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Negative Emission Technologies in an Intermittent Electricity System

Master's thesis in Sustainable Energy Systems

ANNA EMANUELSSON

Department of Space, Earth and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

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ANNA EMANUELSSON

Supervisor: Mariliis Lehtveer, Energy Technology
Examiner: Mikael Odenberger, Energy Technology

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Department of Space, Earth and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Department of Space, Earth and Environment
Chalmers University of Technology

Abstract

Carbon dioxide removal (CDR) from the atmosphere is likely to be needed to limit global warming to 1.5°C or 2°C and thereby meeting the Paris Agreement. Negative Emissions Technologies (NETs) can be used to remove carbon dioxide (CO_2) from the atmosphere, thereby lowering the atmospheric concentration. Bio-Energy Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS) are NETs that have a direct relation with the electricity system. In this work, it is investigated how BECCS and DACCS interact with an intermittent electricity system to achieve net negative emissions in the sector. A literature study and energy systems modelling are performed to achieve the aim. DACCS is the main focus of the literature study since the technology is to be applied in the energy systems model while BECCS is already implemented in the model. The work shows that DACCS has a higher capturing cost per ton of CO_2 than BECCS, implying that it is less costly to capture CO_2 using BECCS under the assumptions made in this study. However, due to BECCS having a high Levelised Cost of Electricity (LCOE) in combination with electricity being the main product by quantity in the system, the total system cost is lower using DACCS as negative emission provider. Moreover, DACCS outcompetes BECCS in Spain (ES3), Ireland (IE) and Hungary (HU) for the Base case where both DACCS and BECCS are allowed to provide the system with negative emissions. However, in the case where a low biomass price is applied for IE, BECCS and DACCS co-exist in the system.

Keywords: Negative emission technologies, DACCS, BECCS, Electricity system modelling, Wind power, Solar PV

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Anna Emanuelsson, Gothenburg, July 2020

Contents

Abbreviations

BECCS	Bio-Energy Carbon Capture and Storage
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
COP	Coefficient of Performance
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
DACCSHTel	DACCS using a fully electrified High Temperature liquid solvent system
DACCSLTel	DACCS using a fully electrified Low Temperature solid sorbent system
DACCSWG	DACCS with a biogas driven a High Temperature liquid solvent system
DACCU	Direct Air Carbon Capture and Utilization
EAF	Electric Arc Furnace
ES3	Region in Spain
G	Gas condense
G_{peak}	Gas condense peak power
GHG	Greenhouse Gas
HT	High Temperature
HP	Heat Pump
HU	Hungary
IE	Ireland
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCOC	Levelised Cost of Capture
LCOE	Levelised Cost of Electricity
LB	Low Biomass Price
LT	Low Temperature
MOF	Metallic Organic Framework
MSA	Moisture Swing Adsorption
NET	Negative Emission Technology
NG	Natural Gas
OPEX	Operational Expenses
PSA	Pressure Swing Adsorption
$PV_{c-SiOPT}$	Crystalline Silicon Solar Photovoltaic Cells with Optimum Tilt

TSA	Temperature Swing Adsorption
TVSA	Temperature Vacuum Swing Adsorption
VSA	Vacuum Swing Adsorption
WON	Onshore wind power
WG_{peak}	Biogas fired gas turbine

1
Introduction

Human activities have lead to an increase in the concentration of greenhouse gas (GHG) emissions in the atmosphere compared to pre-industrial levels [1]. The concentration of carbon dioxide (CO_2) has increased from 280 ppm in year 1750 to approximately 407 ppm in 2018 [2]. During 2018, the global CO_2 emissions rose by 1.7% and the growth of CO_2 emissions during this period is so far the largest growth rate ever recorded. Furthermore, the global energy consumption is predicted to double until the year 2050 according to the International Energy Agency (IEA) [2]. Due to increasing atmospheric levels of GHGs, temperatures both in the atmosphere and in the ocean are rising compared to pre-industrial levels [3]. An increase in temperature can cause disturbances in different systems, such as disturbances for unique and threatened ecosystems, but it could also result in altered weather patterns and more extreme weather events. To mitigate the worst disturbances, the Intergovernmental Panel on Climate Change (IPCC) has established that the temperature rise compared to pre-industrial levels should stay well below 2ºC and preferably even below 1.5ºC [1]. To keep global warming below these limits, the Paris Agreement was established in 2016 [4]. At the time of writing, 187 of 197 Parties have ratified the convention [5]. To limit global warming according to the agreement, the global carbon budget must be considered. The estimates of the global carbon budget vary depending on several factors such as the probability of limiting global warming, lagging feedback mechanisms and tipping points in the climate system. If all globally emitted GHG emissions ceased instantly, the atmospheric temperature will continue to rise. This is partly due to the long atmospheric lifetime of CO_2, and partly due to lagging feedback mechanisms from the temperature rise that could result in more GHGs being emitted to the atmosphere from carbon that is currently being stored on earth [1, 3].

Carbon dioxide removal (CDR) from the atmosphere is needed to limit the global temperature rise to 1.5ºC, with limited or no overshoot according to the IPCC [1]. CDR from the atmosphere can be achieved by the deployment of Negative Emission Technologies (NETs). There are primarily seven NETs mentioned in literature that have potential to be of importance when mitigating climate change [6], these are:

- Bio-Energy with Carbon Capture and Storage (BECCS)
- Afforestation and Reforestation
- Direct Air Carbon Capture and Storage (DACCS)
- Enhanced weathering
- Ocean fertilization
- Biochar
- Soil carbon sequestration

Out of these seven NETs, two of them, DACCS and BECCS, are directly connected to the electricity system and are therefore of special interest in this work.

To meet the Paris Agreement and limit global warming to 1.5°C, it is predicted that current yearly emissions need to be halved by mid-century [7] and that net negative emissions in the second half of this century are likely to be needed [8]. The IEA has developed a Sustainable Development Scenario for a global transition within the energy sector to meet climate targets [9]. According to this scenario, the European electricity system is mainly powered by wind, solar, hydropower and biomass [9]. Thus, to limit the temperature rise to 1.5°C, investments in low-carbon technologies in the energy sector are needed. Investments in wind and solar power are predicted to increase by a factor of 4-6 by 2050 compared to 2015 [10]. With an increased amount of intermittent electricity generation in the energy system, new challenges arise. The value of intermittent generation in the electricity system decreases as their share increases. Moreover, electricity production from variable electricity generation will result in more varying electricity supply and prices [11]. Due to the variability in electricity supply and prices, it will become more important at what times electricity is consumed and produced. The two NETs discussed in this work, DACCS and BECCS, have different properties regarding their contribution to electricity production and consumption, as will be discussed further in this report.

1.1 Aim

The aim of this study is to investigate the performance of BECCS and DACCS in an electricity system including large scale employment of variable renewables. The work is carried out with the aid of an electricity system model investigating scenarios prescribing net negative CO_2 emissions.

1.2 Limitations

The study will be limited to investigating a future scenario in the electricity system in the year 2050, no other years will be considered. The work is not a dynamic study about system development, but an analysis of a system at about year 2050. Technologies providing negative emissions will be the main focus of the study, therefore, Direct Air Carbon Capture and Utilisation (DACCU) will be excluded.

2

Description of technologies

In the following chapter, the two NETs relevant for this work, DACCS and BECCS, are introduced. The main focus in this section is on DACCS technologies and its properties, such as energy consumption and cost estimation. This is due to that DACCS is going to be implemented in the energy systems model used in this work while BECCS is already implemented in the model.

2.1 Direct Air Carbon Capture and Storage

DACCS provides an opportunity to reduce the concentration of CO_2 in the atmosphere, while society transitions from fossil fuel dependency. After the transition, DACCS can be used to keep removing CO_2 from the atmosphere to reach pre-industrial concentrations. Since the CO_2 in the atmosphere is well mixed, the capture technology could be located anywhere, independent of where the CO_2 is released. Therefore, the system could be placed for example on degraded land to not compete with other land use in a way other NETs do. It could also be placed near the CO_2 storage location, reducing the need for transportation and the energy consumption related to the transportation of CO_2 [12]. With a reduced airborne fracture of CO_2 in the atmosphere, the effectiveness of natural carbon sinks, such as the terrestrial sphere and the oceans, might weaken. Less CO_2 could be solved into the oceans and taken up by the terrestrial sphere due to the lower partial pressure of CO_2 in the atmosphere. These sinks might even become GHG emitters. This implies that NETs are needed to an even larger extent to lower the concentration of CO_2 in the atmosphere further [13].

With DACCS, CO_2 is captured through ambient air and the gas can then be stored geologically. By using DACCS, even distributed emissions of CO_2, which accounts for approximately 50% of total global emissions, could be captured [14]. Distributed emissions are for example emissions from transportation and aviation. A challenge with DACCS is that the air contains a relatively low concentration of CO_2 compared to off-gases from large point emitters. Large amounts of energy are therefore needed to capture CO_2 from air using this technology compared to for example Carbon Capture and Storage (CCS) that captures CO_2 from flue gases [15].

2.1.1 Capture Technologies

Several technologies exist to separate a particular species from a gas. The goal with DAC is to separate CO_2 from ambient air. Despite the variation of technologies for achieving this goal, all of them have two basic steps in common, capture and release. To be able to capture CO_2 using DAC, ambient air comes in contact with a sorbent in a contactor. CO_2 rich air enters the contactor where the CO_2 is captured by the sorbent and CO_2 depleted air leaves the contactor. The sorbent could be of either absorbing or adsorbing nature [16]. In the case where absorption is used, CO_2 is dissolved into a liquid, while if using adsorption, CO_2 is adhered onto a solid. The amount of gas being dissolved into the liquid or adsorbed onto the solid, depends on the concentration of CO_2 in the air as well as already existing concentration of CO_2 in the sorbent [17]. The capture of CO_2 generally occurs spontaneously through an exothermic reaction [18], meaning that energy is being released. An equilibrium between the concentration of CO_2 in the gas and the sorbent will appear, the equilibrium is dependent on both the temperature and molecule interaction between the gas and the sorbent. With a higher concentration of CO_2 in the air compared to the sorbent, CO_2 will transfer to the sorbent phase [17]. To ensure that CO_2 is being captured at the low concentrations of ambient air, it is of importance to use a sorbent with a high capture rate of CO_2 at low partial pressures. To ensure a high uptake of CO_2 under these conditions, a sorbent with strong chemical interaction with the species is needed [18]. The amount of ambient air that comes in contact with the sorbent could either be dependent on the natural airflow or be enhanced using fans [16]. Since ambient air has a relatively low concentration of CO_2 (approximately 400 ppm), large volumes of air must be transferred through the contactor. A pressure drop is created over the contactor, the size which depends on the contactor design [18].

The second step in the process is the desorption, where CO_2 is being separated from the sorbent, thus regenerating the sorbent to be used again [16]. During the regeneration of the sorbent, a nearly pure stream of CO_2 is released [19]. The desorption is generally an endothermic reaction, meaning that activation energy is needed for the process to occur. This step is also considered to be the most energy-intensive step of the process [18].

The focus of this report will be on two main types of Direct Air Capture systems: a system using a High-Temperature (HT) liquid solvent and a system using a Low-Temperature (LT) solid sorbent, as these are the furthest developed and have available estimates of cost data. The HT liquid solvent system has a sorbent of absorbing technology and uses high-temperature heat to regenerate the sorbent. The LT solid sorbent system uses adsorption and can use either a temperature, pressure, vacuum or moisture swing adsorption to regenerate the sorbent [20].

2.1.1.1 High Temperature Liquid Solvent

The HT liquid solvent system is based on conventional technology used in flue gas CCS systems [21]. Already in 1996, CCS-technology has been used in industrial scale [22]. Due to that the HT liquid solvent system is based on conventional CCS-technology, this DAC system has gotten quite far on its development curve. The first step using the HT liquid solvent system is absorption of CO_2 from ambient air through a gas-liquid contactor [20, 19]. When the ambient air has been moved through the contactor, the CO_2 has formed a carbonate together with the sorbent [19]. Sorbents typically used in a HT liquid solvent systems are strong alkalines such as sodium hydroxide (NaOH), potassium hydroxide (KOH) and calcium hydroxide ($Ca(OH)_2$) [23]. To ensure good contact between the air and the sorbent, different designs for the contactor are used. Packed absorption columns are one option, where the packing material constitutes a large surface area for the air to flow across. Depending on what packing material is used, the pressure drops over the contactor will vary. A larger pressure drop implies increased energy requirement to transfer the air through the contactor. Other methods to enhance the contact between the gas and the sorbent are also used, such as spray towers [17].

