LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Energy Systems
Master's Programme in Sustainable Technology and Business
Department of Energy Technology

Master's Thesis

Daniel Salas Zavala

CO_2 REDUCTION POTENTIAL OF RENEWABLE SYNTHETIC NATURAL GAS PRODUCTION USING POWER-TO-GAS TECHNOLOGIES. A CASE STUDY FOR SCOTLAND.

Examiners: Professor, D.Sc. (Tech) Risto Soukka

Assistant Professor, Ph. D. (Tech) Ville Uusitalo

ABSTRACT

Lappeenranta University of Technology

LUT School of Energy Systems

Degree Programme in Energy Technology

Daniel Salas Zavala

CO_2 reduction potential of renewable synthetic natural gas production using Power-to-Gas technologies. A case study for Scotland

Master´s Thesis

2018

73 pages, 27 figures, 9 equations, 10 tables

Examiners: Professor, D.SC. (Tech) Risto Soukka

Assistant Professor, Ph. D. (Tech) Ville Uusitalo

Keywords: Power-to-Gas, SNG, methane, life cycle assessment, electrolysis, methanation, Scotland, surplus renewable electricity, hydrogen.

The purpose of this thesis work is to conduct a Life Cycle Assessment (LCA) regarding the potential for reduction of CO_2 emissions from production of Synthetic Natural Gas (SNG) with Power-to-Gas (PtG) technology utilizing surplus renewable electricity generated from wind in application for a proposed general study case based on two local authorities located in the North-East of the Scottish coastline: Aberdeen City and Aberdeenshire. All these done using Life Cycle Assessment (LCA) methodology performed with statistical, reliable data from year 2015 for modeling the required inputs, outputs, material flows, and energy balances of the system, using LCA-GaBi 6.0 software. The interpretation of the results was performed based on the environmental impact category of Global Warming Potential (GWP) for 100 years. The results conclude that the PtG concept holds the potential to play a key role in the overall reduction of CO_2 for the conducted study, under the conditions assumed for the analysis on the selected location. Showing that the highest reduction potential of overall GWP was achievable through the up-scaled scenario proposed for 2030. When

assuming a substantial increase of available surplus renewable electricity from offshore wind and implementing a PtG system with the benefit of direct utilization of CO_2 from the CCS facility located at Peterhead, available in the proximity. The results concluded that the highest GWP reduction potential was achieved for the Scenario 2, when the case of the PtG for 2030 is available, yielding in -2.1745 $kg_{CO2\text{-}eq}$. for the 2 714 938 MWh (8.42E+09 MJ_{el}) introduced in the system. Therefore, proposing a compelling case for promoting the potential for CO_2 reduction via PtG technology utilization for the North-East of Scotland as a suitable pathway to follow towards achieving the ambitious pursued targets for the quick de-carbonization of the current, and future, Scottish energy system.

ACKNOWLEDGEMENTS

I would like to gratefully acknowledge my supervisors, Professor Risto Soukka and Ville Uusitalo, for their support and guidance throughout my work, particularly during the final stages upon completion.

Special thanks go also for all the friends I had to the opportunity to make, the time to enjoy, and the bliss to learn from and be supported by during this whole process.

Finally, I would like to dedicate this thesis work to my family. For this effort could not have been possible without their unconditional love and support in every step of the way. For always encouraging me to push further my limits and never letting me down. Even in the distance you were always there with me.

Daniel Salas Zavala

May 30th, 2018

NOMENCLATURE

ASBCP	Advanced Solvent Based Capture Process
AEC	Alkaline Electrolysis Cell
CAES	Compressed Air Energy Storage
CH_4	Methane
CH_3OH	Methanol
CO	Carbon monoxide
CO_2	Carbon Dioxide
COP	Conference of Parties
CCU	Carbon Capture and Utilization
CCS	Carbon Capture and Storage
FU	Functional Unit
GaBi	LCA software
GB	Great Britain
H_2	Hydrogen
H_2O	Water
HHV	Higher Heating Value
MEA	Monoethanolamine
MJ	Megajoule
NG	Natural Gas
LCA	Life Cycle Assessment
LVH	Lower Heating Value
O_2	Oxygen

PEM	Proton Exchange Membrane Electrolysis
PHES	Pumped-Hydro Energy Storage
PtG	Power-to-Gas
PtX	Power-to-X
RE	Renewable Electricity
SOEC	Solid Oxide Electrolyte Cell
SNG	Synthetic Natural Gas
UK	United Kingdom
UNFCC	United Nations Framework for Climate Change

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Background

Global warming potential, acidification of the oceans, rise of the sea levels, and depletion of the ozone layer, are just a few of the harmful environmental impacts that are known to be caused by the high levels of greenhouse gas (GHG) emissions released into the atmosphere. Making the energy sector the major contributor to this problem, accounting for approximately 65% of global GHG emissions, specifically due to combustion of fossil fuels, according to figures released by the United States Government´s Environmental Protection Agency (EPA, 2014). Renewable energy production has proven to provide flexibility to the integration of alternatives for energy production, a must towards the de-carbonization of the current and future energy systems, and as a strategic approach towards mitigation of climate change environmental impacts brought by the polluting emissions. Hence, several government incentives and legislations supported by climate change policies have targeted to reduce greenhouse gas emissions throughout the globe, mostly in Europe such as the EU-20-20-20, aiming to reduce 20% of GHG emissions compared to 1990's levels, improve energy efficiency by 20%, and increase 20% of installed capacity for renewable energy production by the year 2020 (Götz, et al., 2015).

These collaborative efforts are undertaken not only within the EU but have become a joint venture to pursue by most of the nations worldwide. As evidently established in the unprecedent achievement of the Paris Agreement, signed by 195 of the assisting country representatives in the Conference of Parties (COP) during its 21st edition of the United Nations Framework for Climate Change (UNFCC) in year 2015. In order to attempt to comply with the three main objectives accorded, regarding to (a) avoid the increase of the global average temperature bellow 2°C compared to pre-industrial levels and pursue efforts to reduce climate change impacts and significant risks by keeping the increase of global temperature in less than 1.5°C above pre-industrial levels; (b) to improve the ability to adapt to negative climate change impacts, lower GHG emissions and foster climate resilience without compromising food production; and (c) to make a consistent financial flow that enables the global lowering of GHG emissions and improve resilience against climate change (United Nations, 2015).

This has lead towards a substantial and rapid increase of renewable energy capacity installation worldwide, particularly within the European Union (EU). According to the statistics released by the International Energy Agency, in 2015 approximately 33.1% of the total installed capacity for all the OECD countries was met by renewables and waste energy. Awarding for a total of 957.3 GW of global installed capacity of renewable energy by 2015, presenting an increase of 31.5GW compared to 2014 and the highest increase was reported for wind and solar PV power (IEA, International Energy Agency, 2017). Some countries, such as Germany, Denmark, Norway, and Scotland, have rapidly increased their renewable energy installed capacity in the recent years, emphasizing on wind and solar power, and even have successfully achieved to cover their entire electricity demand without the need for fossil fuels to a limited extend, thus presenting with statistical excess of electricity production, or surplus electricity, from renewable energy sources (Uusitalo, et al., 2016).

Regardless of however progressive this achieved milestones may root in benefit of the renewable power generation scene, yet several challenges arise from the fluctuance and intermittency characteristics of renewable electricity production. Due to its high dependence on geographical position and changing weather conditions for the required availability of the resource, these aspects have an impact when it comes to supplying reliable baseload power. Therefore, creating considerable needs for bringing flexibility and energy storage for expected recurrent scenarios as to the above mentioned, in order to address the forecasted tendencies towards the enhancing of international energy systems for the procurement of energy security, to reduce the import of energy resources, and subsequently the overall dependency on energy imports (Schiebahn, et al., 2015). Power-to-Gas (PtG) technologies provide with an alternative for the smart and efficient utilization of this surplus electricity. By producing hydrogen through electrolysis with this electricity produced from renewable sources, and the synthetization of carbon dioxide in the methanation process to produce suitable carbon-containing energy carries, as methane. It can also serve as an attractive alternative for the reduction of greenhouse gas emissions and help to reduce the negative environmental impacts associated to their conventional production methods from fossil fuels ((DENA), Deutsche Energie-Agentur GmbH. German Energy Agency, 2015; Spath & Mann, 2004). Hence, supplying a bridging alternative to integrate these valuable synthetic fuels to the energy systems and markets with high commercial demand, by promoting cleaner alternatives for other sectors than energy production, such as transportation, heat,

and building sectors (Uusitalo, et al., 2016). In addition, PtG technologies can assist in coping with the constantly increasing development trends for renewable electricity production, the need for the expansion of the power grids to cope with the constant increase of global population and demographic growth, the requirements for short and long-term energy storage applications, in its multiple forms, and the technological innovations yet required to achieve them (Lehner, et al., 2014).

Interest in the applications of PtG concept for production of synthetic fuels from renewables has been on a rise in the recent years, consequently several papers have been written on the topic, achieving to prove its feasibility and operational viability for small and large-scaled systems (Götz, et al., 2015; Schiebahn, et al., 2015; ENEA Consulting, 2016; Qadrdan, et al., 2015). Subsequently, a few LCA studies from various approaches have been performed on the potential to reduce environmental impacts brought by this technology, proving its substantial potential to do so under certain defined conditions ((Reiter & Lindorfer, 2015; Spath & Mann, 2004; Uusitalo, et al., 2016; Sternberg & Bardow, 2016). However, what these commonly lack is the allocation of the study case to a specific area. Therefore, this is what we propose as a study case for this master's thesis. Performing an LCA on the potential CO_2 reduction narrowed down to two Council areas of the Scottish North-East coastal line: Aberdeen city and Aberdeenshire.

For the purpose of this thesis, and in accordance with the Institute of International and European Affairs in the updated publication *'Brexit: A status Report'* issued on January 2017, the delimited location selected for this study in Scotland, belonging to the United Kingdom (UK), will remain considered as a member state of the EU-28 for all concerning purposes until its predicted official departure from the European Union scheduled for March 29, 2019 (IIEA, The Institute of International and European Affairs, 2017).

1.2 Objectives

Th objective of this thesis is to conduct a Life Cycle Assessment (LCA) using GaBi 6.0 for the modelling, to assess the potential reduction of Global Warming Potential for 100 years (GWP100) of Power-to-Gas (PtG) technologies for a study case narrowed to a delimited location in the North-East of Scotland for three different energy scenarios.

1.3 Structure of the thesis

In the second chapter of this thesis work are reviewed the state-of-the-art technologies involved in a Power-to-Gas (PtG) system, focusing on the description of the main commercially available methods for electrolysis and chemical methanation processes. Chapter three gives a glanced overview of some energy storage technologies and challenges. In chapter four, is introduced an overview of the energy system of the nation in question and gives the description of the narrowed location objective of this study case. Followed by chapter five, were LCA applications for PtG technologies are evaluated using GaBi software for the modelling. Finalizing with interpretation and discussion of the results and conclusions.

2. THE CONCEPT OF POWER-TO-GAS PRODUCTION

In order to address the intermittency brought by the fluctuation of renewable energy sources and the need for further developed energy storage alternatives, the Power-to-Gas (PtG) concept provides with an effective approach to cover these demands via the chemical energy conversion of surplus electrical power into energy carriers as synthetic gaseous fuels such as hydrogen (H_2), oxygen (O_2), Synthetic Natural Gas (SNG) or methane (CH_4), and methanol (CH_3OH), which are of great value for several industries and sectors (Lehner, et al., 2014).

