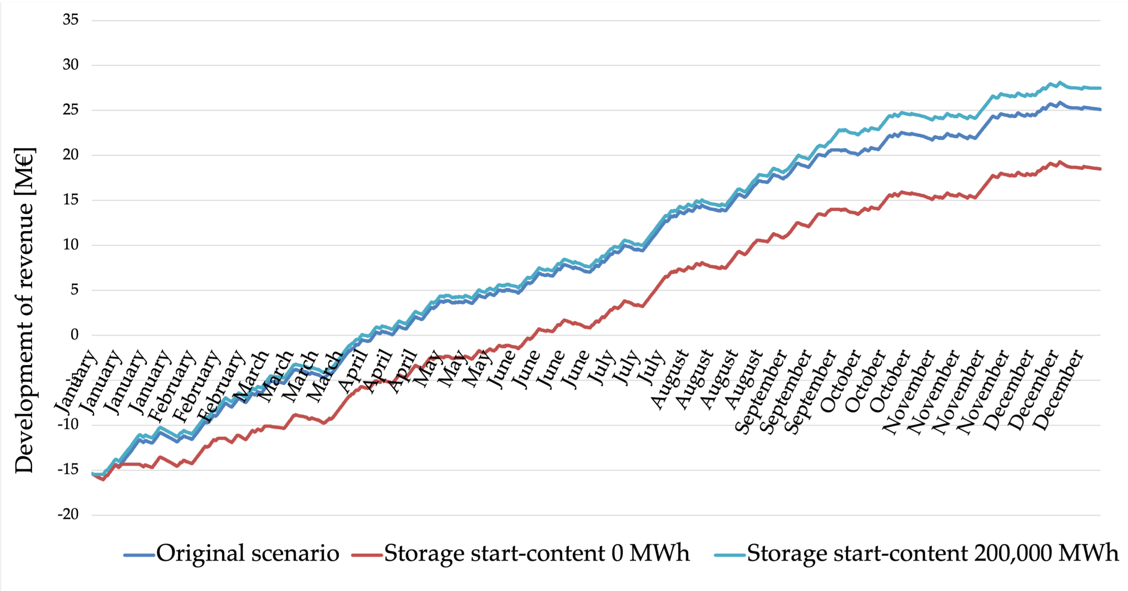

Figure 7.12. The sensitivity of the development of revenue from the GHH system when altering the storage content in the beginning of the simulation.

The sensitivity analysis found that changes in the assumptions do change the outcome, which means that the GHH model is sensitive to changes in the assumptions. This emphasises that it is relevant to gather accurate data to simulate the system properly. However, the changes in the storage content, revenue streams etc., are not too significant, and it is evaluated that, when being aware of the error sources, the simulation gives a proper framing of the operation of GHH even though it is based on assumptions.

8 Discussion

The analysis creates the basis for discussion on several aspects. The analysis is split into three overall sections; the first analysing the potential for sustainable bioenergy use, the second analysing window of opportunity for PtX development, and the last analysing the GHH system in the context of minimising the bioenergy use in the electricity system of Denmark. The different parts of the analysis are associated with different exciting discussions. Furthermore, as the theoretical approach plays a vital role in this thesis, it is interesting to discuss potential outcomes if alternative theoretical approaches were applied.

8.1 Should the use of bioenergy be minimised?

Denmark's bioenergy potential is investigated by analysing different existing literature through the use of the literature study method. It is acknowledged that there are considerable differences in the estimations of the bioenergy potential among the different researchers. The analysis found evidence for the bioenergy potential in the future being very uncertain. The uncertainty of the future potential is what is acclaimed in this analysis, and it is what leads to the logic of minimising the use and thus the dependency on bioenergy. The interesting part of discussing this is that some of the predictions assess a bioenergy potential higher than the used bioenergy in the *IDA 2050 scenario*. One might argue that if the analysis were solely based on one or a few of these sources for assessing the sustainability of the use of bioenergy in the *IDA 2050 scenario*, the bioenergy use would not be analysed as being problematic because it would not exceed the potential. The fact that this analysis focus on the uncertainty of the predictions and the additional negative externalities that the bioenergy use is associated with dictate the path and the way that this topic is analysed further - by seeking to minimise the bioenergy use and thus the dependency. Additionally, when estimating the potential sustainable bioenergy consumption in Denmark for 2050, a global perspective is applied.

The choice of analysing a specific system, the GHH system, based on the collaboration and the accessibility of data, does naturally rule out a deeper investigation of alternative technological solutions: this might engender speculations about if the GHH solution is the most suitable solution for minimising the bioenergy use in the electricity system of Denmark, which is difficult to conclude by using the findings of this thesis. The analysis does not create a foundation for concluding if the GHH system is the most optimal solution for overcoming the challenge of dependency on bioenergy but merely clarify if the GHH system can be used to minimise bioenergy use.

8.2 The Energy System Analysis based on the *IDA 2050 scenario*

The energy system analysis is as mentioned based on the *IDA 2050 scenario* which is a limitation of the analysis because it does only investigate the GHH system based on the spot market prices associated with this scenario, and other electricity prices would likely lead to other results. Additionally, the minimisation of the bioenergy used in the system only withhold the strategy that the *IDA 2050 scenario* is based on. When comparing the *IDA 2050 scenario* with other scenarios, it appears that the *IDA 2050 scenario* has a strategy that involves sustaining considerable amounts of CHP and PP in the transition to a climate-neutral energy system in 2050. One natural limitation of only analysing one model with input variables from one year is that it only creates results valid for the simulated year. It can not be guaranteed that the electricity prices, weather conditions, demands etc., will be the same for other years, and therefore the operation and results of the system can vary for different years. Because of this limitation, a sensitivity analysis is created for some of the input variables. However, it could be relevant to do further analysis with different input variables considering, for example, electricity prices; this is, however, not done in this thesis since it is not the electricity distribution profile that is used for the modelling of the GHH, but the spot price. If the spot price for other electricity distribution profiles were to be analysed the same way as the one from the *IDA 2050 scenario*, they would have to be modelled in EnergyPLAN, which would have changed the whole output of the model. The analysis is based on an electricity price distribution where the electricity prices seem very stable. At this stage of understanding, it is believed that it would be relevant to test the model using different electricity price distributions, including predictions of the future electricity price fluctuations. In the climate-neutral energy system of the future, more fluctuating energy sources will be implemented, which can contribute to making the electricity prices fluctuate more as well. Contrary to this, the integration of more transmission capacity to other electricity markets, DSM, electric vehicles and V2G technologies can contribute to pulling the development of the fluctuations in electricity prices in the other direction. The future electricity price distribution remains unknown, but the use of different distributions and predictions could make the model and results more valid and realistic.