During the regeneration, the sorbent is exposed to a high temperature to release the CO_2 in a relatively pure stream [19]. The regeneration occurs in a regeneration facility that generally consists of several steps. In the first step, the carbonate formed during capture is moved into a causticizer where calcium carbonate ($CaCO_3$) slurry is formed. Water is thereafter removed from the slurry in a clarificatory and filter press. The calcium carbonate is then moved to a calciner where high-temperature heat is added to produce solid calcium oxide (CaO) as well as a stream of nearly pure CO_2 [18]. Two different processes are commonly used during the regeneration of the sorbent, either a Kraft process or a Pellet reactor [24]. The Kraft process is traditionally used in the chemical pulping industry and most often uses NaOH as sorbent. A Pellet reactor, using KOH as sorbent, could replace the Kraft caustic recovery loop. This would lower the investment cost and the energy requirement of the regeneration process [24]. Moreover, since the HT Liquid Solvent system is based on conventional CCS technology, it is assumed that the technology is quite inflexible and that its flexibility resembles the one of conventional CCS-technology.

2.1.1.1.1 Energy requirements

Thermal and electrical energy are required, both during the absorption and regeneration step. Collected data for the energy requirements can be found in Chapter 4.1.1. If fans are used during the absorption process, electrical energy is needed. To achieve a high capture rate, different design options for the contactor exists. A spraying tower could, for example, be used to distribute the liquid solvent and enhance the contact between the CO_2 and the sorbent [20]. By increasing the capture rate of CO_2 per unit of sorbent used, the amount of air needed to be passed through the contactor is decreased. Thereby, the electrical energy required for the fans would be reduced [25]. The regeneration of the sorbent is the most energy-intensive part of the process [20]. CO_2 is being released when the sorbent is exposed to high-temperature heat in the calciner, approximately 900°C is needed [18]. The thermal energy demand in the calciner is often satisfied by combusting natural gas (NG). However, the system could also be fully electrified using an Electric Arc Furnace (EAF) to supply the high-temperature heat [24]. Apart from the thermal energy required in the calciner, electrical energy is used to run pumps when moving the liquid solvent in the regeneration facility. Lastly, electrical energy is also consumed during the compression, transportation and storage of the gas [20].

2.1.1.2 Low Temperature Solid Sorbent

For the LT solid sorbent system, energy is needed both during the adsorption and the desorption process. Energy requirements for the LT system is found in Chapter 4.1.2. In the adsorption step, electrical energy is needed if fans are used. It is also needed during the regeneration step, as well as to compress, transport and to store the CO_2 [20]. The first step of a LT solid sorbent system, is transferring air through a contactor. In the contactor, CO_2 is adsorbed onto a solid sorbent. There are mainly two types of solid sorbents used for DAC, amine adsorbents and inorganic solid sorbents [18]. However, amines are more frequently used in LT solid sorbent DAC systems [26].When the solid sorbent is saturated by CO_2, regeneration of the solid occurs. To regenerate the material, the adsorber is either switched into desorption mode, or the solid sorbent is moved to a desorption unit, thus the technology is working in a cyclic manner. The most common practice today is to have the adsorption and desorption in the same unit [20].

There are four different methods used for regenerating the sorbent in a LT solid sorbent system. Low grade heat, humidity, pressure or vacuum could be used. The desorption methods are referred as the following:

- Temperature swing adsorption (TSA)
- Moisture swing adsorption (MSA)
- Pressure swing adsorption (PSA)
- Vacuum swing adsorption (VSA)

The regeneration technologies can be used separately or in combination. TSA works with low grade heat, ranging from 70-100°C. MSA uses humidity to accomplish desorption, PSA uses pressure and with VSA, a vacuum is created to release the CO_2 into a stream with high purity. The desorption methods could also be used in combination, it is for example common to use a combination of temperature and vacuum, temperature vacuum swing adsorption (TVSA) [18, 20, 23]. The energy required for the desorption methods differ, and the PSA is for example in general not used due to its high energy intensiveness [26]. The low grade heat needed in the TSA could be obtained using different methods. Waste heat from thermal generation or industry could be used, or heat could be created using a heat pump and electricity from the grid [20].

The desorption step is the most energy-intensive step in the LT solid sorbent system [18]. When the sorbent has been regenerated, it is reused to capture more CO_2. The already captured CO_2 is further processed to later be compressed and transported to the storage location [12]. The sorbent will deteriorate with time due to exposure to the ambient environment as well as to the conditions inquired by the process, such as sunlight, wind, temperature, humidity and pressure [12]. Different levels of sorbent degradation and sorbent losses occur during regeneration depending on the sorbent used [27].

2.1.2 Technology comparison

The HT liquid solvent system and LT solid sorbent system present different advantages and disadvantages. The HT liquid solvent system can work continuously, and the sorbent is less impacted by contaminants entering the system [24]. Since the technology is based on conventional CCS technology, it has been further developed than the LT solid sorbent system. However, the HT system is assumed to be less flexible than the LT solid sorbent system due to its continuous operation requirement. The flexibility of the HT system is assumed to be similar to the flexibility of other thermal generation. Another advantage with the HT liquid solvent system is that the contactor can be built using already commercial mechanical components, which could result in a lower investment cost in the technology compared to the LT solid sorbent system. Some disadvantages of a HT liquid solvent system are the high energy intensiveness and the large investment cost of the regeneration facility [24]. Both the investment cost and the energy requirement for a LT solid sorbent system is generally lower compared to a HT liquid solvent system. The HT liquid solvent system also has a quite high water- and chemical loss [17], compared to the LT solid sorbent system [17].

2.1.2.1 State of the art

DAC is still under continuous development. As previously mentioned, the HT liquid solvent system is further developed than the LT solid sorbent system, since the HT system is based on conventional CCS technology. Research to improve the characteristics and economics of the sorbents used in the LT system is proceeding. Moreover, a number of companies are present at the market, see Figure 2.1, but only one major player (Carbon engineering) works with the HT system. A number of other companies are instead involved in developing the LT solid sorbent system [20].

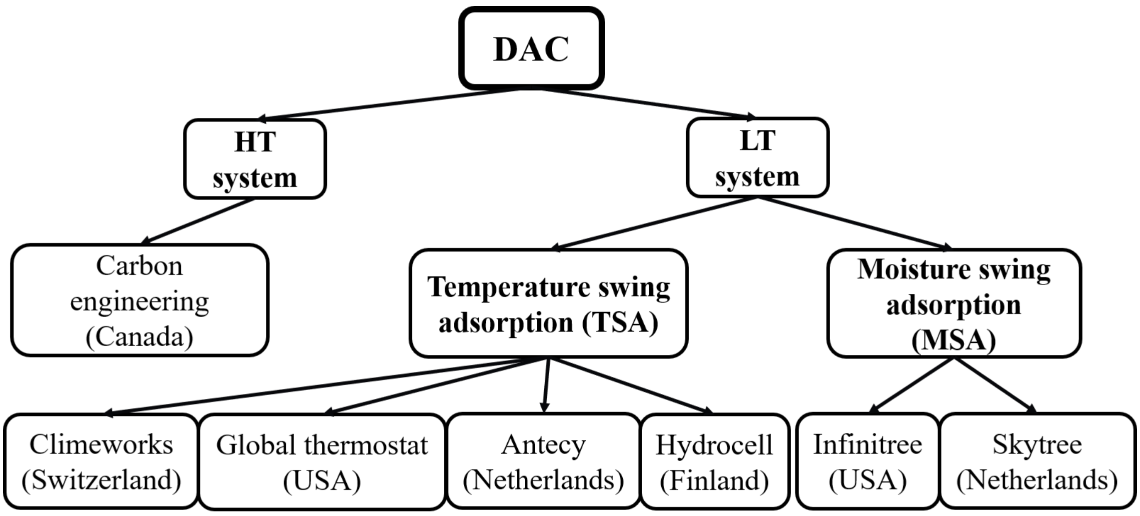

Figure 2.1: Categorization of DAC technology with companies present at the market at respective technology.

2.2 Bio-Energy Carbon Capture and Storage

BECCS is a combination of bioenergy and CCS. CO_2 is being removed from the atmosphere through natural carbon sinks in the biosphere. When biomass is combusted and emissions are captured, negative emissions are achieved [28]. BECCS produces energy while combusting biomass. Therefore, BECCS can supply electricity to cover for the demand that cannot be covered by variable electricity generation during periods with low wind and solar infeed [11]. While providing this service, negative emissions are also created. The CCS technology used in BECCS has similar properties to the CCS technology used in the HT liquid solvent DACCS system.

3
Method

This work consists of two parts, a literature review and energy systems modelling. The approach of the literature review, and the basic characteristics of the energy systems model used in this work, will be presented in the following chapter. The specific scenarios to be modelled will also be described in further detail. Moreover, some central concepts will also be introduced.

3.1 Literature review

A literature review is conducted to mainly gain knowledge about the DAC technologies since the technology is to be implemented in the energy systems model, while BECCS already is implemented. The literature review will consider a categorization and understanding of how the technologies works as well as on gathering data on important parameters of each technology. A quite extensive literature review regarding DACCS technologies was recently performed by Fasihi et al. [20]. Some data presented in this work will be from the original papers while other data will be from the findings of Fasihi et al. The data collected will be used to show the variation of different parameters of DACCS, such as the thermal and electric energy demand and costs. However, the characteristics needed for the input to the energy systems model will be according to the final model presented by Fasihi et al. Some characteristics of the DAC technologies will be of importance when considering how the energy system should be designed to achieve negative net emissions when implementing DACCS on large scale. DACCS provide negative emissions but also has an energy demand. Simultaneously, DACCS and BECCS will both be available to the system as negative emission providers. Some parameters that will be of interest in this study is costs, flexibility, capture rates and thermal and electrical energy demand. BECCS was already implemented in the model and technical details can be found in the work by Johansson, Lehtveer and Göransson [11].

3.2 Energy systems modelling

This work uses the ENODE model to analyse the questions posed. ENODE is a linear optimisation model used to optimise a problem with specified constraints. In this work, the model is used to minimise the total investment cost in a future electricity system. The model used in this study builds on the work of Johansson, Lehtveer and Göransson, and a more detailed description of the model can be found at the following reference [11]. Moreover, further descriptions of alterations made in the model during this work can be found in Appendix A. The model works with a 3h temporal resolution and presents a cost minimising solution of the electricity system. The model is a green-field model, meaning that an electricity system is built from scratch, regardless of any already installed capacity. With this approach, the electricity system proposed by the model will not represent a realistic scenario. However, it will be possible to study how different parts of the system interact with each other. When studying the interaction between different sources of energy generation and NETs, it is possible to study how DACCS can be implemented in the energy system from a system perspective context. The model considers a single copperplate-region at a time, allowing for no transmission between regions. Three regions will be considered in this work, a region with good conditions for solar insolation, Spain (ES3), a region with good conditions for wind power, Ireland (IE), and a region that is considered to have relatively poor conditions for both wind and solar, Hungary (HU). It is investigated how DACCS interacts with other technology in the energy systems, such as BECCS and if both the HT and LT DAC technologies can exist simultaneously in the system or if they out-compete each other. Only one year will be considered, 2050, and no net emissions of CO_2 are allowed in the system. Moreover, the level of negative emissions of CO_2 will be modelled to 10% of the emission level in the electricity sector in the year 1990. This level of negative emissions is chosen to be able to investigate how the system composition will be affected of such a requirement. This level of negative emissions are reasonable due to the fact that the system is modelled at year 2050 together with the fact that scaling up the capacity of NETs takes time. In addition, characteristics for thermal generation such as start-up time, start-up costs and minimum load level are also accounted for in the model. The model also uses perfect foresight.

Both the HT liquid solvent system and the LT solid sorbent system will be included in the model to investigate how they interact with the energy system. As previously mentioned, in literature it is most common for the HT liquid solvent system to have both an electric and thermal energy demand. The thermal energy demand is usually supplied through NG combustion. This alternative will be investigated but it will also be investigated how the energy system composition is affected if NG is substituted with biogas. Moreover, a fully electrified system of the HT liquid solvent system will also be approached using an EAF to supply the thermal energy demand. Moreover, the LT solid sorbent system requires both thermal and electric energy. To supply the thermal energy, literature often mentions installation of renewable energy generation in connection to the DAC plant, for example concentrated solar power. To use waste heat from industry or thermal generation plants is also a common strategy to reduce the total cost of the LT solid sorbent system. However, since available thermal generation is projected to decline in the future and be rather limited by 2050 [9], waste heat will not be considered to be an option in this work. Instead, a fully electrified LT solid sorbent system will be considered using heat pumps (HP) to provide for the thermal energy demand. A Coefficient of Performance (COP) of three will be used for the HP [29].

3.2.1 Model scenarios

Three scenarios for each region will be considered. First, a scenario where both BECCS and DACCS are allowed to act as negative emission providers, this scenario will be referred to as *Base*. Both the HT liquid solvent system, using NG or biomass, a fully electrified HT system and a fully electrified LT solid sorbent system will be allowed in this scenario. In the second scenario, only BECCS will be allowed to supply the system with negative emissions, the scenario will be referred to as *noDACCS*. In the third and final scenario, a sensitivity analysis regarding the biomass price will be performed. In the first two scenarios, *Base* and *noDACCS*, a biomass price of 30 €/MWh is used, while a low biomass price of 20 €/MWh will be used in the sensitivity analysis. In this scenario, both BECCS and all four versions of DACCS are allowed to provide the system with negative emissions, and the scenario will be referred to as *Low Biomass Price*.