The first step of the process is the introduction of a high direct electrical current into an electrolyzer to split the water (H_2O) molecules to obtain hydrogen (H_2) and oxygen (O_2). Whilst the former can be stored and distributed as a valuable fuel or have multiple alternative purposes, after upgrading into other chemical energy carriers; the latter can be either released into the atmosphere or be stored and distributed to be utilized in the chemical industry, aviation, or metallurgy, just to mention a few possibilities for oxygen utilization. This process is known as electrolysis (Lehner, et al., 2014), and its three most commercially available methods will be discussed further in this Chapter.

The following step in the PtG process is to convert the obtained "green hydrogen" (H_2) into methane (CH_4) in a downstream process by synthetization with carbon dioxide (CO_2). This process is called methanation, and the gas produced in this process is also known as Synthetic Natural Gas (SNG), considered as a synthetic hydrocarbon containing combustion properties almost identical as those of natural gas (NG) currently obtained from fossil fuel sources. With >95% volume of methane of the yielded gas, this provides the suitability for being directly fed into the available infrastructure for conventional natural gas based on equivalence of their respective lower heating values (LHV) (Sternberg & Bardow, 2016).

One of the environmental advantages of this system is the creation of a demand for CO_2 as a raw material for the process, which is vastly abundant in the atmosphere and is known to have become a key factor of significant negative environmental impacts because of the constantly arising levels of polluting emissions released form carbon combustion. CO_2 can be captured from different sources using various methods (Reiter & Lindorfer, 2015). Thus, this alternative approach of synthetization of CO_2 with hydrogen to produce methane (SNG) from renewable electricity, as in PtG systems, is proved to help with the reduction of GHG

emissions. Especially when parred with other energy systems, as it is the case for the combination of an electrolyzer with a biogas plant, allowing to nearly double the methane production due to the utilization of the available carbon dioxide released from the biogas plant for the methanation process. (dena, German Energy Agency, 2015).

The utilization potential of the fuels obtained from PtG systems is expected to play a role of considerable importance in the balance and support of future energy systems by bridging with the required energy storage applications (Ferreroa, et al., 2016). The available markets and infrastructures for valuable energy carriers, such as CH_4 and H_2, will benefit from the integration of PtG systems mainly due to the flexibility brought by the facility of fuel distribution and transportation in the available natural gas (NG) networks. According to literature, natural gas has a composition of 95% methane, and hydrogen can be injected into the network rather in considerably lower concentrations of about 2% due to its high volatility. The whole PtG process has an efficiency rate of 50 to 75% after losses (Lehner, et al., 2014).

Figure 1 illustrates a general schematic representation of the Power-to-Gas system concept and its integration possibilities to power grid and existing transmission networks for the final utilization sectors of the produced fuels.

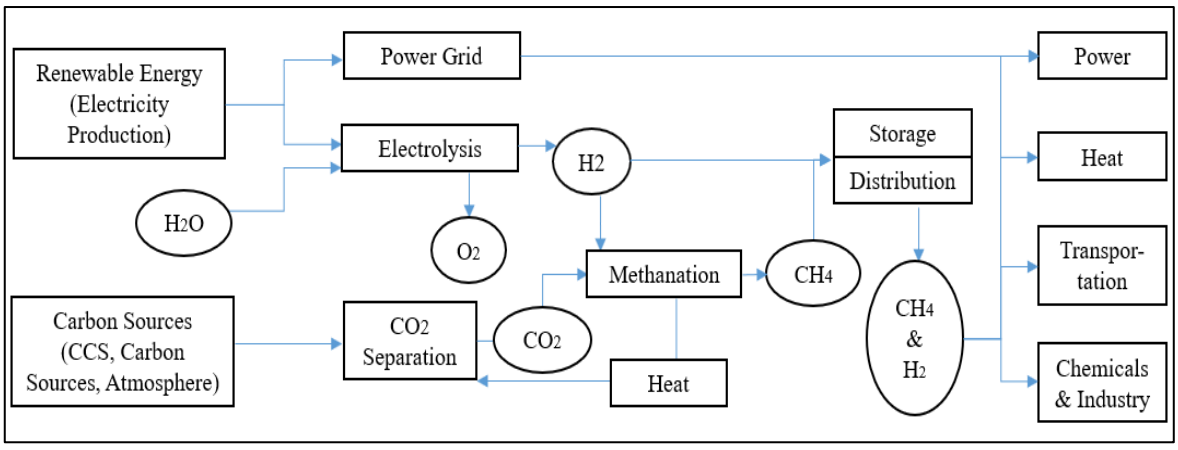

Figure 1. Flow diagram of the PtG system concept.

The production and utilization of new generation bio-fuels, such as Synthetic Natural Gas (SNG) and hydrogen (H_2), are an effective alternative for energy carriers to be produced in an approximately closed loop of the carbon cycle, enabling a viable solution for renewable energy storage (Leonzio, 2016) whilst providing with a feasible possibility for replacing feedstock from fossil fuel sources in the chemical industry, currently obtained predominantly by steam-methane-reforming (SMR) from natural gas (Sternberg & Bardow, 2016).

In Figure 2 is shown a flow diagram illustrating the different processes, resources and material flows involved for two pathways for methane production: Conventional methods against Power-to-SNG.

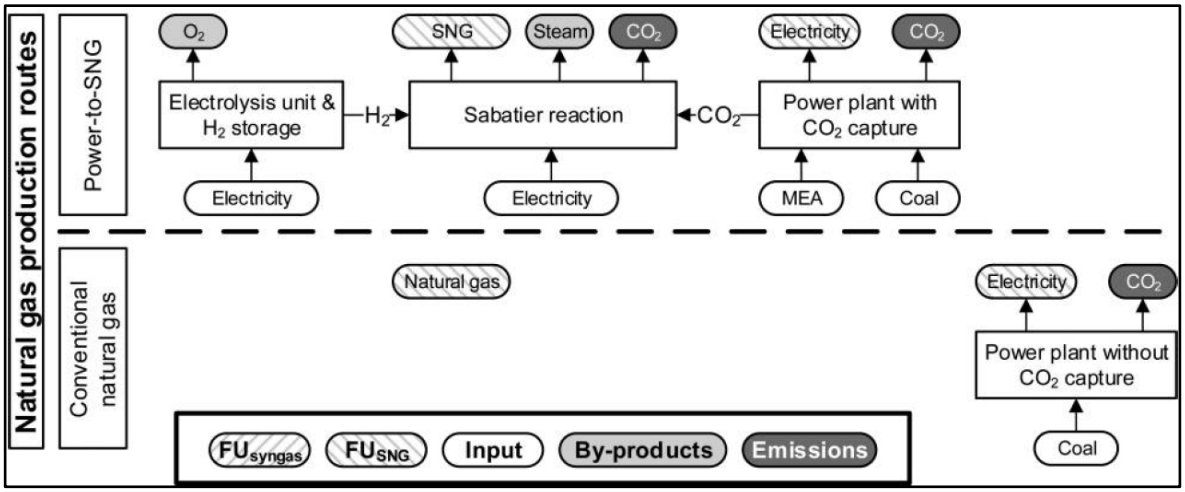

Figure 2. Flow diagrams of Natural Gas production routes. Conventional natural gas VS Power-to-SNG. Source: (Sternberg & Bardow, 2016).

This approach was presented in the comparative Life Cycle Assessment (LCA) study conducted by Sternberg and Bardow in 2016, evaluating the environmental thresholds of three PtX pathways compared to conventional fossil-based production methods to calculate the potential for reduction of environmental impacts of these pathways and to which extend of their respective capacities (Sternberg & Bardow, 2016). The methodology approach to be followed in this thesis work is compatible with the above mentioned.

2.1 Hydrogen production

The production of hydrogen is the first step in the PtG system to convert excess renewable electricity into chemical energy carriers (Uusitalo, et al., 2016). According to the relevant literature reviewed, the global annual demand for hydrogen production in year 2014 was of 55 million metric tonnes for multiple industrial processes and applications (Lehner, et al., 2014). In addition, from Da Rosa we know that the demand for hydrogen fuel, only with the purpose of ammonia production, accounted for 50 million tons in year 2011, and a relatively same amount was required in oil refineries for the purposes of quality improvement for 'heavy' crude oil and for Sulphur removal from fuels such as diesel. Thus, awarding the major consumption rates of this valuable fuel to the chemical industry and the oil & gas industry (Rosa, 2013).

Hydrogen can be produced from various methods. It is currently obtained mostly from Steam Methane Reforming (SMR) of natural gas, the most conventional production method (Decourt, et al., 2014), where steam reacts with the fossil hydrocarbon at high temperatures, in the range of 700°-1100° C, whilst requiring the presence of a catalyst, commonly nickel is used. This yields in the production of hydrogen of low purity and high concentrations of carbonaceous species as carbon monoxide (CO) (Carmo, et al., 2013). Therefore, since SMR is based on fossil fuel sources, its production results in high levels of GHG emissions if compared to alternative production pathways (Uusitalo, et al., 2016).

However, with the rapid development of hydrogen markets, the versatility in use and implementations of this fuel at a commercial scale, as well as the improvement of technical and economic feasibility of diverse technologies for cleaner production methods, the utilization possibilities for hydrogen have widen at a global scale. Given the flexibility of operation of processes such as water electrolysis, known as Power-to-H2 in the Power-to-Gas concept, this technology can help in the integration of the renewable electricity production sector with viable energy storage solutions through the chemical transformation of electricity into valuable energy carriers (Sternberg & Bardow, 2016). Thus, for the purpose of this thesis work, the relevance of the literature reviewed relies on hydrogen generation through water electrolysis technologies.

2.2 Electrolysis

The process of utilizing a direct electric current to separate the components of a water (H_2O) molecule into hydrogen (H2) and oxygen (O_2) in an electrochemical reaction for the purpose of generating hydrogen, since this cannot be found in any of its forms naturally (Barbir, 2004). This process is called electrolysis and is a fundamental process involved in PtG systems, therefore initiating the transformation of electric power into chemical energy carriers (Decourt, et al., 2014).

Water electrolysis technology is considered to have achieved the required levels of maturity and competitiveness for commercial applications with efficiencies >70%, and production ranges high as thousands of m^3/h, down to a few cm^3/min to (Barbir, 2004).

The overall reaction and basic working principle of electrolysis consist in passing a direct current at a thermoneutral voltage of the cell (1.47-1.48 V) thought two electrodes in a reactant medium, called electrolyte. Consequently, after the split of the water molecules, the production of hydrogen occurs at the negative terminal (cathode), while the oxygen is formed at the negative terminal (anode) (Koponen, 2015). Finally, electrolysis holds the need for a continuous supply of water supply due to its consumption during the reaction (Lehner, et al., 2014). The overall electrochemical reaction for water electrolysis goes as followed:

$$H_2O \xrightarrow[Electriciy]{} H_2 + \frac{1}{2}O_2 \qquad \text{(Eq. 1)}$$

As expressed in Equation 1, the electrochemical reaction of electrolysis of water yields in the double the production of hydrogen related to co-produced oxygen per unit of volume (Buttler & Spliethoff, 2017).

The detailed explanation of the complex electrochemistry involved in electrolysis can be obtained by referring to Buttler, Spliethoff, Barbir and Koponen (Buttler & Spliethoff, 2017; Koponen, 2015; Barbir, 2004). From these we gather that, for a general basis, the efficiency of an electrolyzer is determined as expressed in following Equation 2.

$$\eta_{electrolyzer} = \frac{\dot{V}_{H2} * HHV_{H2}}{P_{el}} \qquad \text{(Eq. 2)}$$

Where: $\eta_{electrolyzer}$ is the electrolyzer efficiency, $\dot{V}_{H2}$ corresponds to the volumetric flow of hydrogen in units of Nm^3/h, HHV_{H2} is the higher heating value of hydrogen corresponding to 3.54 kWh/Nm^3, and P_{el} represents the electric power in kW consumed by the electrolyzer.