8.2.1 Can the modelling of the GHH be considered valid?

The GHH system has, as stated, been modelled as joint units concerning the operation of the pump, turbine and storage. This approach may negatively impact the results concerning the flexibility of the GHH units; it can not harvest the benefits of the system's flexibility that is, in reality, would be able to. The hydrogen produced from the electrolyser can, in the modelled system, only be used for the CAES turbine, and therefore it is only used when the electricity prices are high and rise above the cut-in price; this can create a situation where the hydrogen storage is filled without the ability to use the hydrogen in the case of low electricity prices over an extended period. In reality, the hydrogen produced can be used for several other sectors such as transport and industry. Notably, this limitation in the model additionally limits the ability to potentially create an increased revenue. Another limitation in the modelling involves the identification of cut-in prices.

The cut-in prices are, as mentioned, calculated by finding the cut-in prices that create the largest revenue in the chosen year, using Excels solver tool. In reality, the cut-in price for the operation of a unit will often be defined regarding the operational costs of the unit and will be operated when the operation of the unit makes a profit. However, it can be argued that one will seek to increase the revenue from their units the most, so under the assumption that the units can be operated and still make a profit at the chosen cut-in prices, the results imply that these cut-in prices are creating the highest revenue.

The sub-model of the GHH system is delimited from the external world and is only affected by the exogenous variable, spot market prices. The GHH system is not modelled to affect the external world. In reality, implementing such systems in the energy system will affect the electricity prices because of the addition of electricity-producing units and, therefore, an increase in supply; this may alter the aspect of the revenue that can be created.

The GHH system is analysed using only fixed capacities resulting in the analysis not being able to conclude the most optimal capacities of the units. In contrast, this makes it possible to focus on the planned GHH system and the possibility of optimising the revenue by altering the cut-in prices - and thereby find the most optimal cut-in prices under the model's assumptions. The system does solely operate in FLH, which, as mentioned, does not exhaustively illustrate the flexibility of the system; however, it is a simplification of the GHH system that makes the modelling more simple and the computing time for the simulation faster while being a well-used modelling simplification that is believed to be well justified. Using flexible capacities would make the Excel model more complex, and it is left outside of the scope.

The revenue stream calculated in the modelling of the GHH system is calculated as a yearly revenue, including the investment costs for the different units, the operation and maintenance costs and the expenses and revenues from the purchase and sales of electricity. The investment costs are converted into yearly costs by including the technical lifetime of the units in the calculation. The calculation has not been associated with any discount rate as it is an initial analysis of the yearly revenue of the system; this could be added in a further analysis of the economy of the GHH system. The yearly investment costs of the CAES storage do seem a bit high compared to the hydrogen storage costs, taking into account that the hydrogen storage has a far bigger capacity; this can be explained by the fact that the investment costs for the CAES both include the air compressor and the turbine, whereas the hydrogen storage investment costs only imply the storage. The investment costs used are from The Danish Energy Agency [2020], and it is uncertain whether these costs reflect the actual costs that the GHH system can accomplish.

The electricity market used in the modelling of the GHH system is simplified and does only consider the day-ahead market (spot market prices), which can potentially distort the understanding of the price mechanisms and the potential revenue that can be created from interacting with the different markets. It can be argued that the GHH has the potential to create a larger revenue by acting in both the intraday market and the balancing markets because of its ability to up-and down-regulate the production from the CAES turbine quickly. The additional revenue that the GHH system could make by entering other markets has not been calculated and does therefore remain unclear.

When looking into the actual results of the modelling of the GHH system, it can be seen that the storage is mainly filled at the end of the year due to the low spot market prices in December. The heating and electricity demand is higher in the winter, which would be expected to cause the electricity price to be higher. The reason for this mechanism could although be that the production from wind turbines - especially offshore wind turbines - is substantially higher in the winter, which can be seen in the simulation results in Appendix A, whereas the supply/demand factor is higher in the winter. It can also be seen that the revenue curve is flattening out in this winter period, which is because of the delay of the revenue of filling the storage. Only costs are associated with filling the storage, while the revenue is created when emptying the storage. This negative financial impact of filling the storage could be mitigated by associating the storage content with some level of value. This mechanism is relevant to observe and be aware of.

The assumptions and results of the energy system analysis have been presented for the actors of the GHH. The assumptions of a system efficiency of the pump and turbine slightly lower than 80%, an excess heat potential of 10%, and the fact that the model is simplified to only operate in FLH have been considered as being valid and correspond well to the actual practice. This can be seen in a mail correspondence with HV in Appendix B.

8.3 What if alternative theoretical approaches were used?

The theoretical approach is playing quite an important role since it is the basis for the research design forms the outcome of the thesis. It is in this context interesting to discuss how the outcome of the thesis would form if this exact theoretical approach were not applied. The carbon lock-in theory, in general, made it obvious to discover technologies or resources which potentially could replace bioenergy without fostering similar lock-ins. If this theory was not the approach, a potential outcome could be looking into a more extensive implementation of biogas, for instance, since this seems like an obvious choice and is well-known, but this is within the same path as bioenergy, and the carbon lock-in theory does not approve changing to technologies or resources within the same path, even though the direction is different. Furthermore, the carbon lock-in theory introduced the term TLC which refers to the complex understanding of how technologies become locked-in due to subsidies, policies, infrastructures etc. The TLC can be anticipated to create the basis for a regime in the MLP theory, which elaborates on the idea behind the TLC. In order to escape from a regime, which might be locked in, it is necessary to understand the rules within the regime because it then becomes possible to understand what the new niche developments have to compete with. The MLP theory, therefore, helps to understand that using bioenergy as the primary dispatchable electricity resource is a regime associated with rules, and in order to evaluate if green hydrogen can compete, it is essential to understand the mechanisms that lock in this regime. Additionally, in order for green hydrogen to become a main actor in this field, the regime must be undermined. This approach would or could have been very different if another theoretical approach was applied for this thesis.