3.3 Central concepts

Two central concepts, Levelised Cost of Capture (LCOC) and Levelised Cost of Electricity (LCOE) will be described in the following section.

3.3.1 Levelised Cost of Capture

The LCOC is the cost for capturing one ton of CO_2 and includes costs for investment, operation and maintenance, fuel, transportation and storage costs. The LCOC is calculated according to Equation 4.11 [20].

$$\text{LCOC} = \frac{\text{CAPEX} \cdot \text{CRF}}{\text{FLh}} + \text{OPEX}_{fix} + \text{OPEX}_{var} + \text{C}_{Fuel} + \text{C}_{Transportation} + \text{C}_{Storage} \tag{3.1}$$

where CAPEX is the Captal Expenditures, FLh is the full load hours of the technology, OPEX_{var} and OPEX_{fix} is the variable and fixed operating expenditures, C_{fuel} is the fuel costs, $\text{C}_{Transportation}$ is the transportation cost and $\text{C}_{Storage}$ is the cost for storing CO_2. CRF is the capital recovery factor and is calculated according to Equation 3.2.

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.2}$$

and i is the interest rate which is set to 5% in this work and n is the lifetime of the technology.

3.3.2 Levelised Cost of Electricity

The LCOE is the cost for producing energy which includes investment costs, operation and maintenance costs and fuel costs for the technology. The LCOE is calculated according to Equation 3.3 [20].

$$\text{LCOE} = \frac{\text{CAPEX} \cdot \text{CRF}}{\text{FLh}} + \text{OPEX}_{var} + \text{C}_{Fuel} \tag{3.3}$$

4
Results

In the following chapter, results from both the literature review and the energy systems modelling will be presented. The results from the literature review includes data collected from multiple studies which are compared and later on the data used as input to the energy systems model are described. The results from the energy systems model will show the annual electricity generation, differences in electricity generation and demand on an hourly basis for each scenario and region. Moreover, the Levelised Cost of Capture and Levelised Cost of Electricity will be presented for each scenario.

4.1 Literature review

The following chapter will present the data regarding DACCS gathered from the literature review. An extensive techno-economic literature review was recently performed by Fasihi et al. [20] in 2019. The data presented in this chapter will partly be based on the findings in the report of Fasihi et al. Due to the extensive research in that paper, the parameters used as input to the energy systems modelling, both economical and technical, will be according to that article. However, other data will also be presented in the following chapter in order to make a comparison and to evaluate the range available. Data was collected from studies ranging from year 2006 to 2019. The data has been ordered from most recently published to the oldest. Some studies had a purely technical approach while other had a techno-economical perspective. Some studies have included the full scope ranging from capture to compression and storage of CO_2, while others have focused their studies up until and including the desorption of the sorbent. The studies differ regarding efficiencies used for system components, some use 100% efficiency while other use a lower efficiency down to approximately 70% for certain components to receive results for worst case scenarios.

4.1.1 High Temperature Liquid Solvent

The basic characteristics of each study selected is presented in Table 4.1, together with the final input to the energy systems model presented in bold by Fasihi et al. For all references marked with an R as source, the data is extracted from the article by Fasihi et al., and references marked with an O has data extracted from the original source. For the liquid solvent systems, both Kraft processes and Pellet reactors have been used. Two types of sorbents are commonly used in the literature studied, NaOH and KOH. Concentration of CO_2 in the inlet air varies from 380-500ppm and the fraction of CO_2 captured ranges between 35-75%. The capture rate tends to be higher in more recently conducted studies and lower in earlier studies, which is probably due to technological development and scientific advances.

Table 4.1: High temperature liquid solvent system basic characteristics.

Sorbent	Process	CO_2 conc. inlet	Size of plant	Capture rate	Source	Reference
		ppm	$MtCO_2$/yr	%		
KOH	Pellet	400	1	74.5	O	Keith (2018a)
KOH	Pellet	400	1	74.5	O	Keith (2018b)
NaOH	-	-	-	-	R	Li et al. (2015)
NaOH	-	500	1	-	R	Socolow et al. (2011)
NaOH	-	-	-	-	R	Stolaroff (2008)
NaOH	Kraft	380	-	50	O	Zeman (2007)
NaOH	Kraft	500	0.42	50	O	Baciocchi (2006)
NaOH	Pellet	500	0.42	50	O	Baciocchi (2006)
NaOH	Kraft	Ambient	0.3	35	O	Stolaroff (2006)
NaOH	-	-	0.28	-	R	Keith et al. (2006)
KOH	**-**	**400**	**1**		O	**Fasihi (2019)**

Some technical characteristics for the liquid solvent system is presented in Table 4.2. The characteristics shown is the thermal and electric energy demand, the lifetime of the plant and some cost data.

Table 4.2: High temperature liquid solvent system technical characteristics.

Th. energy	El. energy	Lifetime	CAPEX	OPEX	Reference
kWh_{th}/tCO_2	kWh_{el}/tCO_2	years	€/$tCO_2 \cdot$ yr	%	
1458	366	25	1032	3.7	Keith (2018a)
2447	0	25			Keith (2018b)
-	-	-	-	-	Li et al. (2015)
2250	494	20	1583	4	Socolow et al. (2011)
-	-	-	-	-	Stolaroff (2008)
1420	764	-	-	-	Zeman (2007)
2444	498	-	-	-	Baciocchi (2006)
1677	440	-	-	-	Baciocchi (2006)
4667	541	-	846	2.7	Stolaroff (2006)
-	-	20	-	-	Keith et al. (2006)
0	**1535**	**25**	**815**	**3.7**	**Fasihi (2019)**

How the thermal energy requirements for the HT liquid solvent system in literature varies is shown in Figure 4.1a.

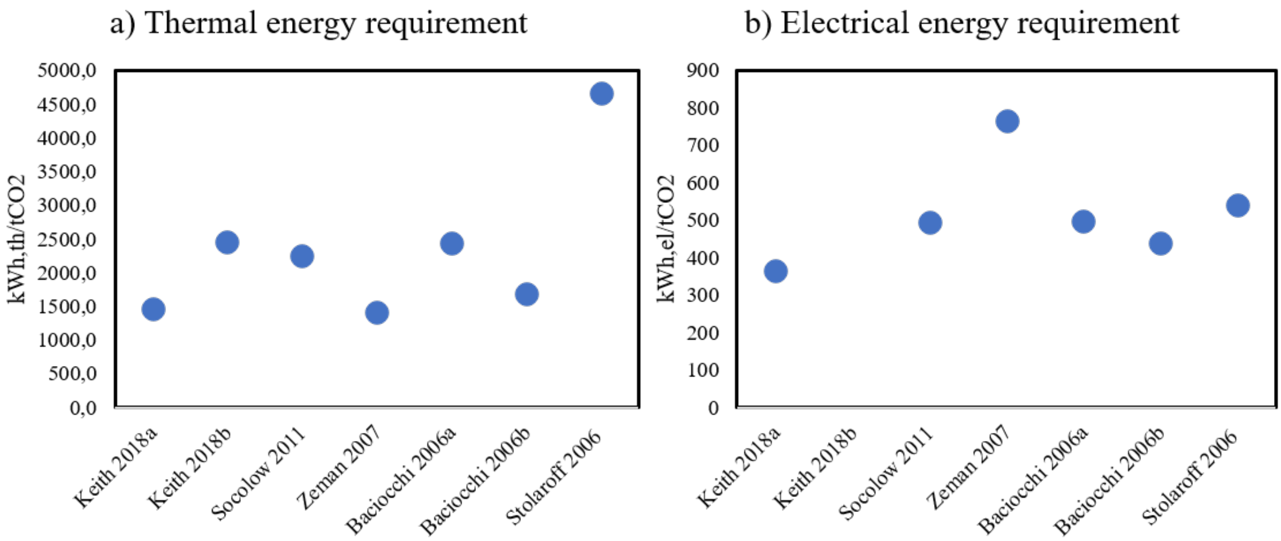

Figure 4.1: Thermal and electrical energy requirements for the HT liquid solvent system.

The variation of electrical energy requirements for the HT liquid solvent system is shown in Figure 4.1b. The electrical energy requirement is in general lower than the thermal energy requirement for the HT liquid solvent system. This is due to the large thermal energy requirement during the desorption process where a temperature of approximately 900 °C is needed.

4.1.2 Low Temperature Solid Sorbent

Desorption methods commonly used in literature for the LT solid sorbent system are either a temperature swing, or a combination of temperature and vacuum swing. The desorption temperature varies between 80 and 480°C. The concentration of CO_2 in the inlet air is kept at 400 ppm for all studies and the fraction captured ranges from 65 to 75%. Basic characteristics for the systems are shown in Table 4.3.

Table 4.3: Low temperature solid sorbent system basic characteristics.

Desorption method	Desorption temp.	CO_2 conc. inlet	Size of plant	Source	Reference
	°C	ppm	$MtCO_2$/yr		
TVSA	80-120	-	-	O	Beuttler (2019)
-	85-95	400	1	R	Ping et al. (2018) (Global Thermostat)
TVPSA	95	400	0.0000493	O	Vogel (2017); Climeworks (2018)
-	135-480	400	-	R	Sinha (2017)
TVSA	80-100	-	0.0036	O	Roestenberg (2015); Antecy (2018)
-	150-250	400	-	R	Derevschikov (2014)
-	110	400	-	R	Kulkarni&Sholl (2012)
-	**100**	**400**	**0.36**	**O**	**Fasihi (2019)**

Technical characteristics for the LT solid sorbent system is presented in Table 4.4. Parameters presented are cycle time, thermal and electrical energy demand, the lifetime of the plant and cost data. The sorbent lifetime varies drastically in literature, from 0.25 years to 5 years. However, most studies assumes a sorbent lifetime of 0.5 years.

Table 4.4: Low temperature solid sorbent system basic characteristics.

Cycle time	Thermal energy	Electrical energy	Plant lifetime	CAPEX	OPEX	Reference
min	kWh_{th}/tCO_2	kWh_{el}/tCO_2	years	€/$tCO_2 \cdot$ yr	%	
-	1600	400	-		-	Beuttler (2019)
-	1170-1410	150-260	-	1220	-	Ping et al. (2018) (Global Thermostat)
288	1500-2000	200-300	20	730	-	Vogel (2017); Climeworks (2018)
-	-	-	-	-	-	Sinha (2017)
-	2083	694	25	-	-	Roestenberg (2015); Antecy (2018)
-	-	-	-	-	-	Derevschikov (2014)
-	-	-	-	-	-	Kulkarni&Sholl (2012)
-	**1750**	**250**	**20**	**730**	**4**	**Fasihi (2019)**

The cost estimates vary greatly in literature. This is partly due to that different studies have had different focus, where some reports have included parameters into the costs which have been excluded in other works, such as transportation cost for CO_2. Some costs are also fairly uncertain, for example the CAPEX for the contactor which differs with design choice. Another cost parameter that varies in literature is the cost for solid adsorbents, the LT solid sorbent system is still under much development and a lot of research is still going into finding a cost effective solid sorbent. However, the economical data used as input for the energy systems model are still according to Fasihi et al.

The variation of the thermal energy demand in literature for the LT solid sorbent system is shown in Figure 4.2a. Literature that provided intervals for the thermal energy requirements is shown with a minimum and maximum value while single value data is shown for the other. The variation of electrical energy demand in the studies presented for the LT solid sorbent system is shown in Figure 4.2b.