In actuality, there are main commercially available solutions for hydrogen production through electrolysis: 1. Proton Exchange Membrane Electrolysis (PEMEC), 2. Alkaline Electrolysis Cell (AEC), 3. High temperature electrolysis by Solid Oxide Electrolysis Cells (SOEC). However, other technologies are currently under R&D stages that could potentially increase the efficiency of these process when they reach commercial scale (Buttler & Spliethoff, 2017). These three main technologies will be reviewed in this section.

Nonetheless, the technology holding the greatest relevance to this thesis is PEM electrolysis, since this electrolytic technology, in the latest years, has proven to couple the best for PtG applications in terms of hydrogen production from renewable energy sources, which is the focus of this thesis (Buttler & Spliethoff, 2017).

2.2.1 Alkaline Electrolysis Cell (AEC)

Alkaline electrolysis applications are considered as the most mature technology for electrolysis, since it was discovered in 1789 by Troostwijk and Diemann, these began hydrogen production at large-scale on the megawatt range already from the 20th century and currently holds the highest hydrogen production capacity at global scale (Carmo, et al., 2013).

Alkaline electrolyzers take their name after the alkaline medium, normally a 20-30% aqueous caustic potash solution (KOH), in which the electrodes are immersed with a thin polymeric membrane in-between. The efficiency is slightly higher than compared to other electrolytic technologies since it can reach about 82%. The reactions occurring consist in Equation 3, below, for the Hydrogen evolution Reaction (HER) of the process, whilst Equation 4 represents the Oxygen Evolution Reaction (OER) (Kotowicz, et al., 2016).

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \ (Cathode\ [-]) \qquad \text{(Eq. 3)}$$

$$2OH^- \rightarrow \frac{1}{2}O_2 + 2H_2O + 2e^- \ (Anode\ [+]) \qquad \text{(Eq. 4)}$$

From Figure 3 is appreciated a schematic representation of the basic working principle of an alkaline electrolyzer with the respective reactions at the anode (positive terminal) and at the cathode (negative terminal).

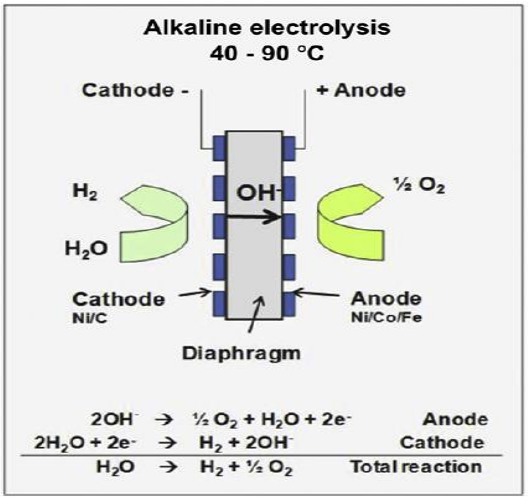

Figure 3. Working principle of an Alkaline Electrolyzer (Source: (Carmo, et al., 2013)).

The reaction occurs in the range of 40-90°C. High purity of products the product can be obtained from this technology, this is between 99.5-99.9% for H_2, and for O_2 99-99.8% (Buttler & Spliethoff, 2017). Non-noble metals such as nickel or nickel-plated steel are the materials typically used for the electrodes (Lehner, et al., 2014). Among the disadvantages to this technology are the limitation of current density from high ohmic losses, low operating pressure because of the liquid electrolyte required, and the most relevant is the low partial load range of operation, which is a problem when electric power is provided by renewable electricity sources (Carmo, et al., 2013).

2.2.2 Proton Exchange Membrane (PEM) Electrolysis

PEM, proton exchange membrane or polymer electrolyte membrane, was developed by General Electric in the decade of the 1960s as an alternative to alkaline technology. Thus, this technology introduced several advantages over AEC, as a compact design for the system, higher operation pressures (up to 350bar) and current densities of much higher values. More importantly, it introduced the idea to replace the electrolyte for a solid sulfonated polystyrene membrane of approximately 20-300μm of thickness, which would yield in high proton conductivity (Carmo, et al., 2013). Figure 4 illustrates a graphic representation of the working principle of PEM electrolysis.

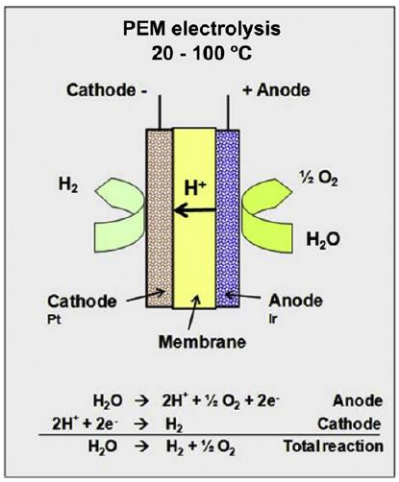

Figure 4. Schematic representation of the working principle of PEM electrolysis (Source: (Carmo, et al., 2013)

Deionised water of high purity and low conductivity is required to be continuously fed only to the anode, unlike AEC. The chemical reactions occur in wider temperature ranges than AEC, between 20-100°C (Carmo, et al., 2013) but the operational temperature is typically kept under 80°C (Lehner, et al., 2014). The oxidation reaction occurs producing free ions of oxygen, electrons, and hydrogen protons in the electrolyzer. Only H_2 protons, containing relatively low moisture, pass through the membrane to be reduced at the cathode, whilst the anode obtains O_2 ions with higher moisture content. In Equations 5 and 6 are expressed the reactions occurring in the PEM electrolyzer (Kotowicz, et al., 2016).

$$H_2O \rightarrow 2H^+ + 2e^- + \frac{1}{2}O_2 \quad (Anode\ [+]) \qquad \text{(Eq. 5)}$$

$$2H^+ + 2e^- \rightarrow H_2 \qquad (Cathode\ [-]) \qquad \text{(Eq. 6)}$$

According to Uusitalo et al., approximately 0.0052 kg of hydrogen can be produced for each 1 MJ of electricity introduced in the reaction above. Additionally, 0.046 kg of water are required, and 0.041 kg of oxygen are produced, or left unreacted. This hydrogen generation technology enhances the utilization rate of the electrolyzer in the presence of a variable source of electricity, whilst yielding in shorter startup periods and higher efficiencies than other H_2 production methods (Uusitalo, et al., 2016).

With the increasing need for flexibility and requirements for greener energy production methods, technologies as Proton Exchange Membrane (PEM) electrolysis, are re-gaining momentum. These provide with a more sustainable solution as an alternative approach to hydrogen generation through water electrolysis compared to alkaline electrolysis cell (AEC) systems (Carmo, et al., 2013; Decourt, et al., 2014). Figure 4 shows a broad outlined layout of a PEMEC system, the system efficiencies are typically in the range of 62-77% based on HHV of H_2 (Koponen, 2015).

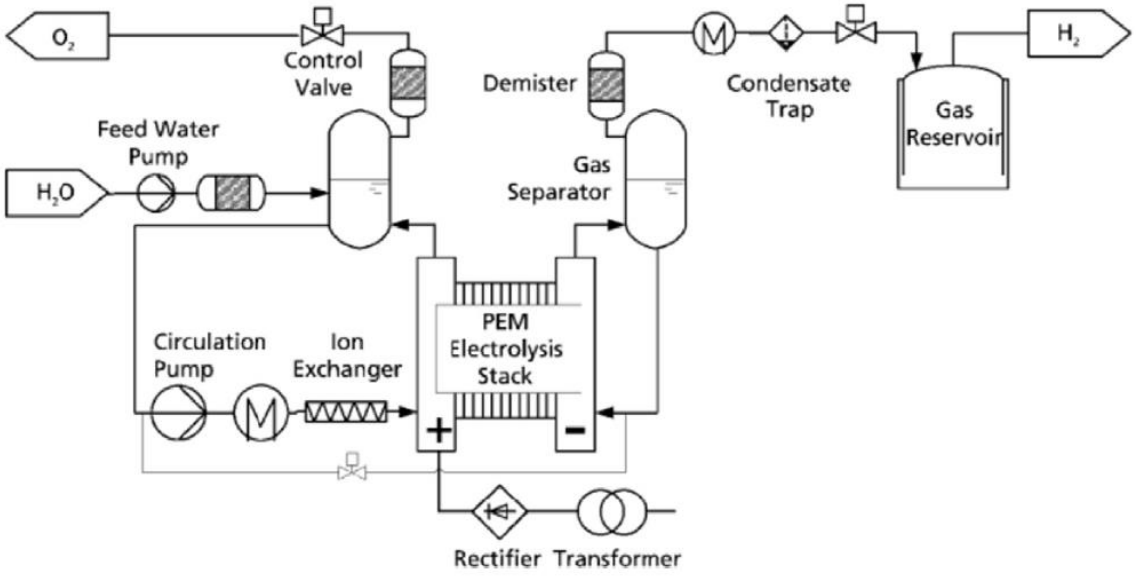

Figure 5. Basic layout of a PEM electrolysis system (Source: (Buttler & Spliethoff, 2017))

The purity levels of 99.999% are achievable for the H_2 produced via PEM electrolysis, slightly higher than that of AEC due to the very low permeation rate (gas crossover rate) allowed by the solid membrane. In addition, PEM offers good partial load range operation, and considering that nominal power density can be covered entirely (0-100%), this allows the PEM electrolysis technology to profile as the best option to couple with PtG systems, when electricity is sourced from fluctuating renewable electricity generation. However,

PEM also faces drawbacks regarding higher operational costs and lower durability of the system against AEC because the material of the catalyst for the electrodes in PEM must be of noble metals, such as iridium for the anode and platinum for the cathode (Buttler & Spliethoff, 2017). An extended and updated comparative table reviewing the largest systems for electrolysis by technology and suppliers can be found at Buttler and Spliethoff.

2.2.3 Solid Oxide Electrolyte Cell (SOEC)

The technology with the less commercial maturity is solid oxide electrolyte cells (SOEC) (Lehner, et al., 2014). The first presented results regarding this technology came from Dönitz and Erdle as a part of a project conducted at the Dornier System GmbH in Germany in the 1980's decade. The hydrogen production of this project yielded in the achievement of 100% Faradaic efficiency when operated at a 3.0A cm^{-2} current density and a low voltage of 1.07V. Since then, SOEC has attracted great interest from companies, universities, research center, focusing the current development of this technology in new, less expensive and more durable materials and manufacturing processes (Carmo, et al., 2013). SOEC operates at high temperatures for increasing the efficiency of hydrogen conversion (700-900°C) (Buttler & Spliethoff, 2017). Hence, water vapor, or steam, at high pressure and temperature is used as the reactant medium, yielding in unfortunate high levels of quick component deterioration, holding back the commercialization stage of this promising technology (Koponen, 2015). The chemical reactions for SOEC electrolysis are shown by Equations 7 and 8, followed by a schematic representation of the working principle of SOEC in Figure 6.

$$H_2O + 2e^- \rightarrow H_2 + O^{2-} \quad (Cathode\ [-]) \qquad \text{(Eq. 7)}$$

$$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^- \qquad (Anode\ [+]) \qquad \text{(Eq. 8)}$$

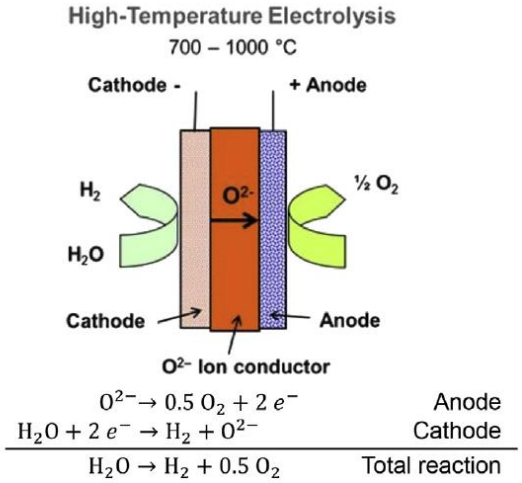

Figure 6. Working principle of SOEC electrolysis (Source: (Schiebahn, et al., 2015)

To maintain reacting conditions, the cathode is supplied with the continuous flow of steam or feed water and un-reacted H_2 recycled from the process to partially converted to hydrogen fuel (Buttler & Spliethoff, 2017). Oxide ions are lead to the anode across the electrolyte to recombine into O_2 molecules (Koponen, 2015). According to Lehner et al., yttria-stabilized zirconia is the electrolyte used most commonly in high temperature due to its high conductivity and ceramic materials for the components because of their high tolerance to increased temperatures and pressures (Lehner, et al., 2014).