8.4 Escaping the bioenergy locked-in dependency

As analysed in Section 7.3.1, it is calculated that the GHH system potentially can contribute with 1.04 TWh/year to the electricity grid. This extra added electricity will potentially contribute as a dispatchable technology because of the storage possibilities in the GHH, and it is therefore assumed that it can substitute bioenergy based CHP and PP, which would eventually decrease the dependency on bioenergy. In the Problem Analysis in Chapter 2 it is stated that bioenergy consumption is associated with some negative externalises when utilised for energy production because of the lack of sustainability and the fact that it is a limited resource. It is, therefore, the aim in the analysis of the sustainable level of bioenergy consumption in Denmark in Section 7.1 to investigate what a Danish sustainable bioenergy consumption by 2050 is; this showed to be difficult to identify since there are considerable differences in the estimates from different researchers to as what the sustainable level is. With the knowledge of the difficulty of estimating a future sustainable bioenergy consumption and the uncertainty of the estimates, it has been the overall aim to minimise and reduce bioenergy consumption.

As described by Unruh [2000] on page 23, the society has previously been carbon locked-in to the usage of fossil fuels to produce different types of energy. The carbon lock-in occurs from path-dependent decisions taken in the past where infrastructures become too well-integrated, resulting in a situation where when a shift is obvious for several reasons, the better alternative remains unused. It has, however, been possible to escape from these carbon locked-in infrastructures since the TIC for the infrastructures has been unfolded. It has, for instance, been possible to escape from the path dependant technologies because awareness of the externalities of using fossil fuels was raised, and politics to solve the issues were implemented. An example of this in Denmark is the PP and CHP, which almost entirely have changed the primary fuel from coal to biomass, which is politically defined as being CO_2-neutral. This sustainable development is positive for the environment; however, this change has created a new path dependence on bioenergy, which likewise is difficult to escape from. One favourable ability of bioenergy usage is its dispatchability, which is an ability it shares with fossil fuels, which is a critical ability to secure in an energy system. The fossil fuel lock-in mechanisms make bioenergy an obvious choice for the transition into climate-neutral energy, because of the similar abilities, concerning the dispatchability, easy storage, utilisation units and infrastructures (combustion in CHP and PP). The applied theories shed light on the fact that even though it seems like the obvious choice because it fits into the created system, there might be better solutions without the same negative externalities. However, when moving towards a 100% climate-neutral energy system in Denmark, bioenergy is estimated to be the primary dispatchable resource, as mentioned in the Problem Analysis in Section 2.3.1.

This thesis investigates how the integration of green hydrogen can diminish this regime of bioenergy as the primary dispatchable energy resource. Green hydrogen has similar abilities to bioenergy, which creates a window of opportunity for green hydrogen as a substitute for bioenergy. However, the lack of infrastructure and price competitiveness of green hydrogen is still the main barriers to large-scale usage. In this sense, it should be discussed that subsidies and other financial goods favouring bioenergy have been applied previously (and some of these are still applicable today). Therefore, it is interesting to follow the upcoming strategic plan for PtX development in Denmark, which will be published by the end of 2021. If subsidies in favour of green hydrogen and P2H2P will be created, green hydrogen certainly has the potential to substitute and minimise bioenergy consumption. An illustration of how green hydrogen currently and potentially, with added subsidies, can be implemented in the MLP context is shown below. The figure shows and describes six different steps with the inspiration of Geels [2011]. The blue circle illustrates the current placement of green hydrogen in the figure, while the green circle illustrates the potential location of green hydrogen if favourable subsidies are added. It should be noted that the green circle is seen from a 1-2 year perspective, and it could potentially further into the future be located near step 6 and influence the landscape as a stabilised regime.