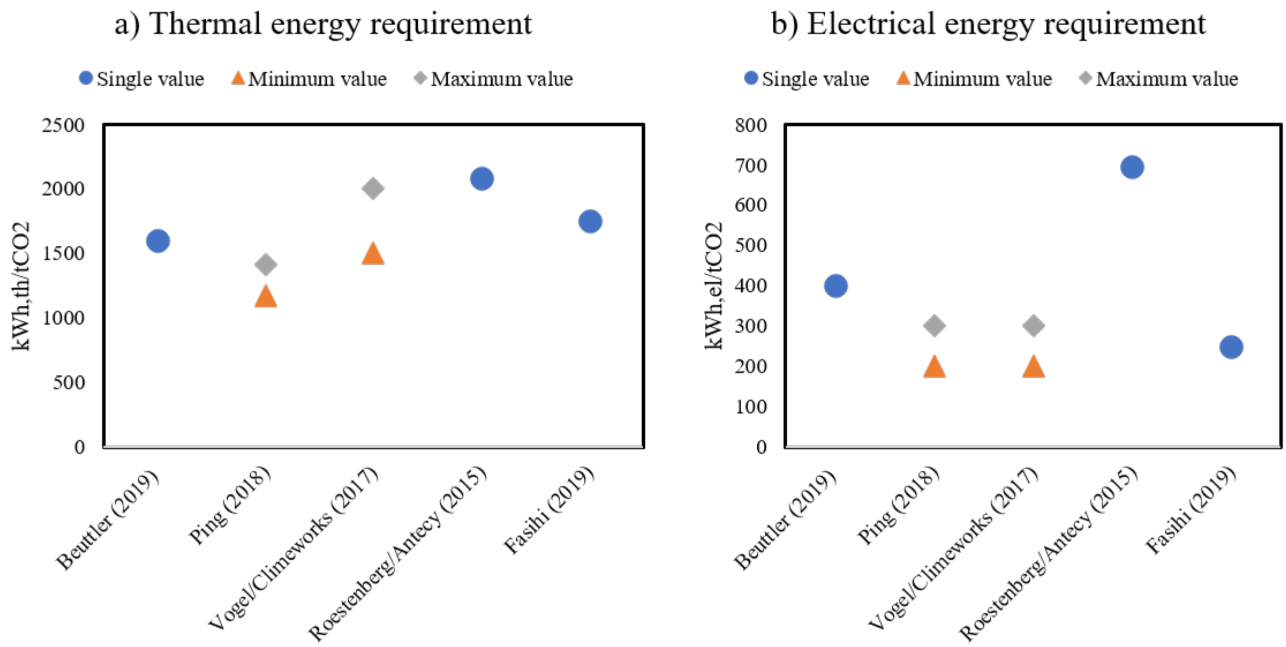

Figure 4.2: Thermal and electrical energy requirements for HT liquid solvent system.

4.1.3 Future cost reductions

Large cost reductions could be made for both the HT and LT system through further research into the contactor designs. For the HT liquid solvent system, the packing material used in the contactor as well as the properties of the solvent could have a large impact on the total cost of the contactor. For the LT solid sorbent technology, developing a low-cost sorbent could have great impact on the costs of DACCS. By extending the durability and the lifetime of the sorbent, costs could decrease. Moreover, lowering the energy requirements needed for both technologies to capture and release CO_2 could also aid in lowering the total cost [18]. However, there is large uncertainty regarding the size of future cost reductions for both technologies.

4.2 Energy systems modelling

Figure 4.3 shows the annual electricity generation for the three scenarios Base, noDACCS and a scenario with a low biomass price in the three regions ES3, IE and HU. In the Base case, both DACCS and BECCS are allowed in the system. However, DACCS outcompetes BECCS at the price level fed into the model for all regions. Moreover, the LT solid sorbent system is consistently outcompeting the HT liquid solvent system for all scenarios and regions. Therefore the HT liquid solvent system is never showing in the results but whenever DACCS is mentioned, this refers to the LT solid sorbent system since this is the only DACCS technology entering the system. In the noDACCS scenario, BECCS is working as the only provider of negative emissions, but the technology is simultaneously producing electricity to the grid. Moreover, in the Base case when DACCS is acting as the only NET, the annual electricity generation increases compared to the case where the negative emissions are provided by BECCS in the noDACCS scenario. This is due to the fact that DACCS consumes electricity and acts as a new load to the system, resulting in a higher total energy demand. Moreover, a larger share of fossil fuels in the form of NG is used in the Base case compared to the noDACCS scenario, and yet, the goal of 10% negative emissions compared

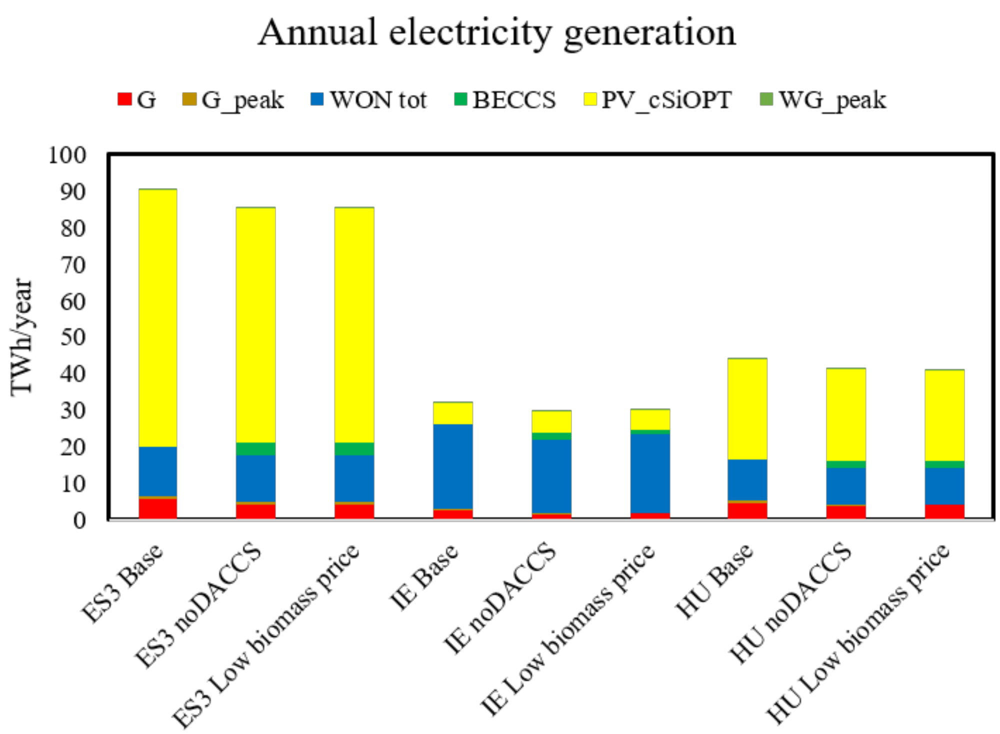

Figure 4.3: Annual electricity generation for the three scenarios in the three regions ES3, IE and HU.

to 1990 levels are provided to a lower total system cost. In the scenario with low biomass price, both DACCS and BECCS are allowed to be used as NETs in the system. The low biomass price allows BECCS to outcompete DACCS in ES3 and HU while the technologies co-exist in IE.

4.2.1 Spain (ES3)

Figure 4.4a shows the electricity generation of ES3 during two weeks in the Base case.

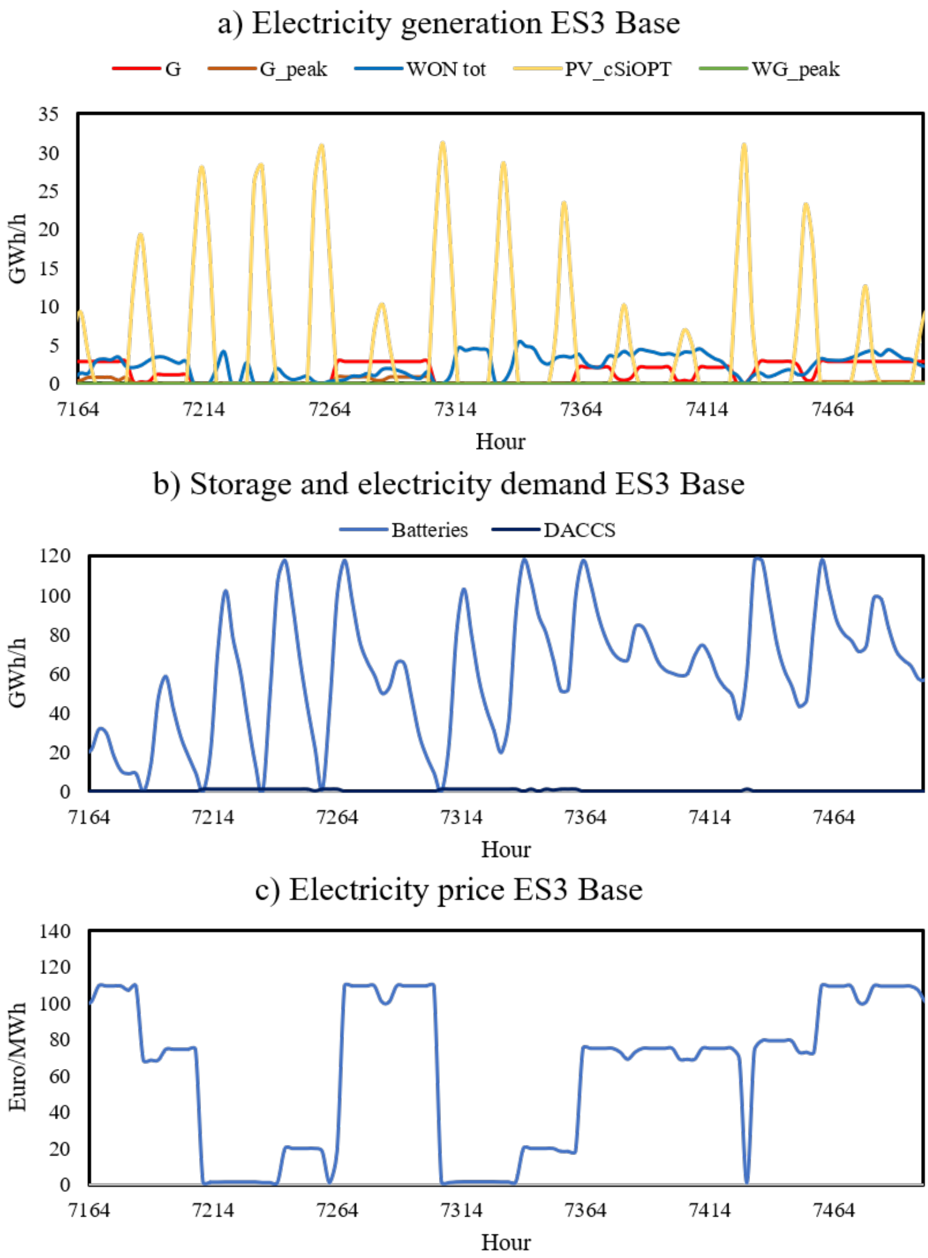

Figure 4.4: (**a**) Electricity generation; (**b**) energy storage; and (**c**) electricity price for region ES3 with DACCS in the system in weeks 42 and 43 of year 2050.

DACCS is outcompeting BECCS, meaning that DACCS is providing all of the negative emissions in the system. During some hours, solar PV and wind power, together with the energy storage in the batteries, seen in Figure 4.4b, provide for the entire energy demand. At other hours, peak generation using NG is used to fulfil the whole demand. The energy demand for DACCS is showed in Figure 4.4b. The capacity of DACCS is minimal compared to the output of the batteries. Figure 4.4c shows the variation of the electricity price. The electricity price is low during hours with large electricity production from variable renewable generation and high when complementary and peak generation is needed. DACCS is responding to low electricity prices, which can be seen in Figure 4.4b and 4.4c. With a low electricity price that results from electricity generation from variable renewables, DACCS is affordable to be run.

Figure 4.5a shows the electricity generation of ES3 during two weeks in the scenario noDACCS where BECCS are providing the negative emissions. Wind power produces more electricity in the first week than in the second week, while the amplitude of the diurnal peaks of solar PV vary during the whole period. However, more electricity is produced by variable renewable power generation in the first week than in the second week. During hours with low production from variable renewable generation, energy stored in the batteries are used in firsthand, and then BECCS and NG in second hand to supply for the entire electricity demand. Figure 4.5b shows that the storage level in the batteries is highly dependent on the diurnal peaks of solar PV. In the first week with large diurnal peaks of solar PV, the energy storage is being filled during peak hours in energy supply and emptied when there is no solar production at night. Figure 4.5c shows the variation of the electricity price. Moreover, in the Low biomass price scenario, BECCS outcompetes DACCS. The results are similar to the noDACCS scenario and are therefore not showed in any graph.