SOEC provides with the alternative to produce a syngas by co-electrolyzing steam and carbon dioxide. Added to the considerably higher efficiencies achievable for hydrogen production, this features position SOEC technology as an option for PtG applications for the future as this is currently at R&D stages. The only SOEC pilot plant is operating in Germany at 96% efficiency based on lower heating value (LHV). It has reported to produce approximately 0.6Nm^3/h rate of H_2 at nominal power of 2.2MW and 10 bar of pressure, offering a load flexibility of 100%. Even if it is a technology currently under development and at pre-commercial stage, it holds the potential for increasing considerably the efficiency of hydrogen production (Buttler & Spliethoff, 2017).

2.3 Chemical methanation

The process of converting methane (CH_4) via the synthetization of hydrogen (H_2) with carbon dioxide (CO_2) or carbon monoxide (CO), either by biological or chemical means, is called methanation and it is the second step in the PtG system. For the purpose of this thesis, only the chemical methanation process is of relevance due to its prove viability for the PtG system in question, and we will refer to this produced product as Synthetic Natural Gas (SNG). The following reaction expressed in Equation 9 was first discovered in 1902 and is known as the Sabatier reaction, after its discoverer Paul Sabatier (Lehner, et al., 2014).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad \Delta h_R = -165\ kJ\ mol^{-1} \qquad \text{(Eq. 8)}$$

This process is highly exothermic; hence it yields in thermal energy and some moisture content in the product as outputs of the overall process, additionally to the produced products (Uusitalo, et al., 2016). This reaction is an opposite alternative to methane production against its conventional production through steam methane reforming (SMR). It occurs at high temperatures ranging between 250-400°C at pressures of 1-80bar and it benefits from high pressure and low temperatures in operation (Schiebahn, et al., 2015). Nickel and ruthenium-based catalysts are the most commonly used for chemical methanation processes given the good performance and economic cost-benefit attractiveness for the CH4 conversion rates (Lehner, et al., 2014). However, the intolerance of this used catalysts also represents the main drawback for the chemical methanation process when in contact with poisonous molecules with Sulphur content (Holopainen, 2015).

Regardless of the multiple available commercial solutions for methanation reactors, the two that have proven to be better options for large scale operation of the methanation process are fluidized bed reactors and a series of adiabatic fix bed reactors including applications of gas recycling and cooling, to overcome the problem brought by heat of reaction when producing methane using large volumes of CO_2/CO (Holopainen, 2015). In Table 1 can be observed a comparison based on the characteristic properties of some of the methanation concepts provided by Lehner et al.

Table 1. Comparison of different methanation concepts (Source: (Lehner, et al., 2014))

Concept	Chemical methanation			Biological methanation
	Fixed bed	Fluidized bed	Bubble column	
Heat release	very poor	good	very good	very good (no issues)
Heat control	very poor	average	very good	very good (no issues)
Mass transfer	average	very good	very poor	very poor
Kinetics	good	good	good	average
Load flexibility	average	very poor	average	very poor
Stress on catalyst	good	very poor	good	very good (no issues)

The produced SNG is compatible with conventional natural gas (NG) in terms of fuel properties, therefore it can be fed directly into the available infrastructure for gas distribution network, bringing a great advantage for enabling the integration of the PtG systems to the energy, transportation, and chemical feedstock sectors (Müller, et al., 2013).

An alternative process to the chemical conversion of methane is the biological methanation. This has gained up-growing popularity in the latest years due to the facility of operation at atmospheric pressure and lower operating temperatures, compared to chemical methanation requirements, typically between 30-60°C. Whilst also providing with an increase in tolerance when the feed gasses contain pollutants. However, this is a technology still undergoing research and not a suitable option for the PtG concept from renewables, because of the yet undefined performance at intermittent operation, as well as regarding the issues of stability of the microbes for longer periods and the required balancing conditions for the biological reactions (Lehner, et al., 2014).

2.4 CO_2 sources and carbon capture technologies

The seven greenhouse gases that contribute to Global Warming Potential (GWP), and that are accounted for on the mentioned report are methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) (Scottish Government, 2017). From these, it is well known that CO_2, even if is not the most damaging emission, it is the most abundant in the atmosphere as a result of combustion of hydrocarbons in either sector used: power

generation, heat production, transportation, to mention a few. For example, emissions from the transportation sector are responsible for more than 50% increase than compared to levels of 1990, currently are hold for almost one quarter of global CO_2 emissions from fuel combustion (Varone & MicheleFerrari, 2015). Therefore, there is a need to decrease the levels of these emissions, driving not only towards the de-carbonization of energy systems but also to a better, more sustainable development, and the carbon capture and storage (CCS) technologies are enablers to this purpose (Tock & Maréchal, 2014).

2.4.1 CO_2 sources

In addition to H_2, carbon dioxide (CO_2) is required as raw material for the synthesis reaction to form CH_4 in the methanation step of the PtG system. CO_2 for methanation requires specific level of purity and a suitable flow rate dependent on the demand and is necessary that it is supplied at low energy and economic intensity of capture. Carbon dioxide can be extracted from many possible sources, it can be either captured from the exhaust pipe of fossil-burning power plants, burning of biomass, industrial processes, or even collected directly from air using strong alkaline substances (NaOH or KOH). This last, however, is a very energy intense process that requires 500-800 $kJ_{primary\ energy}/mol_{CO2}$, equivalent to 3000-5000 kWh/t_{co2} only to separate CO_2 to the required concentration of 400ppm. Therefore, it is currently mostly disregarded as a viable option for PtG, even though it brings some advantages as the lack for CO_2 transportation and availability of CO_2 without direct sources in the proximity (Schiebahn, et al., 2015).

The energy requirement for capturing CO_2 from power plants is between 100-240 $kWh_{el}/t_{CO2.}$ This topic has been addressed intensively for a few years as the Carbon Capture and Storage (CCS) concept. There are many technical solutions for enabling separation of CO_2 as chemical absorption, physical absorption, membrane separation, cryogenic separation, and recently introduced, the advanced solvent-based capture processes. One of the main drawbacks of CCS technologies is the need to transport the CO_2 captured to the methanation plant where it will be utilized. Therefore, the PtG profits substantially from the proximity of the carbon source to the PtG system (Schiebahn, et al., 2015).

2.4.2 Scottish Greenhouse Gas Emissions 2015

According to the Official Statistics publication, released by the Scottish Government entitled "Scottish Greenhouse Gas Emissions 2015", the result of total measure of source emissions accounted for Scotland in the year 2015 was of 48.1 $MtCO_2e$. Reporting a decrease of 3.0% compared to 2014 emissions and an overall 37.6% compared to baseline levels of year 1990 (Scottish Government, 2017).

However, for the purpose of this thesis, the relevant figures diverge from these to a certain degree, since the reported adjusted emissions that account for trade in the EU Emission Trading System (EU ETS) are of 45.504 $MtCO_2e$. These are the competent amount of CO_2 available for capture from the respective sources relevant to this study. Which coincidently devolve in a reported increase of 1.8% compared to the 44.7 $MtCO_2e$ of year 2014, as well an overall decrease of 41% from the 71.1 $MtCO_2e$ in the year 1990 (Scottish Government, 2017). In a further section the specific case for the CO_2 source considered for the methodology is expressed in greater detail, these figures reassure that the required quantity of carbon needed for capture is available in more than the necessary amount.

2.4.3 Post-combustion Carbon Capture technologies

In this section is presented a quick overview of the main carbon capture and storage technologies (CCS), also known as carbon separation methods. Further detailed knowledge of carbon capture technologies is given by Styring et al., Abu-Zahra, Holopainen and Budzianowski (Abu-Zahra, et al., 2007; Budzianowski, 2017; Holopainen, 2015; Styring, et al., 2015). A diagram to overview the existing technologies for CO_2 separation technologies taken from Holopainen is shown in Figure 7.

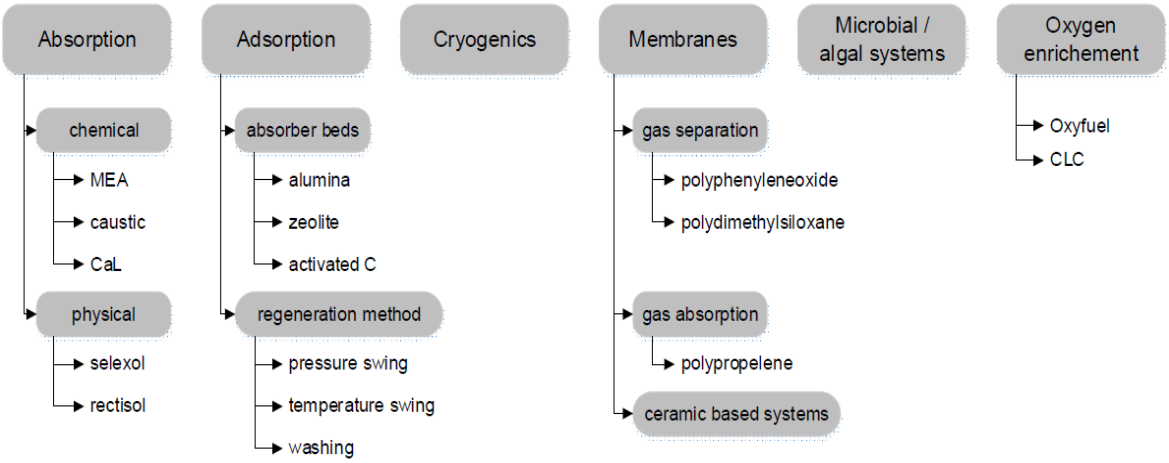

Figure 7. Overview of carbon separation technologies (Source: (Holopainen, 2015))

2.4.4 Membrane separation

The use of membrane technology consists in CO_2 separation from the flue gas stream using a highly permeable and selective material that allows the flow of the remaining flue gas components by a gradient of pressure. These have been in use since 1980 mainly in commercial processes for the purpose of purifying gas. Due to the good level of maturity of this technology, energy consumption and capital costs are lower than for other capture technologies, but high concentrations of CO_2 are required (Holopainen, 2015).