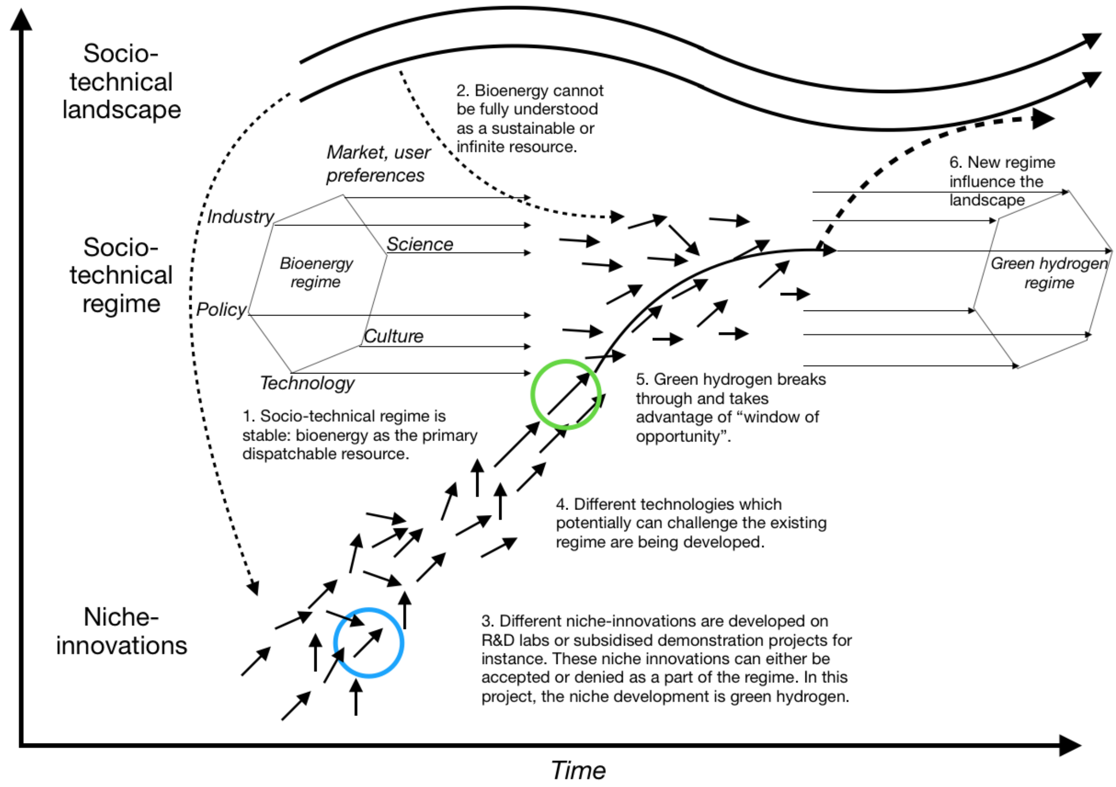

Figure 8.1. An overview of how green hydrogen potentially can develop as a niche and substitute the bioenergy consumption in the dispatchable energy regime, seen from a multi-level perspective. The blue circle illustrates where green hydrogen is currently placed in the MLP figure, while the green circle illustrates where it potentially can be placed if subsidies in favour of green hydrogen are created.

This thesis evaluated that green hydrogen still cannot compete with bioenergy as a dispatchable energy resource when looking at the economy, and it is therefore still considered a niche technology. However, it is a niche that is currently gaining momentum since several projects are investigating the potential for using green hydrogen to add flexibility to the energy system. Several of these projects are still small-scale, and to compete with the existing regime they should be proved on a larger scale. This potential of growth in the development of the scale of the projects leads to the green circle, which describes where green hydrogen potentially can be placed in an MLP figure in 1-2 years, especially if favourable subsidies are applied to the technologies associated with P2H2P. It is located somewhere between step 4 and step 5 because it can potentially eliminate some similar competitive dispatchable fuels at this time, which makes it possible to escape from the path dependant bioenergy lock-in without fostering new lock-ins that can be difficult to escape from in the future. However, it is not evaluated to be applicable for entirely breaking through the window of opportunity and replacing bioenergy as the primary dispatchable energy source since such radical transitions need time. A whole infrastructure to make this happen needs to be established before green hydrogen can break through the window of opportunity, and this is unrealistic to happen in the next two years, but with a longer time horizon, it could be possible, and green hydrogen could potentially influence the future landscape. This thesis only analyse the potential for one GHH unit, and if green hydrogen breaks through the window of opportunity, it is not unrealistic that the number of similar units would be built in Denmark. This would ultimately mean that the bioenergy dependency could be further reduced, and the electricity grid could be stabilised further.

Conclusion 9

This thesis aims to investigate how the Danish bioenergy dependency can potentially be minimised by introducing green hydrogen and CAES in the future Danish electricity sector. More intermittent fluctuating renewable energy sources are being implemented, making the energy system less flexible; this creates a reliance on dispatchable resources to secure the supply. In the future climate-neutral energy system, bioenergy is expected to play an essential role as the primary dispatchable energy resource, but the dependency and use of biomass are associated with negative externalities. In order to overcome these externalities, it is found that bioenergy use should be minimised by substituting it with alternative energy sources or technologies that can take possession of the role of being the dispatchable energy resource. P2H2P can potentially play the role of the dispatchable electricity producer in the same sectors as bioenergy, especially with green hydrogen as the energy carrier. The Danish company Hydrogen Valley collaborates with other stakeholders investigating this potential in a project called Green Hydrogen Hub, where green hydrogen and CAES together create a system that can produce and store electricity (as hydrogen) and utilise it when desired. With this initial knowledge, the presented research question is formulated:

How can green hydrogen utilised through CAES processes contribute to securing sustainable use of bioenergy in Denmark's climate-neutral electricity system in 2050?

This research question is investigated through a theoretical approach that combines three theories; path dependency, carbon lock-in and multi-level perspective. These theories, in combination, create synergies that elevate the analysis and contributes to answering the research question. In order to answer the research question, different methods are used, including stakeholder collaboration, literature study and energy system analysis, including EnergyPLAN and Excel modelling. These methods are used to analyse the potential that the Green Hydrogen Hub system has for minimising the use of bioenergy for electricity production in the Danish energy system in the future.

As this thesis initiates to substitute the bioenergy use, it is aimed to identify a sustainable bioenergy consumption for Denmark in 2050. Several studies investigating this are analysed, and it is generally agreed that there are immense uncertainties concerning the estimation of future potential. It is therefore found that bioenergy consumption should be minimised as much as possible. The next step is to identify if green hydrogen can compete with bioenergy economically. This assessment found that if subsidies in favour of green hydrogen are created in the upcoming strategic plan for PtX, it can compete economically with bioenergy in the future.

By modelling the Green Hydrogen Hub system (with the assumptions described in Table 7.5 on 53), it is found that the system can potentially deliver 1.04 TWh of electricity annually, which can potentially replace bioenergy used for electricity production. Furthermore, it can utilise 1.12 TWh/year electricity from the grid and thus stabilise the supply and demand for electricity. If green hydrogen-based plants break through the window of opportunity and replace bioenergy as the primary dispatchable resource in the regime, the potential for using it to minimise the bioenergy use and stabilise the electricity grid is even more significant.

Bibliography

Arler et al., 2017. Finn Arler, Michael Søgaard Jørgensen and Esben Munk Sørensen. *Prioritering af Danmarks areal i fremtiden.* `https://www.ft.dk/samling/20161/almdel/eru/bilag/162/1742238.pdf`, 2017. Downloaded: 14-04-2021.

Bergek and Onufrey, 2013. Anna Bergek and Ksenia Onufrey. *Is one path enough? Multiple paths and path interaction as an extension of path dependency theory.* `http://dx.doi.org/10.1093/icc/dtt040`, 2013. Downloaded: 19-04-2021.