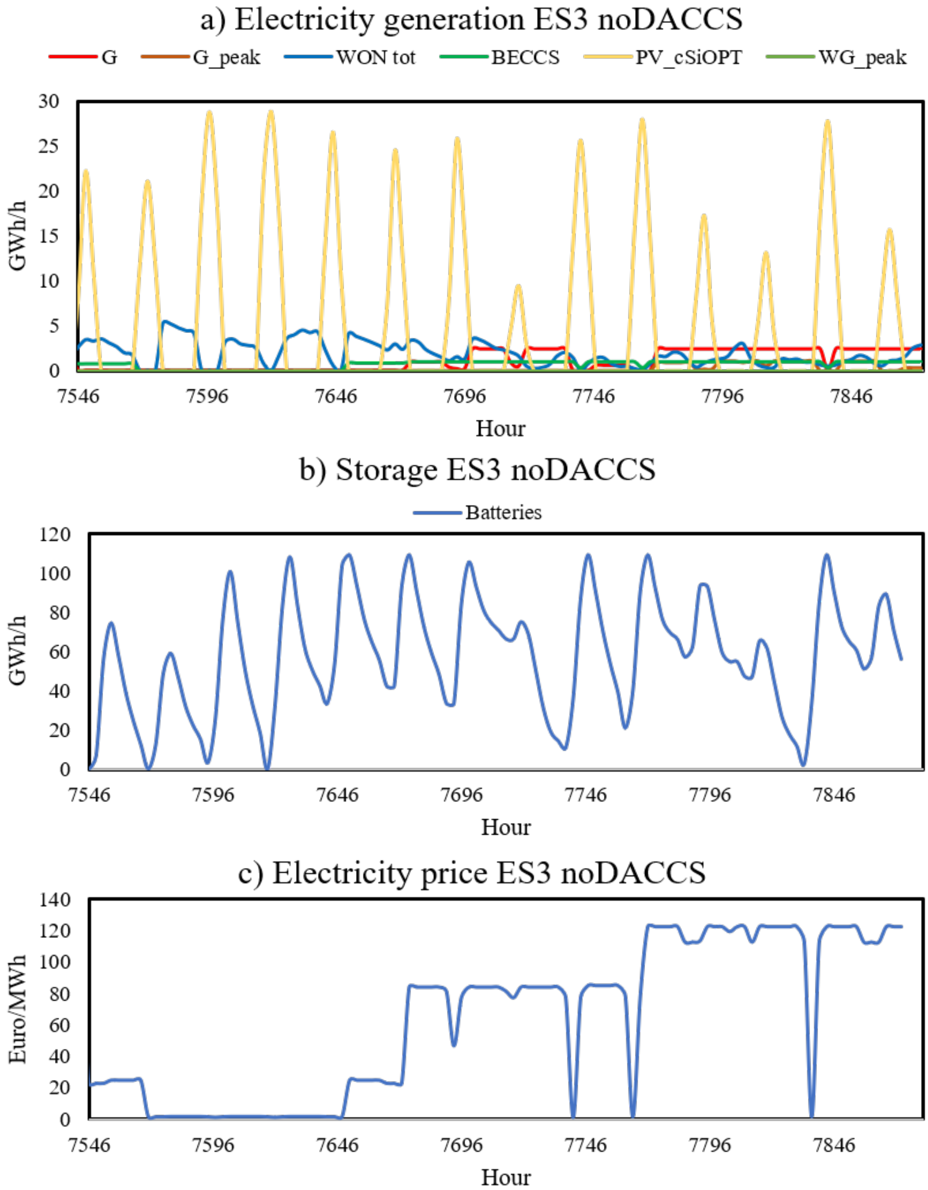

Figure 4.5: (**a**) Electricity generation; (**b**) energy storage; and (**c**) electricity price for region ES3 with no DACCS in the system in weeks 45 and 46 of year 2050.

4.2.2 Ireland (IE)

Figure 4.6a and 4.7a shows two weeks of electricity generation in region IE in the scenarios Base and noDACCS. Generation from wind and solar power is larger in the first week than in the second week in both scenarios. Therefore, variable electricity generation from

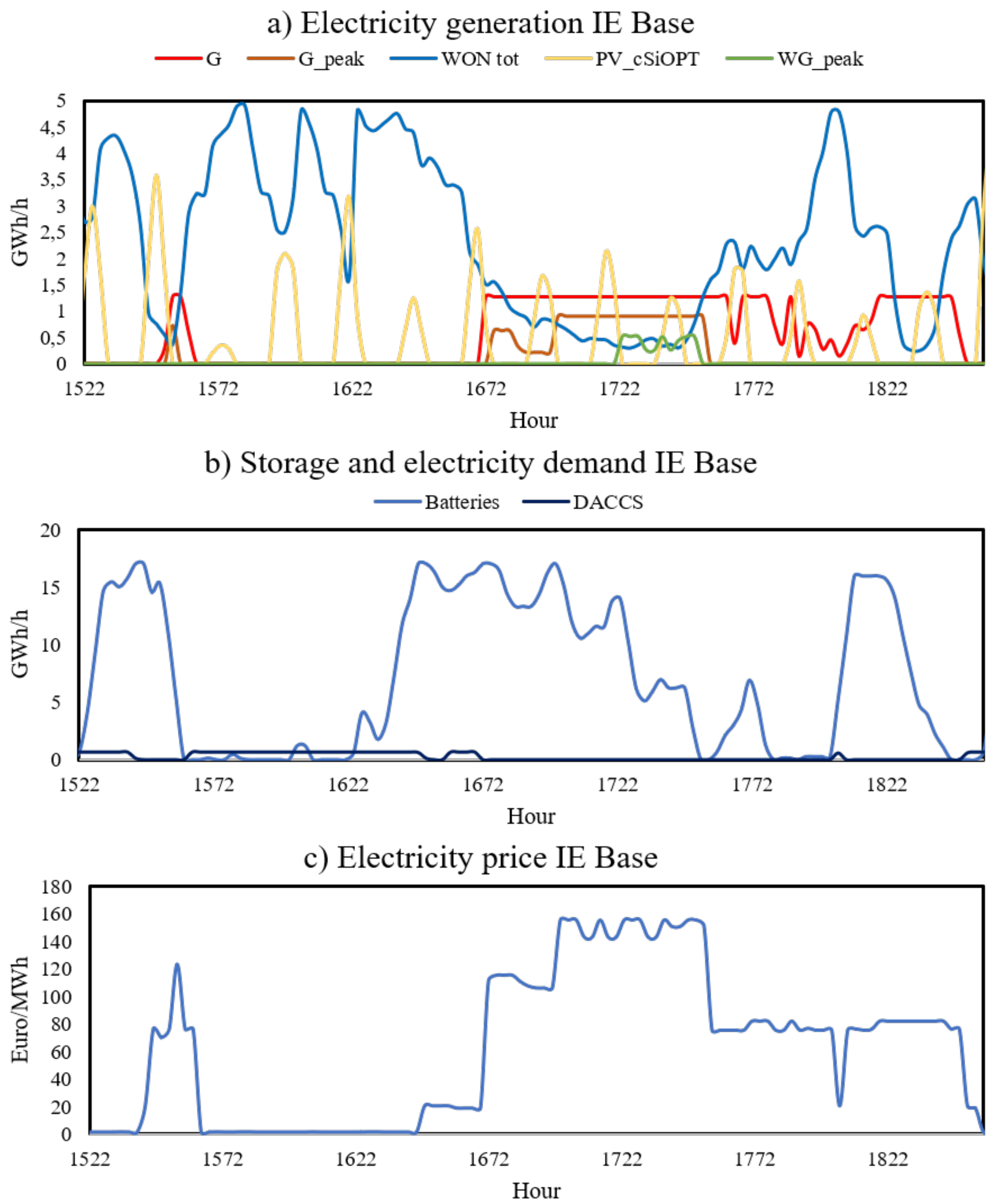

Figure 4.6: (**a**) Electricity generation; (**b**) energy storage; and (**c**) electricity price for region IE with DACCS in the system in weeks 9 and 10 of year 2050.

wind and solar together with the energy storage in batteries covers the whole energy demand in the first week. In the second week, generation from variable renewables decreased and electricity generation from BECCS and NG is needed to supply for the whole energy demand in the noDACCS scenario, while only NG is used for the Base case. Figure 4.6b and 4.7b shows the energy storage in batteries. Due to the IE system being wind dominated, the pattern of the energy storage level is more irregular in the IE case compared to the ES3 system which is solar dominated. Moreover, the installed battery capacity relative to the amount of installed capacity of electricity generation, is much larger for IE than ES3. Implying that a wind dominated system requires larger amounts of battery capacity to be able to handle the fluctuations.

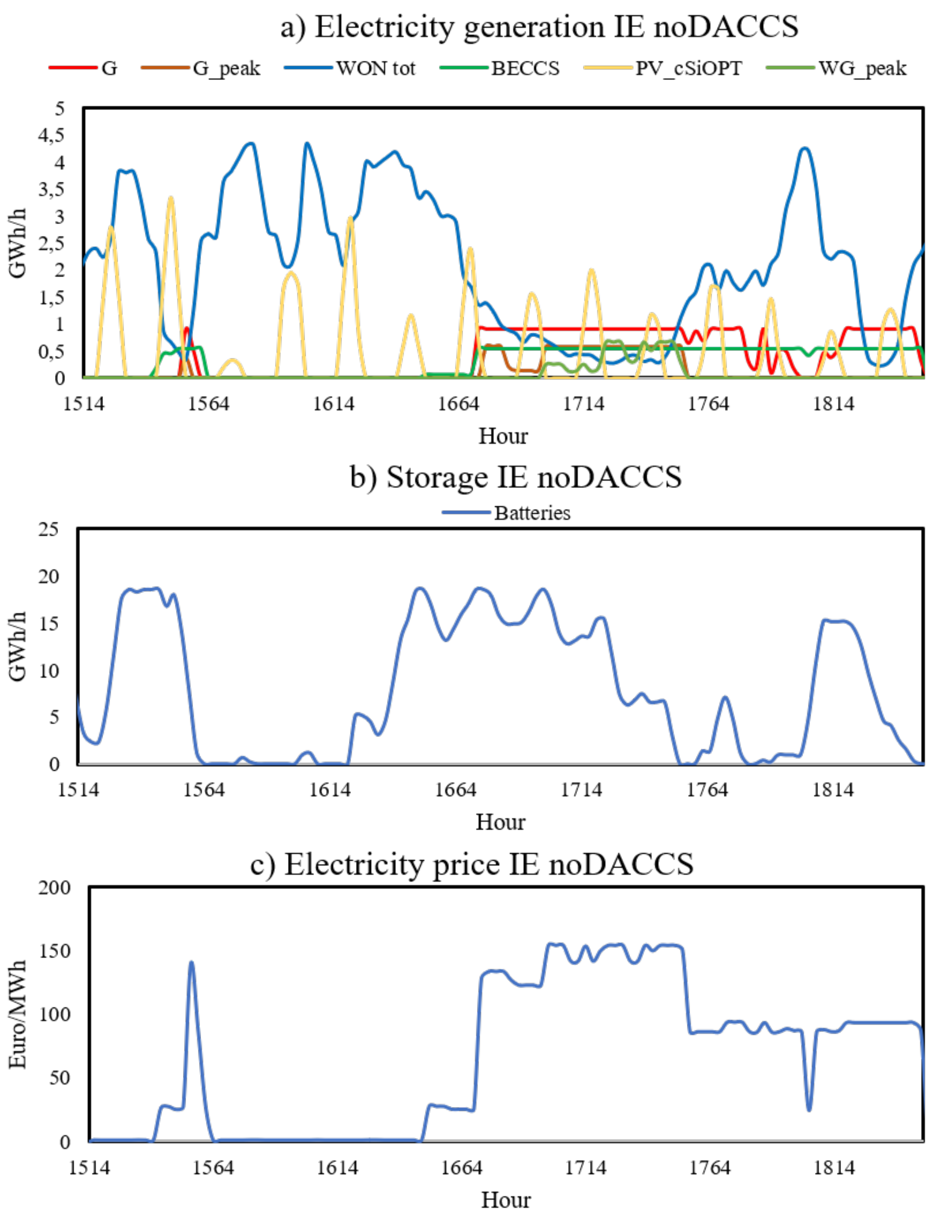

Figure 4.7: (**a**) Electricity generation; (**b**) energy storage; and (**c**) electricity price for region IE with no DACCS in the system in weeks 9 and 10 of year 2050.

Figure 4.6c and 4.7c shows the electricity price. The electricity price increases rapidly when BECCS and fossil fuels are used for electricity generation. Figure 4.6b also shows the electricity demand of DACCS. The electricity demand of DACCS coincides with low electricity prices, seen in Figure 4.6c.