2.4.5 Adsorption separation

Adsorbent agents suitable for the application of this separation method can include zeolites, alumina, metallic oxides or activated carbon. These technologies enable the physical attachment of a gas or liquid to a solid surface for the separation of CO_2. When thermal energy is applied, the regeneration of the adsorbent can be done, as is the case of temperature swing adsorption (TSA); or when the pressure is reduced, as for the case of pressure swing adsorption (PSA). However, these CO_2 separation methods are not the best suitable option when it comes to treating flue gasses from power plants in large-scale solutions as it will face several challenges (Wang, et al., 2010)

2.4.6 Advanced Solvent Based Capture Process (ASBCP)

Budzianowski 2017 provides with accurate and specific calculations for minimum and actual work required for carbon separation based on actual capture plants. Modelling a variety of operating conditions in ideal state for advanced solvent-based capture processes ASBCPs and Monoethanolamine (MEA) separation methods, concluding the influence of increasing thermodynamic efficiencies of CO_2 capture processes in the reduction of the considerably high consumption of heat and power that these require, revealing that for state-of-the-art MEA technologies reach as high as 16% thermodynamic efficiency compared to 25-30% for current and future cases, respectively, for ASBCP processes (Budzianowski, 2017).

The integration of other renewable energy options to the process, such as renewable thermal energy from heat pumps, could help to coup with the limitations brought to these state-of-the-art separation processes. These above-mentioned limitations could come from the contradiction of the thermodynamic limitation possible when open system operation is done at CO_2 capture plants and by the limitation of the second thermodynamic law efficiency, designated for closed systems. In addition, in cases when utilizing thermal regeneration of solvent, heat accounts for the highest fraction of total work requirement in the process of CO_2 separation. Hence, suggesting that appropriate management of the thermal energy of the process acquires characteristic relevance while enhancing the thermodynamic efficiency thought limiting exergy losses and irreversibilities of the system (Budzianowski, 2017)

2.4.7 Chemical absorption (MEA)

The technology of relevance chosen for this thesis is CO_2 separation from the exhaust gas of a power plant using chemical absorption based on aqueous Monoethanolamine (MEA), due to the vast availability of CO_2 from this type of source and the maturity of this capture technology for this application. The use of chemical solvent technologies for the of MEA absorption is a mature technology used for carbon separation mostly in bio-gas production, but it is also a suitable option for CO_2 capture from power plants combusting fossil fuels (Uusitalo, et al., 2016; Holopainen, 2015).

In chemical absorption technologies a chemical solvent is required for the reaction with CO_2 in the generation of an intermediate compound of week bondage that regenerates in the presence of added heat to recreate the original solvent and produce a defined flow of CO_2 with very high purity (Abu-Zahra, et al., 2007). Organic solvents, as MEA, are typically used in aqueous solutions of 70% water and 30% (w/w) concentration of MEA for CO_2 separation from flue gas streams in scrubbers that continuously spray the aqueous amine-rich solution in an absorbing column to be collected after into a stripping column, where it releases the capture CO_2 when heat is applied. This yields in capture rates of 85-90% of the fed flue gas stream even with low partial pressure (Holopainen, 2015; Styring, et al., 2015).

3. ENERGY STORAGE TECHNOLOGIES

In this chapter, an overview of the commercial solutions currently available for energy storage technologies and challenges is delivered with the purpose of comparing the differences and capacities, as well as advantages and disadvantages of the available options in the need for balancing energy systems.

3.1 Challenges for storage technologies

In the current and future energy scenarios, considering the consistent increase of integration of fluctuating renewable electricity production from sources as solar and wind, the need arises for increasing installed capacity for storage of energy in its multiple forms. Thus, enabling the required balancing of energy systems, particularly to electricity grid operation when partial load and variable demand and supply are presented (Ferreroa, et al., 2016).

Classification of energy storage technologies can be roughly done depending on the form of energy stored: mechanical energy (kinetic and potential), chemical energy (organic and inorganic), thermal energy, and electrical energy (Lehner, et al., 2014). Several available market solutions for storing electricity exist at commercial scales, varying in efficiencies of conversion, installed capacity ratings, and time scale for electricity storing periods. A compilation of these technologies is presented in Table 2.

Table 2. Storage technologies by efficiency, capacity rating and time scale. (Source: (Lehner, et al., 2014)).

Technology	Efficiency	Capacity rating MW	Time scale
Pumped hydro storage	70-85%	1-5,000	Hours-months
Li-ion battery storage	80-90%	0.1-50	Minutes-days
Lead acid battery	70-80%	0.05-40	Minutes-days
Power-to-Gas	30-75%	0.01-1000	Minutes-months
Compressed air	70-75%	50-300	Hours-months
Vanadium redox battery	65-85%	0.2-10	Hours-months
Sodium sulfur (NaS) battery	75-85%	0.05-34	Seconds-hours
Nickel cadmium (NiCd) battery	65-75%	45	Minutes-days
Flywheel	85-95%	0.1-20	Seconds-minutes

3.1.1 Pumped-Hydro Energy Storage (PHES)

Among all the available technologies for periodical storage of renewable energy, 99% of the market and installed capacity in Europe, as worldwide, relies on Pumped-Hydro Energy Storage (PHSE) (Ferreroa, et al., 2016).

This technology enables the potential storage of energy from water in large reservoirs that is released upon demand, hence converting the stored kinetic energy of the falling water back into electricity using water turbines (Lehner, et al., 2014). However, its capacity is limited by some factors such as geographical location and the need for construction of large water reservoirs with specific heights to store large quantities of bulk energy storage (Ferreroa, et al., 2016). Additional to the elevated cost of construction for this technology and the social constrain by the low public acceptance due to the alleged visual damaging of landscapes.

3.1.2 Compressed Air Energy Storage (CAES)

According to Ferrero et al., this technology is re-gaining momentum, as it has proven to be an option for energy storage, but its installed capacity is also limited by geographical location and infrastructure required due to the low volumetric capacity for storage and large volumes needed (Lehner, et al., 2014).

CAES consist on pressurizing and storing large volumes of air, either underground (salt caverns) or in large tanks (Ferreroa, et al., 2016), which is later expanded in an air turbine to produce electricity upon demand. This results in low efficiency of conversion, particularly if heat from the process is not utilized (Lehner, et al., 2014).

3.1.3 Flywheel technology

The typically high efficiencies achieved by this technology (85-95%) are the result of the great quantities of electricity that can be a charged and discharged within seconds. However, this characteristic aspect is beneficial only for short-term storage, making it unfeasible for storing energy for longer periods (Lehner, et al., 2014).

3.1.4 Methane and Hydrogen storage

The Power-to-Gas concept converts electricity from excess renewable power into chemical energy carriers such as hydrogen and methane (Varone & MicheleFerrari, 2015). When there is a need for storing large quantities of energy for longer periods of time, days to months, certain parameters, such as high volumetric storage capacity, possibility for decentralized applications, and flexibility of modifiability for specific location for production, become key factors of imperative relevance. Making methane the best available option due to its high volumetric energy storage density and higher calorific value, as is higher than the one for hydrogen by a factor of 3 (Lehner, et al., 2014).

Additionally, distribution and storage of methane and hydrogen profit from the possibility to be directly fed into the available natural gas infrastructure, in the respective concentrations and tolerances of the grid (Ferreroa, et al., 2016; Sternberg & Bardow, 2016).

4. THE SCOTTISH RENEWABLE ENERGY SYSTEM AND THE CASE FOR PTG IN NORTH-EAST SCOTLAND

In this section is described the available renewable electricity and infrastructure of interest to this study case, from which the PtG system could profit and prove its relevance to the objective. This is done first for a national basis and subsequently allocated to the selected location, giving specific data for the council areas of Aberdeen City and Aberdeenshire, in the North-East of Scotland belonging to the Grampian region.

According to the latest publication by The Scottish Government on the energy statistics report entitled *'Energy in Scotland 2018',* a considerable percentage of Scotland's total energy consumption for year 2015 was supplied from renewable energy sources, accounting for a remarkable 17.8%, encouraging progress towards the overall renewable energy target of 30% of total Scottish energy consumption from renewables to be achieved by 2020, and the current target for 50% of all energy could rise up to140% by year 2030 for transportation, heat and electricity consumption. To be able to achieve such ambitious targets, a substantial increase up to 17GW of installed capacity will be required by them, considerably high compared to the 9.7GW up to 2017 (Scottish Government, 2018).

Regardless of consuming approximately 10% of the total energy consumed in the UK, Scotland's richness in energy resources makes it accountable for the largest percentage of indigenous primary energy produced in the UK with a relative contribution of 65%. The entire UK energy system holds a considerably high dependence on imported natural gas to fulfill its needs and so is the case of Scotland, as it is believed to be awarded the first place as the major producer of oil and the second for gas to the EU, whilst supplying 95% and 58% of the total oil and gas, respectively, produced in the UK by 2015. However, in 2015 it was reported that 90% of total primary energy consumption came from oil and gas products but Scotland produced about six times more NG than the national final consumption of this fuel (Scottish Government, 2017).

Scotland is a net exporter of electricity and energy to the UK and EU. According to the statistics, 79% of all primary energy in Scotland was exported in 2015. In addition, the same year 29% of the total electricity in the country was exported. This behavior is common for

the Scottish energy system since some years ago and is expected to continue to evolve in this direction due to the rapid increase of installed renewable energy capacity, added to the fossil fuel richness of the nation. Thus, consistently continuing the strong approach on energy that the Scottish Government has been pursuing to lead dramatic changes in the national energy mix during the last 10 years (Scottish Government, 2018).

Evidenced by the numbers shown in Figures 8 and 9, the energy mix of Scotland relies vastly on Natural Gas as energy resource and a well-established infrastructure for its storage and distribution. Therefore, in the need to procure energy security and reduce dependency on finite fossil fuels, towards the de-carbonization of the systems, alternatives for "green gas", bio-methane, SNG will function as key role players for the current and future scenarios 2030 and 2050 proposed by the Scottish Government in the published report of the Scottish Energy Strategy, providing a need for the ideal integration for PtG system (Qadrdan, et al., 2015; Scottish Government, 2017).

Figure 8. Generation mix Scotland 2015 (Source: (Scottish Government, 2018).

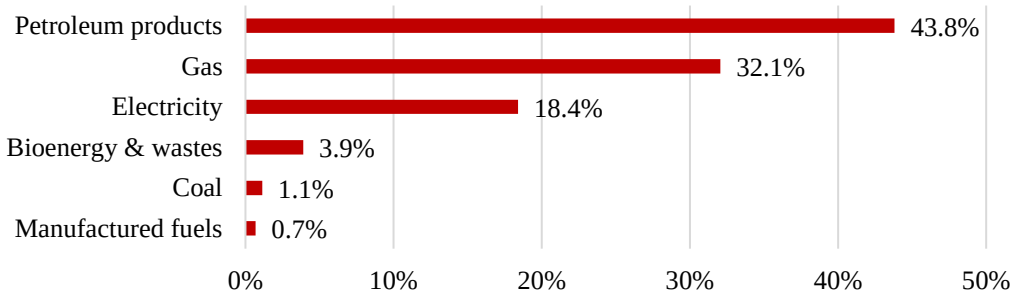

Figure 9. Final energy consumption by fuel 2015 (Source: (Scottish Government, 2018)).

4.1 Renewable Electricity (RE) production in Scotland

A reflection of the clearly marked ascendant tendency shown in Figure 10 illustrates the nearly tripled growth of total renewable electricity generation in Scotland. From the 9058GWh generated in 2008, to the 24 836 GWh reported by the end of the 4th quarter of year 2017. This tracked effort is reported by the National Statistics service on the 6th Chapter on '*Renewable electricity capacity and generation'* of the latest *Energy Trends* publication, issued on the March 29th, 2018, by the Department for Business, Energy & Industrial Strategy (BEIS) of HM Government, with support from the databases issued by the Digest of United Kingdom Energy Statistics (DUKES) (Scottish Government, 2018; Department of Business, Energy & Industrial Strategy (BEIS), 2018).