CAT, 2020. CAT. *Global update: Paris Agreement Turning Point.* `https://climateactiontracker.org/publications/global-update-paris-agreement-turning-point/`, 2020. Downloaded: 16-03-2021.

Clarke and Preto, 2019. Steve Clarke and Fernando Preto. *Biomass Burn Characteristics.* `http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm`, 2019. Downloaded: 27-04-2021.

Collins, 2021. Leigh Collins. *Nel to slash cost of electrolysers by 75%, with green hydrogen at same price as fossil H2 by 2025.* `https://www.rechargenews.com/transition/nel-to-slash-cost-of-electrolysers-by-75-with-green-hydrogen-at-same-price-as-fossil-2-1-949219`, 2021. Downloaded: 27-04-2021.

Colourbox, n.d. Colourbox. *Image: #2940107, Supplier #4824.* `https://www.colourbox.com/image/ecological-concept-symbolizing-renewable-energy-bio-energy-image-2940107`, n.d. Downloaded: 02-06-2021.

Connolly et al., 2014. David Connolly, Henrik Lund, Brian Vad Mathiesen and Martin J. Leahy. *Developing a model of the Irish energy-system.* `https://www.researchgate.net/publication/228798254_Developing_a_model_of_the_Irish_energy-system`, 2014. Downloaded: 19-04-2021.

Cui et al., 2019. Ryna Yiyun Cui, Nathan Hultman, Morgan R. Edwards, Linlang He, Arijit Sen, Kavita Surana, Haewon McJeon, Gokul Iyer, Pralit Patel, Sha Yu, Ted Nace and Christine Shearer. *Quantifying operational lifetimes for coal power plants under the Paris goals.* `https://www.nature.com/articles/s41467-019-12618-3`, 2019. Downloaded: 25-03-2021.

Danish Energy, 2020. Danish Energy. *Anbefalinger til en dansk strategi for Power-to-X.* `https://www.danskenergi.dk/sites/danskenergi.dk/files/media/dokumenter/2020-11/Anbefalinger-til-en-dansk-strategi-for-Power-to-X.pdf`, 2020. Downloaded: 27-04-2021.

Danish Energy Agency, 2020a. Danish Energy Agency. *Basisfremskrivning.* https://ens.dk/sites/ens.dk/files/Basisfremskrivning/basisfremskrivning_2020-webtilg.pdf, 2020a. Downloaded: 12-03-2021.

Danish Energy Agency, 2020b. Danish Energy Agency. *Biomasseanalyse.* https://ens.dk/sites/ens.dk/files/Bioenergi/biomasseanalyse_final_ren.pdf, 2020b. Downloaded: 12-03-2021.

Danish Energy Agency, n.d. Danish Energy Agency. *Dansk klimapolitik.* https://ens.dk/ansvarsomraader/energi-klimapolitik/fakta-om-dansk-energi-klimapolitik/dansk-klimapolitik, n.d. Downloaded: 05-03-2021.

Danish Energy Agency, 2020c. Danish Energy Agency. *Analyseforudsætninger til Energinet 2020.* https://ens.dk/sites/ens.dk/files/Analyser/analyseforudsaetninger_til_energinet_2020-webtilg.pdf, 2020c. Downloaded: 17-03-2021.

Danish Energy Agency, 2019. Danish Energy Agency. *Data, tabeller, statistikker og kort: Energistatistik 2019.* ISSN: 0906-4699, PDF. Energistyrelsen, 2019.

Denchak, 2021. Melissa Denchak. *Paris Climate Agreement: Everything You Need to Know.* https://www.nrdc.org/stories/paris-climate-agreement-everything-you-need-know, 2021. Downloaded: 16-03-2021.

Dincer and Bicer, 2019. Ibrahim Dincer and Yusuf Bicer. *Integrated Energy Systems for Multigeneration.* ISBN: 978-0-12-809943-8, PDF. Elsevier, 2019.

Dym, 2004. Clive L. Dym. *Principles of Mathematical Modeling.* ISBN: 0122265513, 2nd Edition. Academic Press, 2004.

Einstein and Prensky, n.d. Albert Einstein and Marc Prensky. *The problems that exist in the world today cannot be solved by the level of thinking that created them.* http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.186.4598, n.d. Downloaded: 31-05-2021.

Energinet, 2019. Energinet. *INTRODUKTION TIL ELMARKEDET.* https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi15_mfrPvwAhVshPOHHRUXA8cQFjAAegQIAxAD&url=https%3A%2F%2Fenerginet.dk%2F-%2Fmedia%2F41F2C6A30A834208B0225DB3132560C7.PDF&usg=AOvVaw0N3TZdjrCdiVdQzpf7qfU4, 2019. Downloaded: 03-06-2021.

Energinet, n.d. Energinet. *Elspot Prices.* https://www.energidataservice.dk/tso-electricity/elspotprices, n.d. Downloaded: 31-05-2021.

Energinet and Danish Energy, n.d. Energinet and Danish Energy. *Gamechangere for PtX og PtX-infrastruktur i Danmark.* https://energinet.dk/ptxinfrastruktur, n.d. Downloaded: 27-04-2021.

EnergyPLAN, **n.d.** EnergyPLAN. *Existing Country Models.* https://www.energyplan.eu/useful_resources/existingcountrymodels/, n.d. Downloaded: 31-05-2021.

Erickson et al., **2015**. Peter Erickson, Sivan Kartha, Michael Lazarus and Kevin Tempest. *Assessing carbon lock-in.* https://iopscience.iop.org/article/10.1088/1748-9326/10/8/084023/pdf, 2015. Downloaded: 25-03-2021.

European Commission, **n.d.** European Commission. *Types of EU law.* https://ec.europa.eu/info/law/law-making-process/types-eu-law_en, n.d. Downloaded: 18-03-2021.