Figure 4.8a shows the electricity generation during two weeks in region IE in the scenario with a low biomass price. In this scenario, BECCS and DACCS co-exist and both provide the system with negative emissions. The electricity production from intermittent generation varies throughout the period. Variable generation together with the energy storage in batteries, seen in Figure 4.8b, satisfies the whole demand at times. At other hours, peak generation is needed. The interaction between BECCS and DACCS can be seen in Figure 4.8a and b, where they never run simultaneously. This is due to that DACCS is responsive

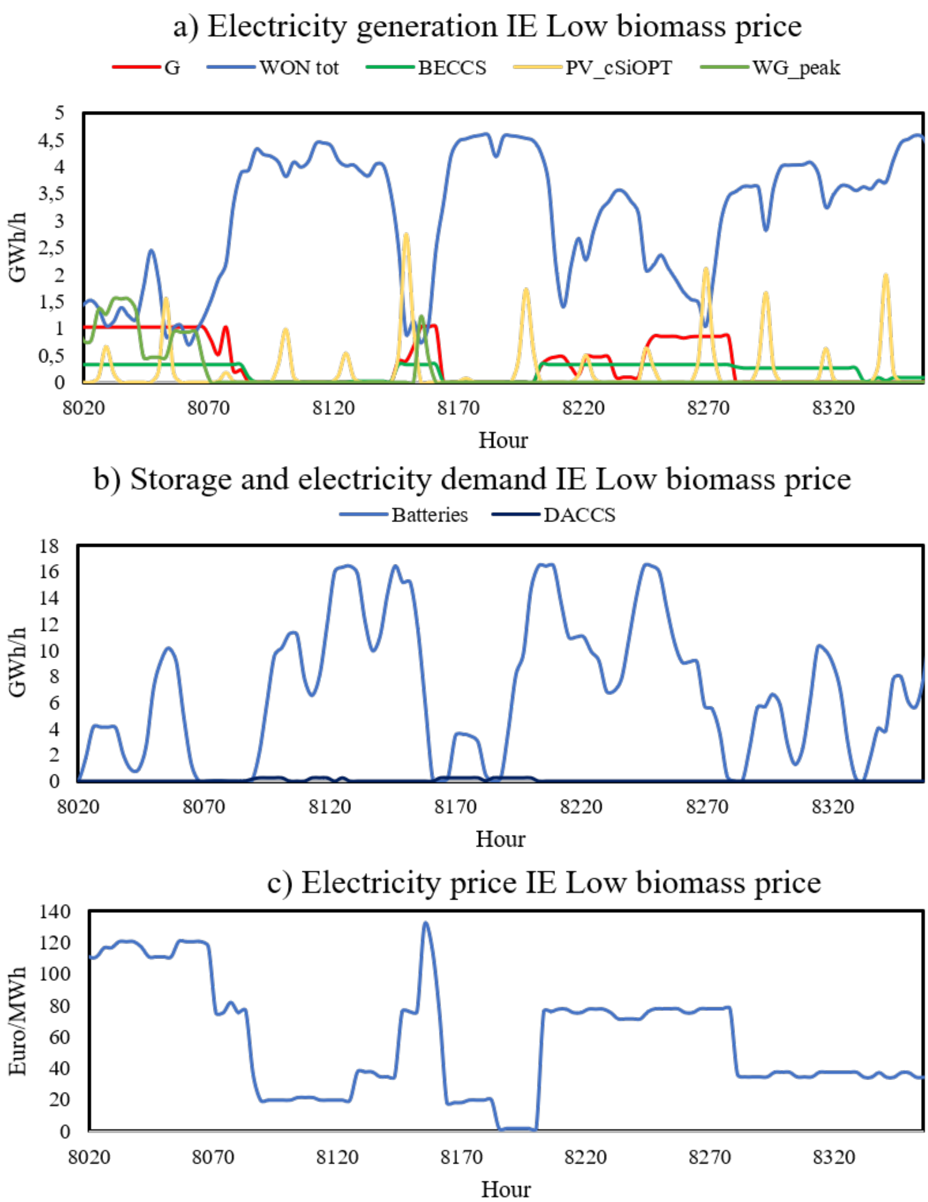

Figure 4.8: (**a**) Electricity generation; (**b**) energy storage; and (**c**) electricity price for region IE scenario Low biomass price in weeks 48 and 49 of year 2050.

to low electricity prices while BECCS increases the electricity price, see 4.8c.

4.2.3 Hungary (HU)

Figure 4.9a and 4.10a show the electricity generation in region HU in scenarios Base and noDACCS. The first week shows poorer conditions for wind and solar generation, meaning that electricity generation from BECCS and NG is needed to supply for the whole demand. In the second week, enough electricity is generated from variable renewables to

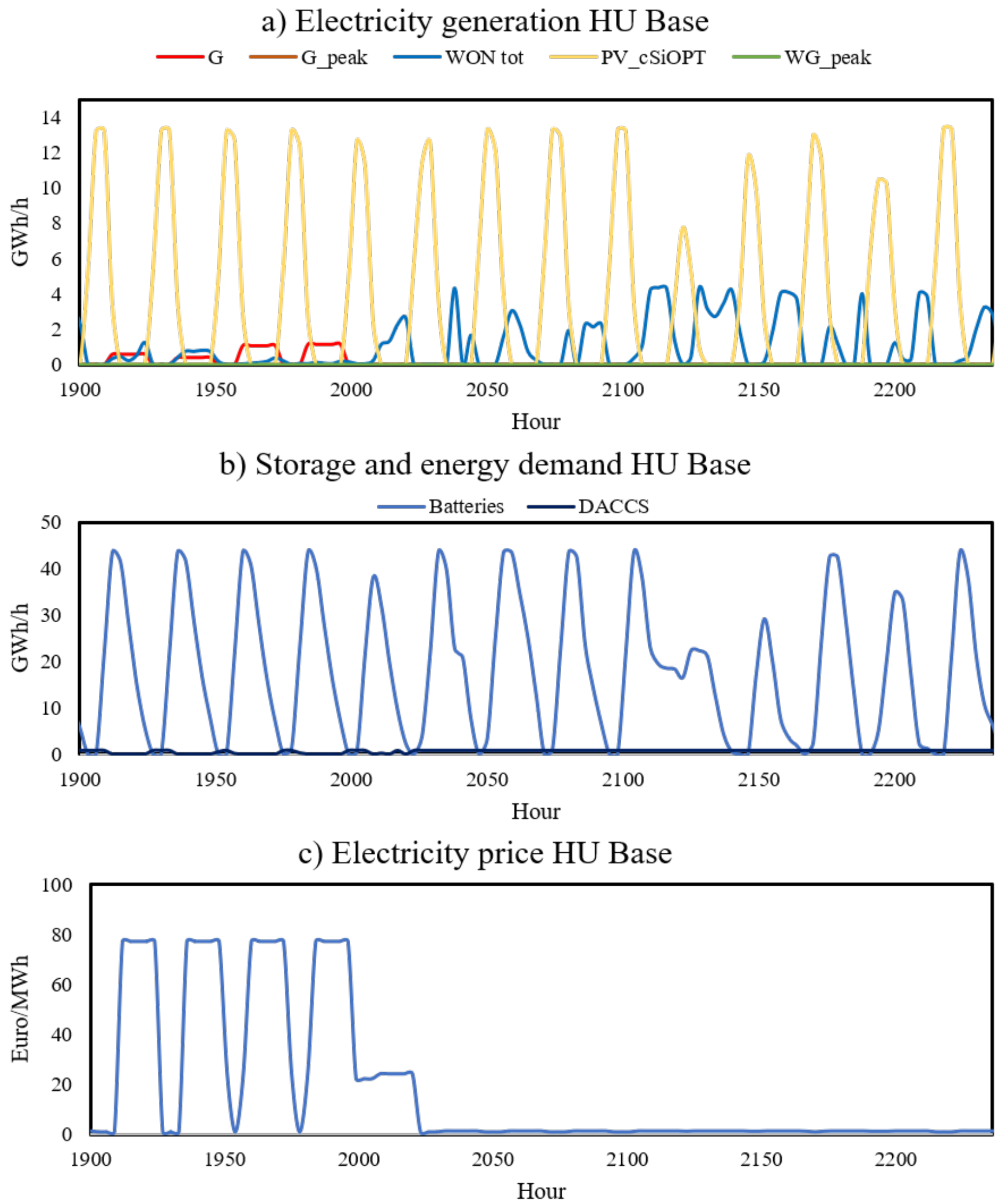

Figure 4.9: (**a**) Electricity generation; (**b**) energy storage; and (**c**) electricity price for region HU with DACCS in the system in weeks 11 and 12 of year 2050.

meet the demand. Figure 4.9b and 4.10b shows the level of the energy storage in the batteries. The level is highly dependent of the diurnal peaks of solar PV. Figure 4.9c and 4.10c shows the electricity price. The price is low during hours with high electricity production from intermittent generation and otherwise high. During the second week of the period the electricity price is consistently very low for both scenarios. In Figure 4.9c the energy demand of DACCS is shown. The demand coincides with low electricity price, making DACCS run continuously during the second week of the period when the electricity price is consistently low. Moreover, in the Low biomass price scenario, BECCS

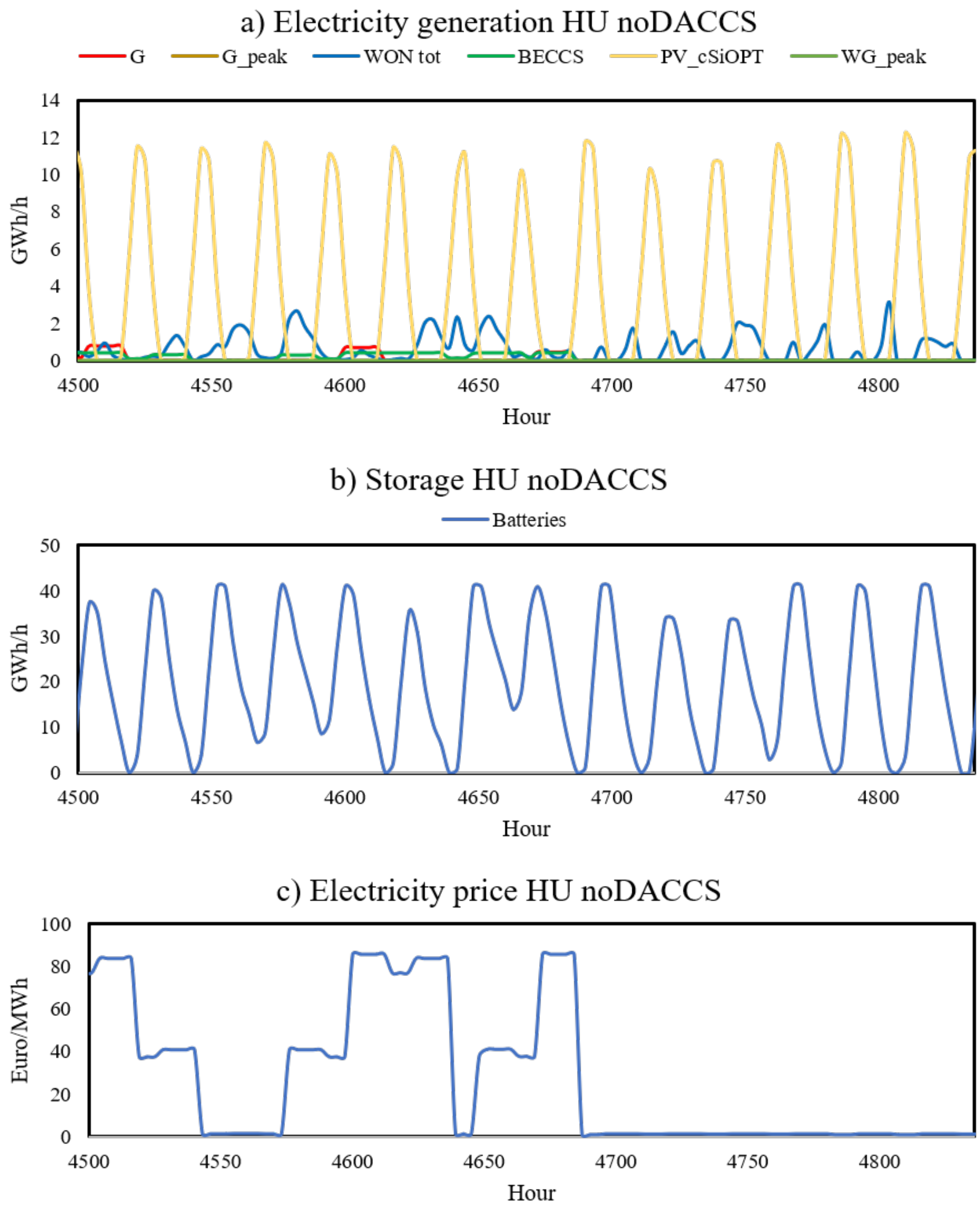

Figure 4.10: (**a**) Electricity generation; (**b**) energy storage; and (**c**) electricity price for region HU with no DACCS in the system in weeks 26 and 27 of year 2050.

outcompetes DACCS, making the results similar to the noDACCS scenario. Furthermore, the electricity prices for HU shown in Figure 4.9 and 4.10 is lower than the electricity prices for ES3 and IE.

4.2.4 Levelised Cost of Capture

To be able to compare how much it costs to capture one ton of CO_2 for each technology and region the Levelised Cost of Capture (LCOC) is calculated. By using a technology with the lowest LCOC, the total cost for capturing CO_2 could be minimised. Figure 4.11 shows the LCOC for BECCS and DACCS for the different scenarios and regions. The LCOC for DACCS is consistently larger than the LCOC for BECCS, meaning that it is more expensive to capture one ton of CO_2 using DACCS than using BECCS. The two largest costs for DACCS are the CAPEX and fixed OPEX. Moreover, the largest costs for BECCS are the fuel cost and CAPEX. The electricity produced by BECCS is sold to the electricity grid, resulting in an income for BECCS which is subtracted from the other costs resulting in a total LCOC. The cost for transporting and storing CO_2 varies between the regions. The cost for storage is cheapest in HU and most expensive in IE, while the cost for transport is cheapest in ES3 and most expensive in HU.