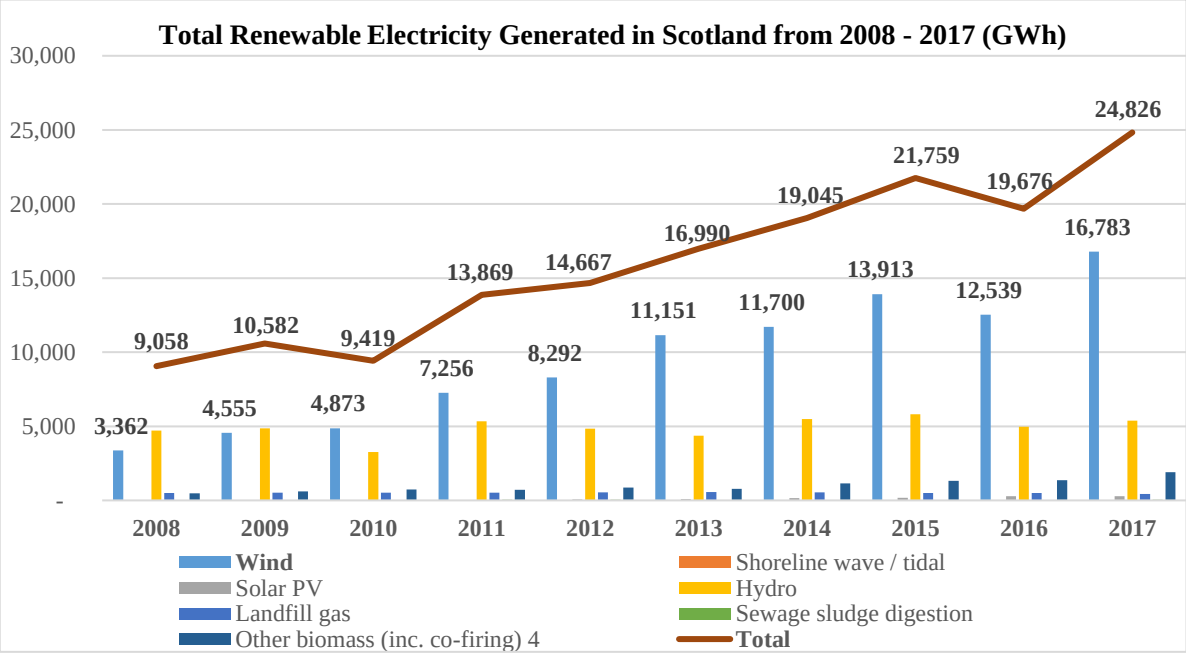

Figure 10. Total renewable electricity generated in Scotland 2008 - 2017 (Source: (Department of Business, Energy & Industrial Strategy (BEIS), 2018).

Subsequently, in Table 3 is presented the same effort illustrated a relative percentage of the national overall electricity gross consumption from renewable sources from 2008-2016. Followed by the specific information on renewable energy for the Scottish mix that was operational and available by 2015, showed in Table 4.

Table 3 Electricity consumption percentage from renewable sources in Scotland from 2008 – 2016. (Source: (Department of Business, Energy & Industrial Strategy (BEIS), 2018)

Electricity in Scotland	2008	2009	2010	2011	2012	2013	2014	2015	2016
Renewable Generation (GWh)	9,058	10,582	9,419	13,869	14,667	16,990	19,045	21,759	19,676
Gross Consumption (GWh)	41,049	38,852	39,237	37,504	37,454	38,209	38,228	36,562	36,458
Renewable % of consumption	22.1%	27.2%	24.0%	37.0%	39.2%	44.5%	49.8%	59.5%	54.0%

Table 4. Renewable electricity generated by fuel source in Scotland 2015 (Source: (Department of Business, Energy & Industrial Strategy (BEIS), 2018)

Renewable Electricity Source Scotland 2015	TOTAL Generation 2015 [GWh]	Total Installed Capacity 2015 [MW]	Load Factor (365 days)	Relative % of RE Gen 2015
Hydro Power	5 815.20	1 572	43%	26.73%
Wind Power (On+Offshore)	13 913	5 595	29%	63.94%
Solar Power	185.20	264	29%	0.85%
Wave Power	2	8	29%	0.01%
Landfill Gas Power	503.40	116	49%	2.31%
Sewage Sludge Digestion	26.20	7	43%	0.12%
Other Biomass (Inc. Co-Firing)	1 314	236	-	6.04%
TOTAL	**21 759**	**7 798**	**-**	**100%**

As a result of these continuously growing actions, Scotland has become one of the few countries, alongside Germany and Denmark, that have registered statistical surplus electricity production entirely from renewable sources. Meaning that more electricity was produced than the required to power the entire country's demand for a defined period of time. In 2016, the entire Scottish electricity needs were powered by wind turbines for one day, generating an equivalent of 106% of the total demand (Lesnen, 2015). Even if this was the first reported statistic of an event of this nature happening, it is highly probable that it had already happen before but was not registered because this statistical data began to be collected only in 2015, which is the record year of the highest electricity production from

renewable sources in Scotland, according to the statistical data released (Department of Business, Energy & Industrial Strategy (BEIS), 2018). From Figure 11 we get that the three major Local Authorities producing RE are the Highlands 27% followed by 10 % from Dumfries and Galloway and 9% from South Lanarkshire. However, the installed capacity of the North-East region will increase in the following years, further developed in the following section.

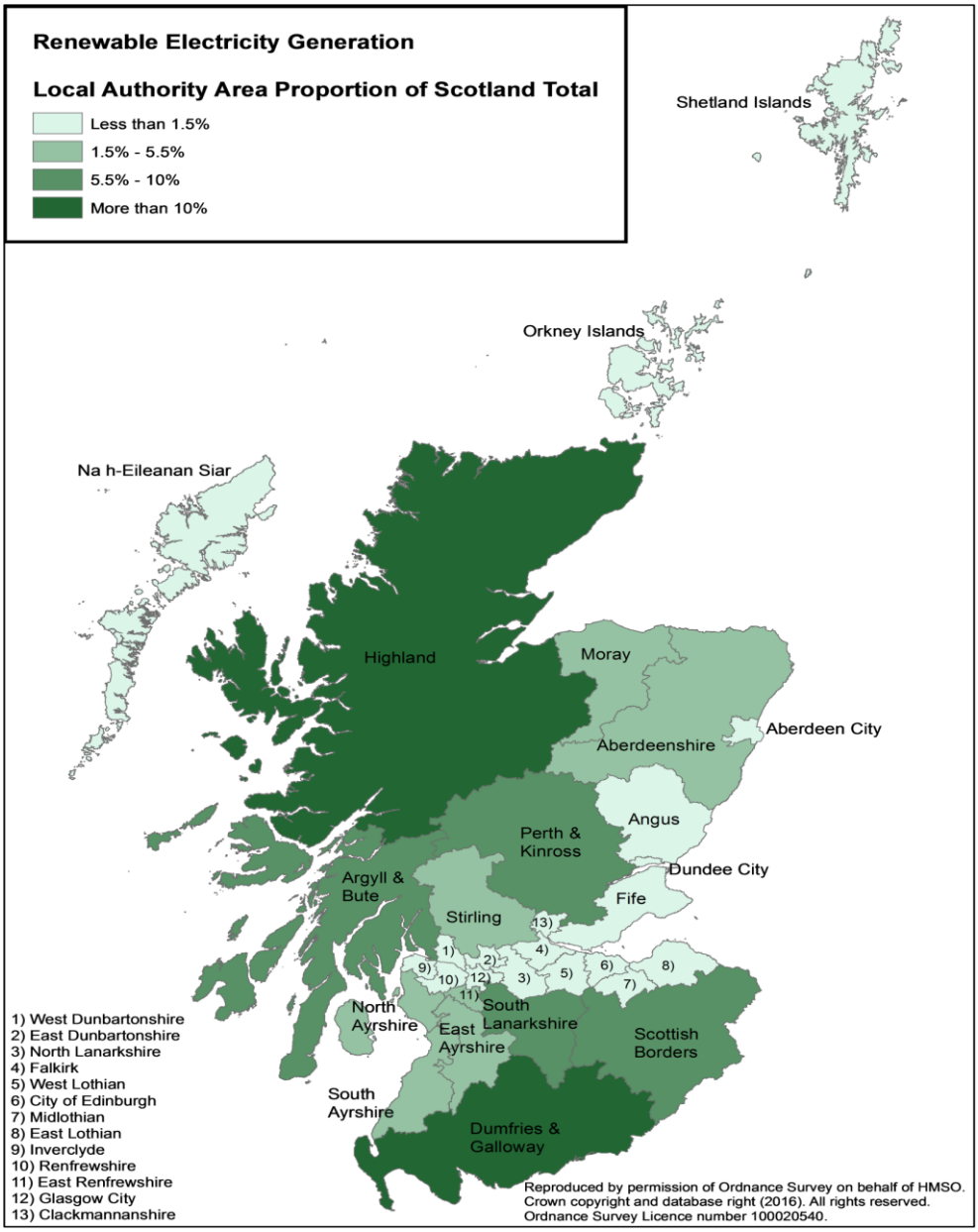

Figure 11. Renewable electricity generation by local authority as a portion of total electricity generation 2015 (Source: (Scottish Government, 2017)).

4.2 Incentives and available infrastructure

Renewable energy production, consumption, demand for supply, as well as future projections for rapid increase of installed capacity will play a role of imperative relevance for the compliance of the ambitious targets settled by the UK government and the European Commission (EU). On Chapter 27 of the Climate Change Act, issued on November 26th, 2008, a target for the reduction of greenhouse gas emissions, among other climate change mitigation actions, was established and strategically planned to be achieved by year 2050. Hence, the responsibility of the UK Secretary of State is to achieve a reduction of at least 80% of the net UK carbon account by the year 2050, compared to baseline levels of 1990. However, is also stated in this report that the net carbon budget of the period including year 2020 has to be reduced by at least 26% compared to baseline levels (HM Government, 2008).

According to The Scottish Government's report on *`Strategy Energy Efficiency Programme´* (SEEP) issued in January 2017, to comply with the targets required by the *`Climate Change Plan´* on an ambitious emission reduction of 42% and 80% across the country by year 2020 and 2050 respectively. Also considered within the scope of the emission reduction for the *'Climate Change Plan'* an ambitious target on decrease of GHG emissions released to the atmosphere must be achieve in the residential and services sectors of 75% and 98% respectively by year 2032 compared to levels of 2014 (Scottish Government, 2017). In addition, the Scottish Government's Renewable Action Plan, issued in June 2009, was established the substantial potential for economic and technical development of fuel cells and hydrogen sectors, which by then were rather small, un-scaled sectors, and considered unlikely factors of influence according to their then-stablished 2020 roadmap (Scottish Government, 2009).

For all of these, the PtG concept is expected to play a key role in the achievement of all these ambitious targets, particularly when and if the renewable electricity target by 2020 is achieved for producing 100% of the national electricity demand from renewables, according to the Scottish Government. Thus, an approximate growth of the renewable installed capacity must be in the range of 14-16 GW. This is expected to be covered by the further development of offshore windfarms, expected to expand substantially in the following years. Strong actions towards the further development of offshore wind in Scottish waters were set in motion on March 2011 as confirmed on the 4th update of the Scottish Renewables Action

Plan, an additional installed capacity for offshore wind renewable electricity generation of about 5GW in at least six suitable sites by year 2020 (Scottish Government, 2009).