Eziz et al., **2020**. Anwar Eziz, Zhengbing Yan, Di Tian, Wenxuan Han, Zhiyao Tang and Jingyun Fang. *Drought effect on plant biomass allocation: A meta-analysis.* https://www.researchgate.net/publication/321024857_Drought_effect_on_plant_biomass_allocation_A_meta-analysis, 2020. Downloaded: 01-06-2021.

Gas Storage Denmark, **n.d.** Gas Storage Denmark. *PowerPoint calculations of Green Hydrogen Hub.* PowerPoint, n.d.

Geels, **2011**. Frank W. Geels. *The multi-level perspective on sustainability transitions: Responses to seven criticisms*, 2011.

Geels, **2020**. Frank W. Geels. *NESTwebinar #3 - Multi-Level-Perspective | Frank Geels*, 2020.

Gorrissen Federspiel, **2020**. Gorrissen Federspiel. *Denmark's climate law is a reality – what are the implications?* https://gorrissenfederspiel.com/en/knowledge/news/denmarks-climate-law-is-a-reality-what-are-the-implications#:~:text=The%20agreement%20resulted%20in%20a,binding%20climate%20targets%20was%20adopted, 2020. Downloaded: 05-03-2021.

Green Hydrogen Hub, **n.d.** Green Hydrogen Hub. *About us.* https://greenhydrogenhub.dk/about/, n.d. Downloaded: 31-05-2021.

Gregg et al., **2014**. Jay Sterling Gregg, Simon Bolwig, Ola Solér, Liva Vejlgaard, Sofie Holst Gundersen, Poul Erik Grohnheit, Ivan Tengbjerg Hermann and Kenneth Bernard Karlsson. *Experiences with biomass in Denmark.* https://backend.orbit.dtu.dk/ws/portalfiles/portal/97912187/Experiences_with_biomass_in_Denmark.pdf, 2014. Downloaded: 16-03-2021.

Gross, **2020**. Samantha Gross. *Why are fossil fuels so hard to quit?* https://www.brookings.edu/essay/why-are-fossil-fuels-so-hard-to-quit/, 2020. Downloaded: 18-03-2021.

Hargreaves and Jones, **2020**. Jeremy J. Hargreaves and Ryan A. Jones. *Long Term Energy Storage in Highly Renewable Systems.* https://www.frontiersin.org/articles/10.3389/fenrg.2020.00219/full, 2020. Downloaded: 16-03-2021.

Hethey et al., 2020. János Hethey, Frederik Dahl Nielsen, Hans-Henrik Lindboe and Peter Børre Eriksen. *Green Hydrogen Hub*, 2020.

Hydrogen Valley, n.d. Hydrogen Valley. *Hydrogen Valley.* https://hydrogenvalley.dk/hydrogen-valley/, n.d. Downloaded: 31-05-2021.

IDA, 2009. IDA. *IDA's Klimaplan 2050.* https://ida.dk/media/4624/ida-klima-hovedrapport-dk_1.pdf, 2009. Downloaded: 15-04-2021.

Ideahy, n.d. Ideahy. *Liquid Hydrogen Outline.* https://www.idealhy.eu/index.php?page=lh2_outline, n.d. Downloaded: 27-04-2021.

IEA Bioenergy, 2017. IEA Bioenergy. *Bioenergy's role in balancing the electricity grid and providing storage options – an EU perspective.* https://www.ieabioenergy.com/wp-content/uploads/2017/02/IEA-Bioenergy-bio-in-balancing-grid_master-FINAL.pdf, 2017. Downloaded: 16-03-2021.

IPCC, 2014. IPCC. *Climate Change 2014 Synthesis Report.* https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf, 2014. Downloaded: 16-03-2021.

IRENA, 2012. IRENA. *Wind Power Biomass for Power Generation.* https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-BIOMASS.pdf, 2012. Downloaded: 27-04-2021.

IRENA, 2021. IRENA. *World energy transistions outlook: 1,5°C pathway.* International Renewable Energy Agency, Abu Dhabi., 2021.

Jacobsen, 2020. Jette Jacobsen. *Denmark Becomes a Leader in Climate Change Mitigation.* https://www.brinknews.com/denmark-becomes-a-leader-in-climate-change/, 2020. Downloaded: 18-03-2021.

Johnston, 2014. Melissa Johnston. *Secondary Data Analysis: A Method of Which the Time has Come.* https://www.researchgate.net/publication/294718657_Secondary_Data_Analysis_A_Method_of_Which_the_Time_has_Come, 2014. Downloaded: 23-03-2021.

Keynes, 1987. John Maynard Keynes. *Quotations John Maynard Keynes.* https://mathshistory.st-andrews.ac.uk/Biographies/Keynes/quotations/, 1987. Downloaded: 28-04-2021.

Klima-, Energi- og Forsyningsministeriet, 2019. Klima-, Energi- og Forsyningsministeriet. *Lov om klima.* https://www.retsinformation.dk/eli/ft/201912L00117, 2019. Downloaded: 18-03-2021.

Klimarådet, **2018**. Klimarådet. *The Role of Biomass In The Green Transition.* https://klimaraadet.dk/en/rapporter/role-biomass-green-transition, 2018. Downloaded: 17-03-2021.

Klimarådet, **2020**. Klimarådet. *Kendte veje og nye spor til 70 procents reduktion.* https://www.klimaraadet.dk/sites/default/files/downloads/70_pct_analyse.pdf, 2020. Downloaded: 09-03-2021.

Lazard, **2020**. Lazard. *Levelized Cost of Energy and Levelized Cost of Storage – 2020.* https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/, 2020. Downloaded: 27-04-2021.

Liebowitz and Margolis, **1995**. Stan Liebowitz and Stephen Margolis. *Path Dependence, Lock-In, and History.* Journal of Law Economics and Organization, 1995.

Lund, **2014**. Henrik Lund. *Renewable Energy Systems.* ISBN: 978-0-12-410423-5, ebook. Elsevier Inc., 2014.