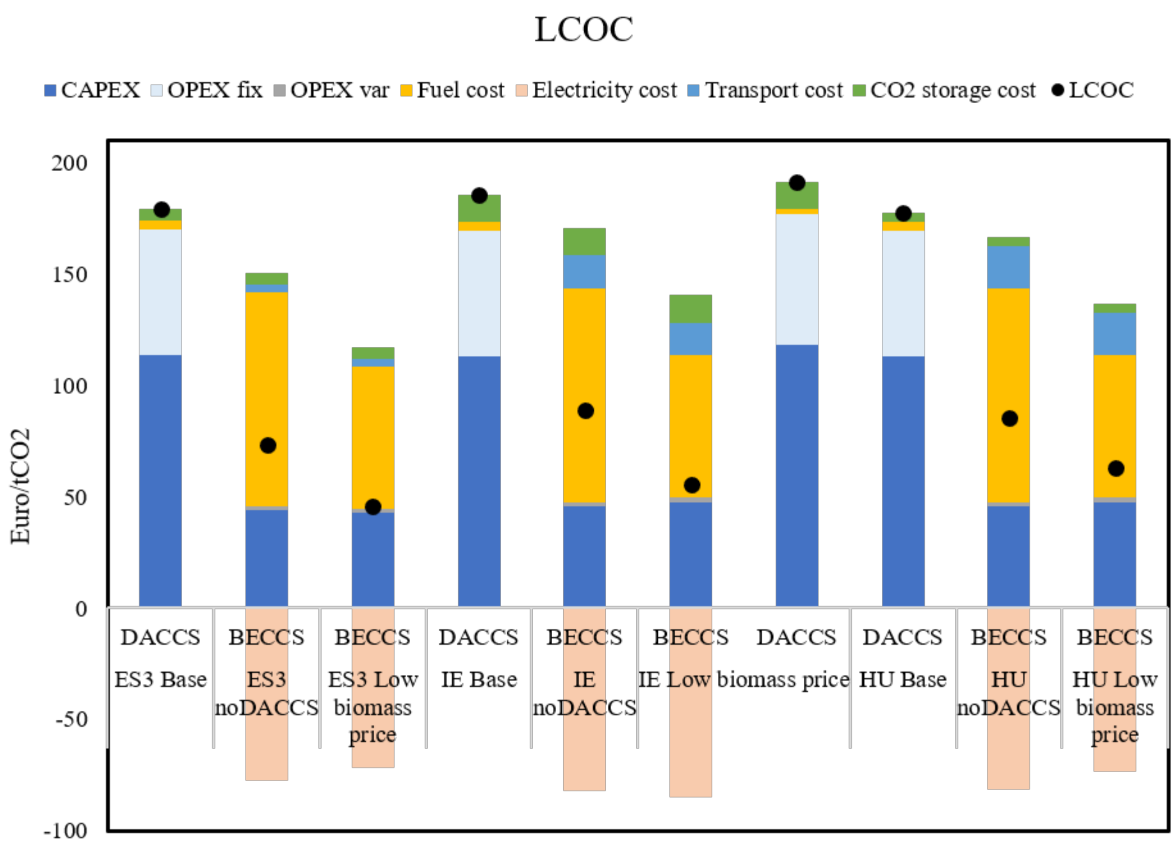

Figure 4.11: LCOC calculated for DACCS and BECCS for the scenarios in ES3, IE and HU.

4.2.5 Levelised Cost of Electricity

One of the main functions of the system studied is electricity production. Since the modelling aims to minimise the total system cost, it is of interest to investigate how expensive the electricity produced by different technologies in the system is. Therefore, the Levelised Cost of Electricity (LCOE) of Wind power, Solar PV and BECCS is calculated. Figure 4.12 shows the LCOE for wind power, solar PV and BECCS for the different scenarios and regions. The LCOE has been divided into its components CAPEX, fixed OPEX (OPEX fix), variable OPEX (OPEX var), fuel cost and CO_2 price. For BECCS it is assumed that the scenario specific cost for CO_2 is received as an income, therefore shown as negative in the graph. The largest cost for both wind power and solar PV is the fixed OPEX, which is dependent on the load factor of the technology. A higher load factor results in a lower fixed OPEX. This fact can be seen for wind power in the Irish case where the load factor is higher, resulting in a decreased fixed OPEX and therefore also a reduced total LCOE. The LCOE for BECCS is consistently larger than that for wind power and solar PV for all ES3 scenarios. However, for the scenarios where BECCS is present in IE, the LCOE for BECCS is lower than the LCOE for solar PV, the same applies for the HU scenario with low biomass price. The fuel cost has the largest impact on the LCOE for BECCS, resulting in that the LCOE decreases significantly in the scenario with low biomass price.

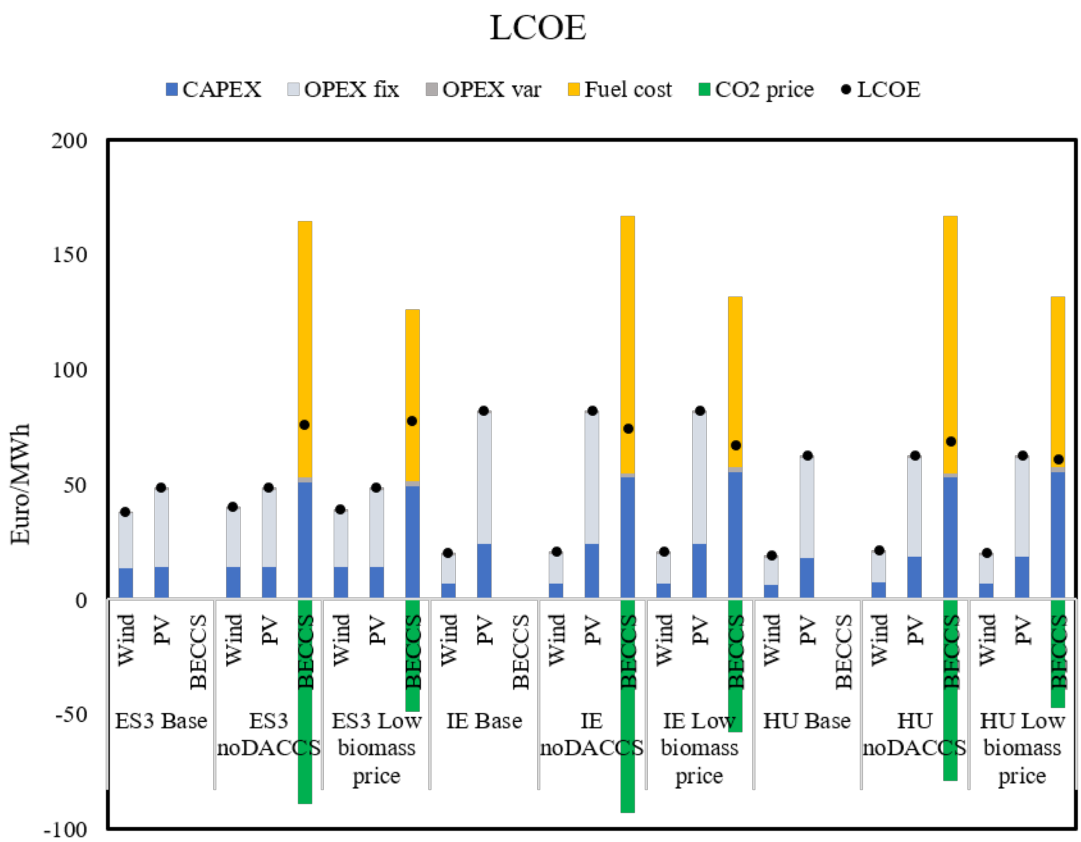

Figure 4.12: LCOE calculated for onshore wind power, solar PV and BECCS for the scenarios in ES3, IE and HU.

5
Discussion

When both DACCS and BECCS are available as NETs, BECCS gets out-competed in almost all scenarios, leaving DACCS to be the only source for negative emissions in the system. This occurs even though BECCS has a lower LCOC than DACCS for all scenarios and regions, suggesting that it is cheaper to capture CO_2 using BECCS than DACCS. The system modelled has two major functions, producing electricity and providing negative emissions. There are only two technologies that can provide negative emissions, BECCS and DACCS, while there are several technologies that can provide for electricity generation. However, BECCS can provide for both system functions, negative emissions and electricity generation and are required to provide both functions simultaneously. The LCOE for wind power and solar power are for all cases in ES3 lower than the LCOE for BECCS. Therefore, it is cheaper from a system perspective to produce electricity using wind and solar power than by using BECCS in ES3. BECCS are providing the system with both electricity generation and negative emissions simultaneously, thus providing the system with cheap negative emissions but expensive electricity. Therefore, an opportunity cost on electricity is created when using BECCS, which production is concentrated to hours when the electricity price is high, meaning little wind and solar electricity generation. Electricity production and negative emissions are both vital system functions. However, electricity is the main product in the model by quantity, therefore, the price of electricity will dominate the decision of which technologies will be used for electricity production and which technology will be used for negative emissions. Thus, DACCS is preferred over BECCS to provide the system with negative emissions, despite its higher LCOC, since it enables cheaper electricity production from wind and solar power which points to that the standard definition of LCOC can be misleading from a system point of view. This results in a lower total system cost, since electricity production is less expensive which is the main product by quantity, and more expensive negative emissions which are a small cost compared to the total system cost.

Moreover, apart from the costs, it should be noted that DACCS has a higher flexibility compared to BECCS. This will also be an important factor for which technology is used as provider for negative emissions. An other factor that could be important for the final outcome is the difference in start up costs for the technologies. Furthermore, when comparing the different geographical system contexts between the regions, it can be seen that the LCOE in IE is lower for BECCS than for solar PV but larger than the LCOE for wind power. This is due to the system being wind dominated. Thus, when DACCS is allowed to act as negative emission provider BECCS gets outcompeted since the total system cost will be minimised by allowing for cheaper electricity production from wind power and more expensive negative emissions from DACCS. However, in the case when inducing a low biomass price, DACCS and BECCS co-exist in the system. This is due to that the LCOC is further decreased for BECCS due to the low price on fuel while the LCOC for DACCS is actually slightly increased. By shifting the price point for the LCOC for both BECCS and DACCS, a situation occur where it is equally cost minimising to have both technologies working as negative emission providers in the system at once.

Furthermore, the definition and the implication of the LCOC used in this report should be discussed. By using the current definition of the LCOC, a technology with a more expensive capturing cost is preferred over a technology with a cheaper capturing cost since this results in the lowest total system cost. The LCOC gets reduced significantly for BECCS due to that the technology produces electricity during high price hours. The income from selling this expensive electricity to the grid results in a lower LCOC. On the other hand, DACCS do not generate any income and therefore never gets a reduced LCOC. Even though it is more expensive to capture CO_2 using DACCS according to this definition, the total system cost is lower than by using BECCS as a negative emissions provider. By redefining the LCOC to not include the income from selling high price electricity to the grid, another outcome might appear showing that DACCS is the cheapest technology for capturing CO_2. By adding the LCOE for a pure biomass driven alternative it would be possible to give a more fair comparison between negative emissions provided by DACCS or by a biomass alternative since the income from electricity would not be a factor altering the results. However, further research is needed within this matter.

In this work, the amount of negative emissions provided by the system is scaled to the emission levels in the electricity sector in the year 1990 for each region. Emissions from the electricity sector is a quite significant share of the total emissions from each region. However, to be able to compensate for emissions from other sectors, such as transportation, agriculture and industry within the region, the quantity of negative emissions needed would increase significantly. Thereby, the cost for negative emissions might have a larger impact on the total system cost. The total system cost might therefore be lower using BECCS to provide for negative emissions which has a lower LCOC. However, since biomass is a scarce resource, the biomass availability will be of great importance when large quantities of negative emissions are needed using BECCS. Low biomass availability might increase the biomass price, thereby increasing the total fuel cost for BECCS, resulting in a higher LCOE. With a higher LCOE, the balance between total capture and electricity cost might shift towards DACCS being used as negative emission provider.

Both the annual electricity production and the share of electricity produced by combustion of NG is larger in the Base case than the other scenarios for all regions. The increased annual electricity production is due to the new load from DACCS that has been added to the system. Due to that BECCS is outcompeted from the system, NG is used as balancing power during hours with low variable electricity production. In case noDACCS and Low biomass price, both BECCS and NG are used to supply peak power to the system. However, in the Base case, BECCS is not available, meaning that NG is used to supply for the service in this system.