The North-East region of Scotland, particularly the shorelines of the council areas of Aberdeen City and Aberdeenshire, are currently benefitting, or will be in the close future, from the approximately 892 MW of added installed capacity of offshore wind from the ongoing projects circled in red illustrated in Figure12, as this region will be home to most of the main land connections, all expected to be fully operational by 2020. Hence, one of the major criteria for choosing this region for the study case (Scottish Government, 2012).

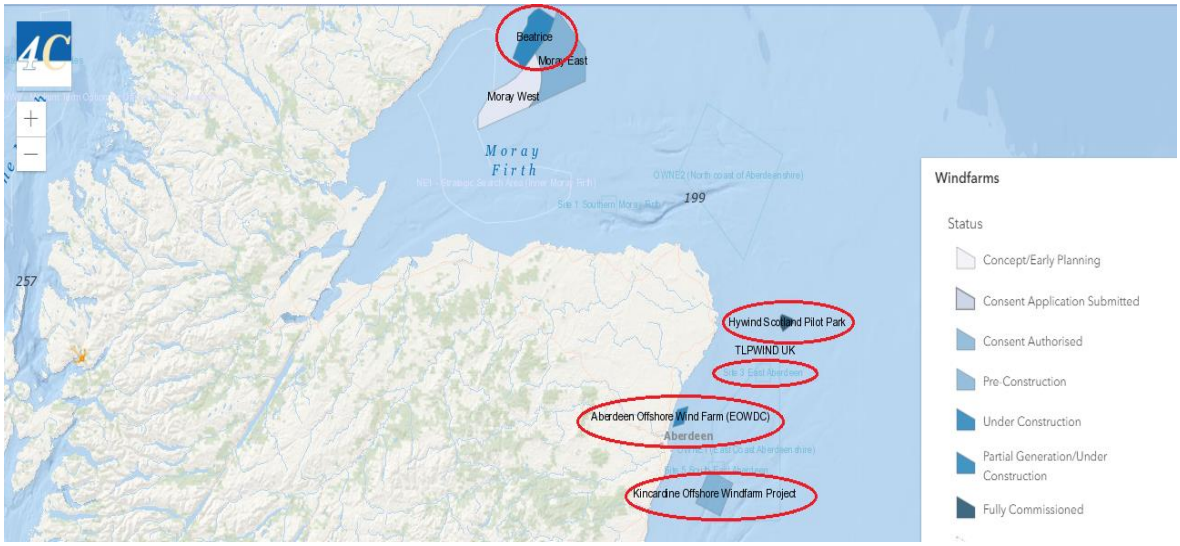

Figure 12. Current and future developments for offshore windfarms in the North-East coast of Scotland (Source: (4C Offshore Ltd., 2018))

4.3 Demand for Natural Gas (Methane) in national markets

Influenced by the vulnerability of energy security in European countries, evidenced by the natural gas crisis as consequence of the supply cut-off from Russia in 2006 and 2009, the need for ensuring the demand of this valuable fuel and to enhance energy security motivated the affected European countries and its leaders to reduce the dependence from Russia's natural gas supply and boosted the diversification of imports and supply, especially since the domestic gas production in European countries, as the Netherlands, has declined rapidly in recent years (Tagliapietra, 2016). However, the increase and demand for gas in the EU-28 energy systems prevails and are expected to keep rising according to the International Energy Agency (IEA,2015) reports and the natural gas consumption statistics reviled by Eurostat (Eurostat, 2017).

4.3.1 Natural Gas (NG) statistics in EU and UK

According to the statistical report and figures reviled on the natural gas consumption statistics by Eurostat, an increase of 7% of gross inland consumption has been reported for the EU-28 compared to 2015, accounting for 17,903 thousand TJ, and a reported increase of 5.8% for the EU-19 yielding in a total of 12,456 thousand TJ. Thus, the major contributing countries to the consumption increase of this valuable energy resource compared against levels of year 2015 were Greece, with the higher recorded increase of 30.2% in consumption; then Sweden with 13% increase; closely followed by the United Kingdom with 12.9%; and Portugal with 12.4%. However, other countries have statistically lowered their national consumption of natural gas in reference to levels of year 2015, such is the case of Lithuania falling by 10.9%; Luxembourg with 7.8% decrease; Finland with 6.7%; and the Netherlands, former major NG producer in the EU, lowering its consumption by 1.6% (Eurostat, 2017).

In year 2016, the UK surpassed the Netherlands and ranked as the first major NG producer among the EU-28 countries for the first time since 2008. This was due to an increase of 4.2% in production compared to the previous year (Eurostat, 2017).

4.3.2 Natural Gas consumption in Scotland 2015

Total annual natural gas consumption for Scotland in 2015 was of 45 469 GWh, decreasing 2.1% compared to the 46 294 GWh of total consumption the year before. A map illustrating the total annual natural gas consumed per local authority in 2015 can be appreciated from Figure 13. As it is visually evident, the majority of Scotland can be considered as an intense gas consumption zone. Particularly the case for the North-Eastern region, yielding in a total of natural gas consumption of 2 280 GWh for Aberdeen City and 1 3433 GWh for Aberdeenshire, for a grand added total of 3 623 GWh of total natural gas consumed in this region in year 2015, according to the most recent sub-national gas consumption data released by the UK Government statistics ((BEIS); Department of Business, Energy & Industrial Strategy, 2017).

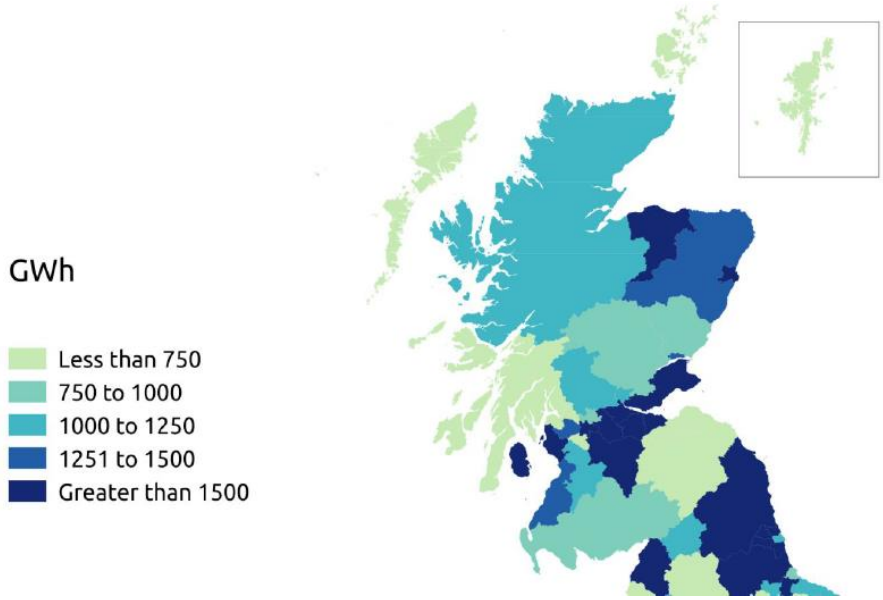

Figure 13. Total natural gas consumption by local authority in Scotland 2015 (Source:

One of the potential reasons for the consumption behavior reflected in the Figure above is the annual pattern variation of NG consumption, influenced by the changing of seasons, as expressed in Figure 14 (Scottish Government, 2017).

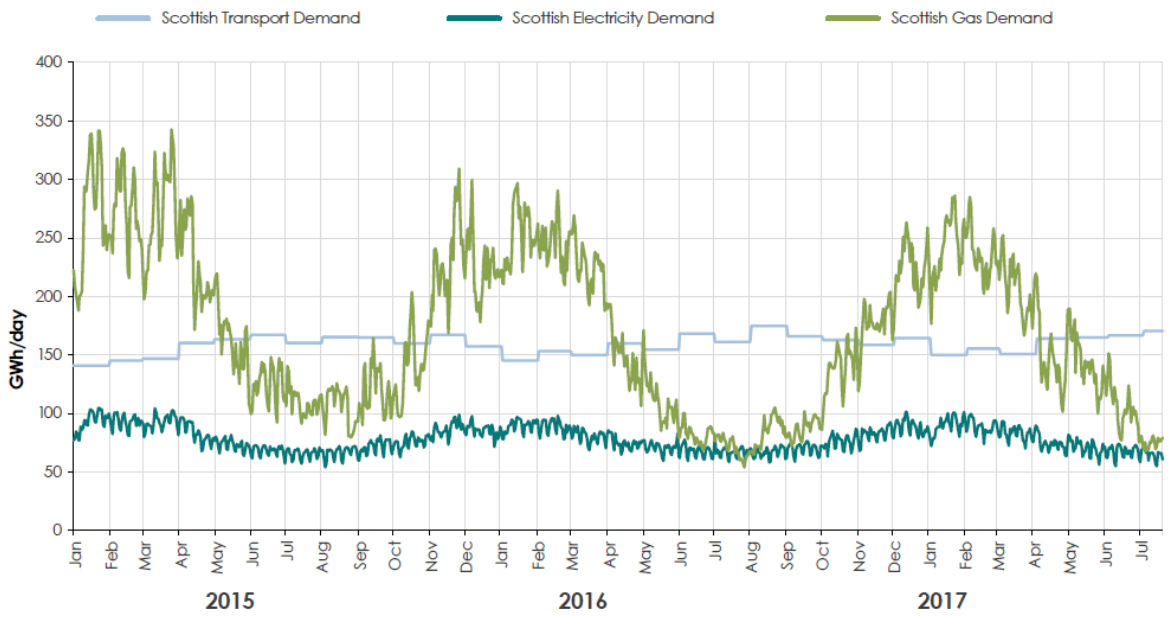

Figure 14. Yearly pattern variation of energy consumption in Scotland 2015-2017 (Source: (Scottish Government, 2017)

Fluctuating behavior for the electricity demand and demand for transportation is not as pronounces, meaning that maintains a stable consumption throughout the year with minimum variations. In contrast, the demand for NG spikes up and down depending on the season given that the major consumption of gas in Scottish households is designated for space heating (Scottish Government, 2018). In addition, the NG consumption patterns may have a correlative dependence on the limitation of availability of access to the Scottish Natural Gas network, as it is further described in the following section.

4.3.3 Natural Gas infrastructure for the domestic sector (Households)

On Chapter 2 of the report *"Scottish Energy Strategy: The future of energy in Scotland"*, published in January 2017, the figures released regarding energy consumption in Scottish households showed that natural gas yielded the highest demanded fuel required for space heating. Regardless of the widespread usage of this fuel along the country still an approximate of 400,000 Scottish households remain with no access to the national gas network, particularly in rural areas of the country, accounting for nearly 16% of households in this country (Scottish Government, 2017). Therefore, is evident that there is a need for local decentralized production and distribution of this most required fuel in the areas where

the infrastructure for NG grid is not available. However, as it is shown from Figure 15, this is not the case for the North-Eastern region of Scotland, particularly regarding the Area Councils of Aberdeen City and Aberdeenshire, which are the locations selected for this study due to compliance of all the required and suggested conditions for the successful implementation of a PtG system according to what stated by Lehner et al., and the German Energy Agency ((DENA), Deutsche Energie-Agentur GmbH. German Energy Agency, 2015; Lehner, et al., 2014)

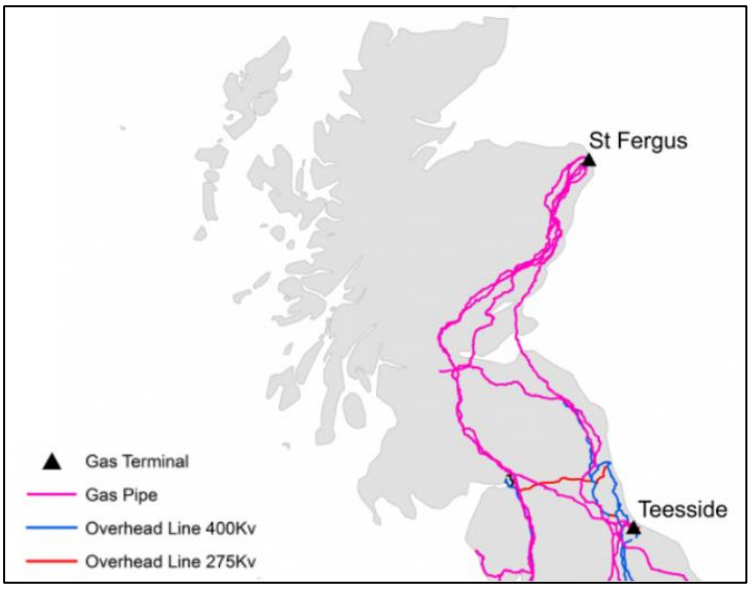

Figure 15. Scottish natural gas grid (Source: Natioanl grid UK (Source, (National Grid, 2018)

As for the case of implementation of a large-scale PtG system, the benefit of having the NG distribution network in the proximity becomes a great advantage for the purpose of injecting the SNG produced to harness the already available infrastructure (Lehner, et al., 2014). Therefore, this requirement it not an issue for Aberdeen City and most of Aberdeenshire, since the infrastructure is moreover well developed in this location, including the gas terminal available at St. Fergus.