Lund et al., **2009**. Henrik Lund, Brian Vad Mathiesen, David Connolly and Martin Leahy. *A review of computer tools for analysing the integration of renewable energyinto various energy systems.* https://reader.elsevier.com/reader/sd/pii/S0306261909004188?token=7F45EF4C0844E94D82753202B7B1D339456718D06833BE06CB76062C37A795E90B6DCB19582E65FC036B240 originRegion=eu-west-1&originCreation=20210419083721, 2009. Downloaded: 15-04-2021.

Lund et al., **2011**. Henrik Lund, Frede Hvelplund, Brian Vad Mathiesen, Poul A. Østergaard, Per Christensen, David Connolly, Erik Schaltz, Jayakrishnan R. Pillay, Mads Pagh Nielsen, Claus Felby, Niclas Scott Bentsen, Niels I. Meyer, Davide Tonini, Thomas Astrup, Kai Heussen, Poul Erik Morthorst, Frits M. Andersen, Marie Münster, Lise-Lotte P. Hansen, Henrik Wenzel, Lorie Hamelin, Jesper Munksgaard, Peter Karnøe and Morten Lind. *Coherent Energy and Environmental System Analysis.* https://www.ceesa.plan.aau.dk/digitalAssets/114/114487_32603_ceesa_final_report_samlet_02112011.pdf, 2011. Downloaded: 15-04-2021.

Lund et al., **2016**. Henrik Lund, Poul Alberg Østergaard, David Connolly, Iva Ridjan, Brian Vad Mathiesen, Frede Hvelplund, Jakob Zinck Thellufsen and Peter Sorknæs. *Energy Storage and Smart Energy Systems*, 2016.

Marion and Lawson, **2008**. Glenn Marion and Daniel Lawson. *An Introduction to Mathematical Modelling.* https://people.maths.bris.ac.uk/~madjl/course_text.pdf, 2008. Downloaded: 31-05-2021.

Masson-Delmotte et al., **2019**. Valérie Masson-Delmotte, Panmao Zhai, Hans-Otto Pörtner, Debra Roberts, Jim Skea, Priyadarshi R. Shukla, Anna Pirani, Wilfran Moufouma-Okia, Clotilde Péan, Roz Pidcock, Sarah Connors, J. B. Robin Matthews, Yang Chen, Xiao Zhou, Melissa I. Gomis, Elisabeth Lonnoy, Tom Maycock, Melinda

Tignor and Tim Waterfield. *IPCC, 2018: Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf, 2019. Downloaded: 15-04-2021.

Mathiesen et al., **2015**. Brian Vad Mathiesen, Henrik Lund, Kenneth Hansen, Iva Ridjan, Søren Djørup, Steffen Nielsen, Peter Sorknæs, Jakob Zinck Thellufsen, Lars Grundahl, Rasmus Lund, David Drysdale, David Connolly and Poul Alberg Østergaard. *IDA's Energy Vision 2050.* https://vbn.aau.dk/ws/portalfiles/portal/222230514/Main_Report_IDAs_Energy_Vision_2050.pdf, 2015. Downloaded: 13-04-2021.

Mokyr, **1990**. Joel Mokyr. *The Lever of Riches: Technological Creativity and Economic Progress.* ISBN: 13 978 0-19-506113-0, 1st edition. Oxford University Press, 1990.

NASA, **n.d.a**. NASA. *The Effects of Climate Change.* https://climate.nasa.gov/effects/, n.d.a. Downloaded: 16-03-2021.

NASA, **n.d.b**. NASA. *The Causes of Climate Change.* https://climate.nasa.gov/causes/, n.d.b. Downloaded: 16-03-2021.

National Academy of Sciences, **2008**. National Academy of Sciences. *WHAT YOU NEED TO KNOW ABOUT ENERGY.* https://www.nap.edu/read/12204/#slide1, 2008. Downloaded: 13-04-2021.

Petersen et al., **2016**. Jens Kjerulf Petersen, Berit Hasler Anne-Belinda Bjerre, Marianne Thomsen, Mette Møller Nielsen and Pernille Nielsen. *Blå biomasse — potentialer og udfordringer for opdræt af muslinger og tang, DTU Aqua-rapport nr. 312-2016.* https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjlsNf77frvAhWVg_0HHYhuAsIQFjAGegQIBhAD&url=http%3A%2F%2Fl.dtu.dk%2Fakqy&usg=AOvVaw2hXlU4A48597UZQ5o7ZsHf, 2016. Downloaded: 13-04-2021.

Pierson, **2000**. Paul Pierson. *Not Just What, but When: Timing and Sequence in Political Processes.* https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-BIOMASS.pdf, 2000. Downloaded: 27-04-2021.

Rambøll, **n.d.** Rambøll. *Power-to-X: Integrating fluctuating renewable energy.* https://ramboll.com/partner-for-change/power-to-x, n.d. Downloaded: 01-06-2021.

Rienecker et al., **2012**. Lotte Rienecker, Peter Stray Jørgensen and Signe Skov. *Den gode opgave - Håndbog i opgaveskrivning på videregående uddannelser, 4. udgave.* ISBN: 978-87-593-1521-7, PDF. Imperiet, 2012.

Singh and Banerjee, **2017**. Amit Singh and Rangan Banerjee. *Encyclopedia of Sustainable Technologies: Demand Side Management.* https:

//www.sciencedirect.com/topics/engineering/demand-side-management/pdf, 2017. Downloaded: 16-03-2021.

Statistics Denmark, n.d. Statistics Denmark. *Population projections.* https://www.dst.dk/en/Statistik/emner/befolkning-og-valg/befolkning-og-befolkningsfremskrivning/befolkningsfremskrivning, n.d. Downloaded: 15-04-2021.

Stein, 2017. Amy L. Stein. *Breaking Energy Path Dependencies.* http://brooklynworks.brooklaw.edu/blr/vol82/iss2/7, 2017. Downloaded: 19-04-2021.

The Danish Energy Agency, 2021. The Danish Energy Agency. *Teknologikatalog for fornybare brændstoffer.* https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-fornybare, 2021. Downloaded: 31-05-2021.