Moreover, the electricity price shown in the results for the three regions seems lower for

HU than for ES3 and IE. However, this is not the case when comparing the electricity prices over the whole year. Due to that ES3 and IE have better conditions for wind and solar insolation compared to HU, these regions have a varying electricity price throughout the year. The large share of intermittent generation used results in a lot of hours with very low electricity prices. However, during hours when balancing power is used, the electricity price instead gets increased compared to the HU case. Although, the average electricity price over the year is still lower for ES3 and IE compared to HU due to the high use of variable renewables in the system.

5.1 Assumptions

The flexibility of the HT liquid solvent system was assumed to be similar to other thermal generation technologies due to the fact that the technology is based on conventional CCS technology. On the other hand, the LT solid sorbent system, being fully electrical, is assumed to be very flexible. The large difference in flexibility between the technologies, together with the price difference, are the reasons for why the LT system outcompetes the HT system. No literature was found during the literature review on the flexibility of the HT system. The technology could therefore be more or less flexible than assumed in this work. However, even if the technology was fully flexible, the HT system would most likely still be outcompeted by the LT system due to its higher overall cost. The costs for DACCS are assumed to be according to the data given by the paper written by Fasihi et al. at year 2020 level, even though the paper also is presenting cost levels at year 2050 at which year the energy systems modelling in this work is performed. However, further sensitivity analysis on cost components of DACCS and the different energy demands of the technologies should be performed.

5.2 Technology comparison

Starting with a comparison between the HT liquid solvent system and the LT solid sorbent system, the LT system consistently outcompetes the HT liquid solvent system. There are several reasons for this outcome, firstly, the LCOC for the HT system is larger. This is due to a higher investment cost as well as higher running costs such as fuel cost. Moreover, all emissions created using NG as fuel are not captured, meaning that the total capture rate of the system is being reduced and less emissions are being captured per unit of NG used. However, if the NG is replaced by biogas, this problem is non-existent, resulting in that more negative emissions are created. Moreover, the LT solid sorbent system are using electricity to run. The emissions created by the electricity generation supplying the LT system with electricity are not included in its LCOC. Furthermore, as seen in the results, the LT technology solely runs at hours when variable renewables and the battery energy storage are supplying for the whole demand. This means that no direct emissions are being emitted from the electricity generation supplying the technology.

Moving to a comparison between DACCS and BECCS, the placement of DACCS is very flexible since it does not require a geographical location close to the emission source. This implies that the system can be placed close to a suitable storage location, thereby, reducing the need for long way transportation of the CO_2. Therefore, the cost for transportation is assumed to be zero for DACCS in this work. Moreover, due to the flexibility of the placement of DACCS, the technology can be placed on degraded land. BECCS on the other hand, is highly dependent on availability of biomass and arable land for biomass production.

5.3 Future work

For future research on this topic, the energy systems modelling should include NETs to compensate for more sectors than just the energy sector, as the work in this work has focused on. This would enable predictions on how much NET capacity is needed to achieve global climate targets. The quantity of negative emissions would also be increased if global emissions reduce slower than predicted or if climate sensitivity is larger than expected. Thus, it is of importance to investigate how the amount of negative emissions needed will affect the system composition. Moreover, allowing trading between regions would mean that better resource availability from example wind could be obtained, by introducing a geographical smoothening effect. Furthermore, it would be of interest to explore a system where historical emissions and already installed energy generation for each region are accounted for. This sort of work could highlight how to make a just global energy transition.

The energy demand of DACCS coincides with low electricity prices. Large scale electrification is expected within many sectors. Therefore, industries with a flexible energy demand might start to compete for low price electricity. Low price hours might therefore be reduced, meaning that the running costs for DACCS will grow. Thus, the LCOC for DACCS will increase.

The flexibility of both HT and LT system DACCS should be further explored to not eliminate any technology from the system composition. The LT solid sorbent system was assumed to be fully flexible being a fully electrified system, meaning that it could start up instantaneously. However, if the LT solid sorbent system were found to be less flexible, the competition between the LT and HT system might differ. Although, the result that the LT system out-competes the HT system would most likely still be the case, since the LT system is less expensive. Moreover, cost components and energy demands for the technologies should be further investigated.

6
Conclusion

To meet the Paris Agreement and limit global warming to 1.5°C, NETs are needed. This work investigates the interaction of NETs with an intermittent electricity system with the aim to provide negative emissions. To conclude, DACCS and BECCS are competing as negative emission providers in the electricity system. For all investigated scenarios, DACCS has a higher cost for capturing CO_2 than BECCS. However, the system modeled has two functions, to provide negative emissions and electricity, where electricity is the main product by quantity. Due to that intermittent electricity generation can provide the system with cheaper electricity than BECCS, DACCS is preferred as negative emission provider even though it has a higher cost for capturing CO_2. Although, the definition of LCOC needs further investigation in whether the definition itself has an effect that results of the LCOC for the technologies and that the definition used in this work migh not be compatible with a system context perspective.

Moreover, DACCS reacts to low electricity prices and therefore, the technology runs during hours where the whole energy demand is supplied by intermittent electricity generation and batteries. Thereby, DACCS is not generating any direct emissions through its energy use since the energy is supplied from carbon neutral sources. However, BECCS could be used to aid the electricity system when generation from variable renewables is low. This system function is instead met by peak-generation, such as combustion of NG which could be replaced by biogas, in a system where DACCS is used as negative emission provider.

Different system compositions occur for the three different regions investigated. For ES3 and HU, DACCS outcompetes BECCS at a normal biomass price, while the opposite occur with a low biomass price. However, when implementing a low biomass price for IE, BECCS and DACCS co-exist in the system, but with different system functions. Moreover, the LT solid sorbent system out-competes the HT liquid solvent system in all scenarios and regions due to its lower investment cost and operational expenses and higher flexibility.

Bibliography

[1] Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, et al. Intergovernmental Panel on Climate Change-Global Warming of 1.5 Degrees Celcius; 2018.

[2] Global Energy & CO2 Status Report 2019 – Analysis - IEA;. Available from: https://www.iea.org/reports/global-energy-and-co2-status-report-2019.

[3] Archer D. Global Warming: Understanding the Forecast; 2012.

[4] The Paris Agreement | UNFCCC;. Available from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

[5] Paris Agreement - Status of Ratification | UNFCCC;. Available from: https://unfccc.int/process/the-paris-agreement/status-of-ratification.

[6] Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, Amann T, et al.. Negative emissions - Part 2: Costs, potentials and side effects. Institute of Physics Publishing; 2018.

[7] Rogelj J, McCollum DL, Reisinger A, Meinshausen M, Riahi K. Probabilistic cost estimates for climate change mitigation. Nature. 2013;493(7430):79–83.

[8] Fuss S, Canadell JG, Peters GP, Tavoni M, Andrew RM, Ciais P, et al. COMMENTARY: Betting on negative emissions. Nature Climate Change. 2014;4(10):850–853.

[9] World Energy Outlook 2018 – Analysis - IEA;. Available from: https://www.iea.org/reports/world-energy-outlook-2018.

[10] Rogelj J, Shindell D, Jiang K, Fifita S. IPCC 2018, cap2. Global warming of 15°C An IPCC Special Report []. 2018;p. 2.

[11] Johansson V, Lehtveer M, Göransson L. Biomass in the electricity system: A complement to variable renewables or a source of negative emissions? Energy. 2019;168:532–541.

[12] Azarabadi H, Lackner KS. A sorbent-focused techno-economic analysis of direct air capture. Applied Energy. 2019;250(May):959–975. Available from: https://doi.org/10.1016/j.apenergy.2019.04.012.

[13] Jones CD, Ciais P, Davis SJ, Friedlingstein P, Gasser T, Peters GP, et al. Simulating the Earth system response to negative emissions. Environmental Research Letters. 2016;11(9).

[14] Baciocchi R, Storti G, Mazzotti M. Process design and energy requirements for the capture of carbon dioxide from air. Chemical Engineering and Processing: Process Intensification. 2006;45(12):1047–1058.

[15] Realmonte G, Drouet L, Gambhir A, Glynn J, Hawkes A, Köberle AC, et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nature Communications. 2019;10(1):1–12. Available from: http://dx.doi.org/10.1038/s41467-019-10842-5.

[16] Viebahn P, Scholz A, Zelt O. German Energy Research Program — Results of a Multi-Dimensional Analysis. 2019;.

[17] Socolow R, Desmond M, Aines R, Blackstock J, Bolland O, Kaarsberg T, et al. Direct Air Capture of CO2 with Chemicals A Technology Assessment for the APS Panel on Public Affairs. Technology. 2011;p. 1–119. Available from: http://www.aps.org/policy/reports/popa-reports/loader.cfm?csModule=security/getfile&PageID=244407.

[18] National Academy of Science. Negative Emissions Technologies and Reliable Sequestration; 2019.

[19] The National Academies of Sciences. Direct Air Capture and Mineral Carbonation Approaches for Carbon Dioxide Removal and Reliable Sequestration. The National Academies Press. 2018;.

[20] Fasihi M, Efimova O, Breyer C. Techno-economic assessment of CO 2 direct air capture plants. Journal of Cleaner Production. 2019;224:957–980.

[21] Martinez Castilla G, Biermann M, Montañés RM, Normann F, Johnsson F. Integrating carbon capture into an industrial combined-heat-and-power plant: performance with hourly and seasonal load changes. International Journal of Greenhouse Gas Control. 2019;82(October 2018):192–203. Available from: https://doi.org/10.1016/j.ijggc.2019.01.015.

[22] Ringrose PS. The CCS hub in Norway: Some insights from 22 years of saline aquifer storage. Energy Procedia. 2018;146:166–172. Available from: https://doi.org/10.1016/j.egypro.2018.07.021.

[23] Broehm M, Strefler J, Bauer N. Techno-Economic Review of Direct Air Capture Systems for Large Scale Mitigation of Atmospheric CO2. SSRN Electronic Journal. 2015;p. 1–28.

[24] Keith DW, Holmes G, St Angelo D, Heidel K. A Process for Capturing CO2 from the Atmosphere. Joule. 2018;2(8):1573–1594. Available from: https://doi.org/10.1016/j.joule.2018.05.006.

[25] Zeman F. Energy and material balance of CO2 capture from ambient air. Environmental Science and Technology. 2007;41(21):7558–7563.

[26] Elfving J, Bajamundi C, Kauppinen J. Characterization and Performance of Direct Air Capture Sorbent. Energy Procedia. 2017;114(November 2016):6087–6101. Available from: http://dx.doi.org/10.1016/j.egypro.2017.03.1746.

[27] Sanz-Pérez ES, Murdock CR, Didas SA, Jones CW. Direct Capture of CO2 from Ambient Air. Chemical Reviews. 2016;116(19):11840–11876.

[28] Santos FM, Gonçalves AL, Pires JCM. Negative emission technologies. Bioenergy with Carbon Capture and Storage: Using Natural Resources for Sustainable Development. 2019;p. 1–13.

[29] Danish Energy Agency. Technology Data: Generation of Electricity and District heating. 2020;6:1–11. Available from: https://ens.dk/sites/ens.dk/

files/Statistik/technology_data_catalogue_for_el_and_dh_-_0009.pdf.

A
Appendix 1

To implement DACCS into the energy systems model alterations were made to the model. A new set under technologies was added with the three types of DAC technologies added to the model, the fully electrified LT solid sorbent system (DACCSLTel), the fully electrified HT liquid solvent system (DACCSHTel) and the HT system using biogas as fuel (DACCSWG), while the HT system using NG was excluded in the final analysis. Input data about the three DACCS technologies researched in this work that were added and later read into the model were:

- Investment cost
- Start-up time
- Start-up costs
- Technology lifetime
- Operation and maintenance cost
- Minimum load

Moreover, equations in the energy systems model were changed in order to incorporate DACCS. In the load balance of the system the electricity demand of the three DACCS technologies have been added. Furthermore, the net amount of CO_2 emitted should be less than the cap. Since DACCS is generating negative emissions, the amount of emissions produced by the system can be larger. The amount of negative emissions produced has therefore been added to CO_2 balance equation. Finally, in order to calculate the total system cost the costs associated with CCS, the storage cost and transportation cost, is calculated. Since it is assumed that DACCS can be located at the site of the storage the transportation cost of CO_2 using DACCS technologies has been neglected. Therefore, only the storage cost has been added for these technologies.

To be able to alter the equations described above and normalise the values to one ton of CO_2 captured, two important parameters, η_{el} and $_{tech}$, has been established for each DACCS technology. η_{el} is used in order to scale the amount of negative emissions retrieved to the amount of fuel input. This parameter is normalised to 1 t_{CO2} captured.
On the other hand $_{tech}$ is used to describe how much emissions each technology have removed per unit of fuel input. This parameter has been calculated according to Equation A.1 and has the unit tCO_2/MWh_{input}.

$$\mathrm{em}_{tech} = \frac{\text{Net negative emissions}[\mathrm{t}_{CO2captured}]}{\text{Yearly fuel input}[\mathrm{MWh}_{fuel,input}]} \tag{A.1}$$