The Danish Energy Agency, 2020. The Danish Energy Agency. *Teknologikatalog for energilagring.* https://ens.dk/service/fremskrivninger-analyser-modeller/teknologikataloger/teknologikatalog-energilagring, 2020. Downloaded: 31-05-2021.

Thollander et al., 2020. Patrik Thollander, Magnus Karlsson, Patrik Rohdin, Johan Wollin and Jakob Rosenqvist. *Introduction to Industrial Energy Efficiency*, 2020.

UNEP, 2020. UNEP. *Emissions Gap Report 2020.* https://www.unep.org/emissions-gap-report-2020, 2020. Downloaded: 16-03-2021.

United Nations, 2016. United Nations. *The Paris Agreement.* https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, 2016. Downloaded: 16-03-2021.

University of Bedfordshire, 2018. University of Bedfordshire. *Writing the method section of a systematic literature review in a dissertation.* https://lrweb.beds.ac.uk/__data/assets/pdf_file/0005/502169/Writing-the-method-section-of-a-systematic-lit-review-in-a-dissertation.pdf, 2018. Downloaded: 31-05-2021.

Unruh, 2002. Gregory C. Unruh. *Escaping carbon lock-in.* https://reader.elsevier.com/reader/sd/pii/S0301421501000982?token=37944069EB6250430B8C44750C5A4815AB76097092C1457D2CE13DD3473812A15CD02E8820C4633C2BADDE
originRegion=eu-west-1&originCreation=20210428123427, 2002. Downloaded: 28-04-2021.

Unruh, 2000. Gregory C. Unruh. *Understanding carbon lock-in.* https://reader.elsevier.com/reader/sd/pii/S0301421500000707?token=57C7612036F8C6AE5CECB0A4875F7301933464DFC6553181227A3BEF94A71F7F96A7A3AABB87B609AE0D8E
originRegion=eu-west-1&originCreation=20210428132609, 2000. Downloaded: 28-04-2021.

Wang et al., 2020. Anthony Wang, Kees van der Leun, Daan Peters and Maud Buseman. *European Hydrogen Backbone.* https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/, 2020. Downloaded: 28-04-2021.

Wenzel et al., 2014. Henrik Wenzel, Linda Høibye, Rune Duban Grandahl, Lorie Hamelin, David Neil Bird and Asger Strange Olesen. *Carbon footprint of bioenergy pathways for the future Danish energy system.* https://ens.dk/sites/ens.dk/files/Bioenergi/carbon_footprint_of_bioeneergy_pathways_for_the_future_danish_energy_system_-_final_210314_l.pdf, 2014. Downloaded: 31-05-2021.

Wittrup, 2019. Sanne Wittrup. *Danske vindmøller stoppes stadigt oftere.* https://ing.dk/artikel/vindmoller-stoppes-stadigt-oftere-230204, 2019. Downloaded: 16-03-2021.

A Energy system analysis

The results from the *IDA 2050 scenario* and the modelling and simulation of the GHH system is attached in an external Excel document.

B Validation of assumptions of the GHH modelling

Fra: Frederik Flensted Madsen frederik@hydrogenvalley.dk
Emne: RE: Validering af resultater
Dato: 26. maj 2021 kl. 12.02
Til: Søren Bjerregaard Pedersen soren@hydrogenvalley.dk

FM

Hej Søren,

Jeg har kigget det igennem og mine svar kommer her:

Vi er efterhånden begyndt at nærme os målstregen, eftersom vi skal aflevere vores projekt d. 4. Juni, som er fredag næste uge. Derfor kunne vi godt tænke os, at I kiggede på vores Excel-resultater. Vi har sat vores GHH system effektivitet til 80% - som vi er meget i tvivl om er retvisende.

- Umiddelbart vil jeg mene at 80% system effektivitet er ret godt placeret – måske i den høje ende, men som i også antager så er der ingen partial-load hours i modellen. De to antagelser spiller godt sammen. I praksis ville det nok være anderledes, men for modellens skyld vil jeg mene at det er validt.

Derudover har vi sat den potentielle excess heat for district heating til 10%, eftersom det forventes at electrolyseanalægget kan producere 20% overskudsvarme (da pumpen på de 310 MW er en samlet enhed af både air compressor og elektrolyse). Dette kunne vi også godt tænke os at få valideret.

- Igen mener jeg at i har nogle gode antagelser, og ved at inkludere pumpen tror jeg man er i den konservative ende af hvad man i praksis kunne få udnyttet af alle varmekilder. Så antagelsen her vil jeg også mene er valid.

Derudover har vi sat de forskellige kip-priser / cut-in prices for de forskellige teknologier til 43 og 48 €/MWh for henholdsvis pumpen og turbinen. Er disse priser repræsentative?

- Jeg har svært ved at vurdere denne antagelse, da jeg ikke har vildt meget forstand på pumper og turbiner. Men det er korrekt at der er cut-in priser, og når systemet er af den skala det nu er, så vil jeg mene at det er realistisk, men måske i den lave ende.

Vi opererer i vores "simplificerede" excel-model udelukkende med full-load hours, og ingen partial-load hours vil være repræsentative, selvom det er i praksis er forkert. Alle disse metodiske overvejelser er dog beskrevet i vores metode-afsnit, som I naturligvis også får tilsendt når det er færdigt.

- Det er fint at i noterer at modellen kun kører med full-load timer, da det som regel også er sådan de fleste modeller analyserer operationen. I praksis er der dog fordele og ulemper ved at køre i partial-load hours – men det er en opgave i sig selv at lave en operationsstrategi der for det første inkluderer fleksibiliteten af elektrolyseteknologien, samt sammenspillet med el-priser og potentielle balance ydelser. Men i kontekst af jeres opgave er det en valid måde at gøre det på.

- Overall disclaimer: Det er komplekse systemer der spiller sammen, og i praksis ville man nok opleve nogle udfordringer som en model har svært ved at tage højde for. Men generelt set synes jeg antagelserne er velovervejet og stemmer godt overens med både praksis og andre modelleringer.

  Det ligner et virkelig godt stykke arbejde i har lavet! Det ville være meget