4.3.4 CO_2 from CCS plant facility available at Peterhead power station

In addition to the availability of the resource for renewable electricity production for electrolysis, the proximity to the distribution network for SNG, and location by the coastline, a constant

A Carbon Capture and Storage (CCS) project for post-combustion capture of an existing power plant is currently under demonstration phase. Located at Peterhead gas power plant, in the North-East Scotland, this project in charge of Shell in collaboration with Scottish and Southern Energy (SSE), will capture post-combustion CO_2 from one of the three gas turbines of 385 MW. The project is targeted to compress and transport the captured carbon by offshore pipelines for storage in the Goldeneye depleted gasfield owned by Shell. Started developing in 2012 and is expected to be fully operational by 2019 at a capacity of capturing up to 1Mtonne CO_2/year (Scottish Carbon Capture & Storage, 2018).

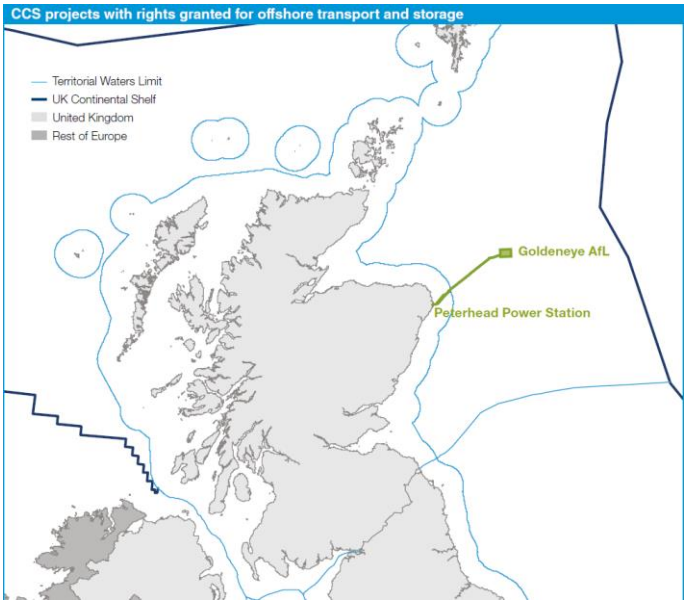

Figure 16. Carbon Capture and Storage (CCS) facility at Peterhead power plant (Source: (The Crown Estate, 2015)

For the purpose of this thesis, it is proposed that this already existing facility, at its designated CO_2 production capacity and assumed enough quality of CO_2 stream could be utilized for feeding the PtG application proposed, since it would avoid the added environmental penalty for transportation of CO_2 if assumed to be directly utilized in-site.

5. LIFE CYCLE ASSESSMENT (LCA) UTILIZING GaBi 6.0 SOFTWARE FOR MODELLING PTG SYSTEM AND CO_2 REDUCTION POTENTIAL

In this section is presented the methodology to follow for the assessment of the study case of this thesis. Life Cycle Assessment (LCA) is an analytical and systematical methodology used to assist the performer in the identification of areas of opportunity for improvement of a product, system, service or process throughout its life cycle, in terms of the measured inputs and outputs influencing the environmental performance indicators and environmental impacts of highest influence. Additionally, this methodology is used to give environmentally-appropriate guidelines to major stakeholders in charge of decision-making towards driving into a more sustainable development. In Figure17 are presented the four consisting phases of the LCA framework in accordance with the European Standard EN ISO 14040:2006 and EN ISO 14044:2006 standards (ISO International Organization for Standardization, 2006).

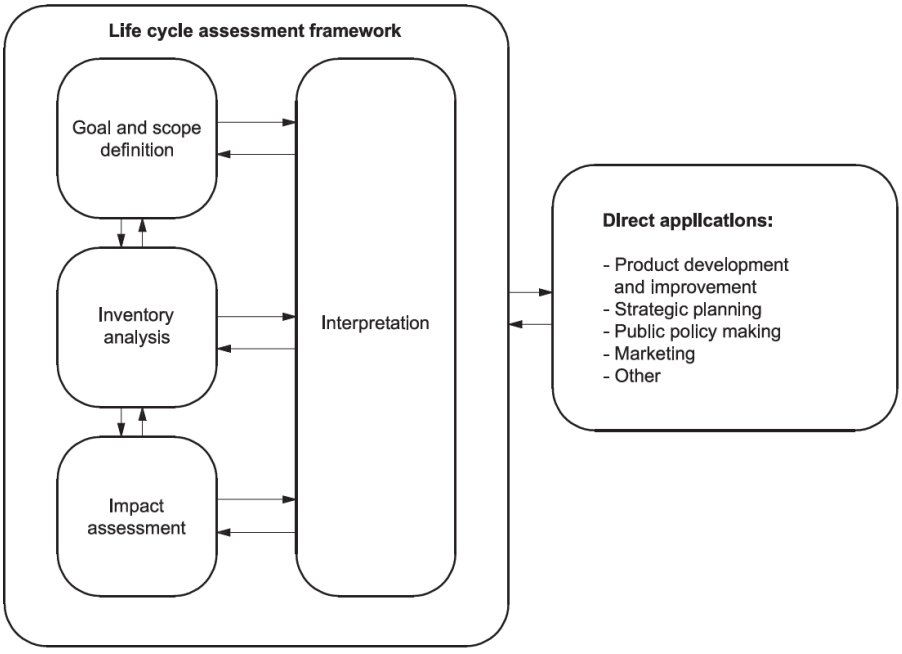

Figure 17. The four phases of LCA (Source: (ISO International Organization for Standardization, 2006)

LCA software: GaBi 6.0 (PE International)

For an accurate and detailed quantification of the environmental stressors and the influence in environmental impact categories awarded to a product, system or service, a specialized LCA software tool is required. For the case of this thesis work, and due to availability of the required license, GaBi 6.0-LCA software is used.

This software tool is used to measure and calculate the environmental stressors, indicators and impacts, as well as the resource consumption and energy balances of the imperative inputs and outputs of the modelled unit processes. Consequently, assisting in the quantification and evaluation of the overall impacts to the Global Warming Potential over 100 years (GWP 100).

5.1 Limitations and system boundaries for the conducted study

5.1.1 Goal and scope definition

The purpose of this conducted study is to perform a Life Cycle Assessment (LCA) following the *cradle-to-gate* methodology, to evaluate the potential CO_2 reduction from the production of SNG from an amount of surplus renewable electricity produced from wind power in A specified region in the North-East of Scotland. The environmental impact category to assess is Global Warming Potential for 100 years (GWP100) in $kg_{CO2\text{-}eq.}$, for the three following proposed scenarios:

1. Baseline Scenario: No PtG available

To establish a baseline, or reference scenario, serves the purpose to assess the environmental impacts of the current energy system, lacking the availability of PtG technology in the study case. Therefore, the assumed current scenario is evaluated when the PtG system is non-existent and the full environmental impacts are awarded to the total domestic natural gas consumption in the North-East region of Scotland (Aberdeen City and Aberdeenshire) in 2015, when is supplied entirely by the Scottish Natural Gas Network. These are modelled considering the available dataset for Natural Gas mix for Great Britain PE from GaBi 6.0 LCA software.

2. Scenario 1: Introducing limited PtG Scenario in Scotland 2015

The implementation of PtG system is proposed, assuming to convert a certain amount of surplus electric power from wind into SNG and modelled accordingly to observe the CO_2 reduction potential, however significant, with the purpose to show its viability in the selected location that could potentially comply with the required conditions for a scalable case for PtG applications with SNG production in North-East Scotland.

3. Future PtG Scenario for year 2030.

Hydrogen production is the first step in the PtG systems, prior to the synthesis of CO_2 in the methanation process to the conversion of SNG. However, the decisive criteria for the relevance of the exclusive assessment of methane production for this case study relies firstly on the high dependence of the Scottish energy mix has on this valuable fuel (Eurostat, 2017; Scottish Government, 2018). Additionally, in order to harness the flexibility of integration to the efficient and the available infrastructure of the Great Britain (GB) combined gas and electricity network (CGEN) assessed by Qadrdan and company, for the fuel distribution, for energy production, for space heating for the household sector, and leave flexibility to incur in the future development and implementation of the grid for adaptation for the transportation sector (Qadrdan, et al., 2015).

5.1.2 Definition of Functional Unit (FU)

The Functional Unit (FU) for this study was defined as a certain amount of surplus renewable electricity produced from the Hywind Scotland Pilot Plant offshore wind farm with 30MW of installed capacity. This amount is assumed to be 384 320GWh (3.0355E+07 MJ_{el}) available as surplus electricity for production of SNG using PtG for Scenario 1, proposed for implementation in specific region in the North-East coast of Scotland, at close range to Peterhead CCS facility. The modelling of the system and all the unit processes was done so for maintaining a dependency of this value throughout the whole system modeled.

5.1.3 Life Cycle Inventory Analysis

The Power-to-Gas case for Aberdeen City and Aberdeenshire, Scotland 2015.

As reviewed from literature, for the feasible implementation of this technology, it is required to comply with a series of specific conditions, outlined by the German Energy Agency (DENA) and Lehner et al., as the adequate criteria for a successful location selection for PtG plants ((DENA), Deutsche Energie-Agentur GmbH. German Energy Agency, 2015). Among the mentioned factors are:

- The availability of abundant renewable energy sources at close range.
- Connection to the natural gas network and storage facilities should be accessible within physical proximity.
- Settled characteristics of demand for balancing of power loads and future grid expansion plans.
- That a downstream source for sufficient and adequate carbon dioxide is available at proximity.
- Availability of hydrogen, methane (SNG), oxygen, and heat outputs.
- As well as the appropriate technical parameters are complied, closeness to potential buyers of products and by-products is advantageable.

Assumptions and Data:

The main assumption established for this study is the possible utilization of a defined amount of electricity generated by offshore wind power and that this amount will be considered as surplus electricity, coming from the 29% of statistically exported surplus electricity produced in Scotland during year 2015 taken from literature review. Excess renewable electricity will be canalized and utilized for the sole purpose of "green" Hydrogen production in-site (coastal shore), which subsequently will be subjected to the methanation process to react with CO_2 and produce SNG with analogical quality and properties required to be injected in the available national network for natural gas distribution, operated mostly by Scottish Natural Gas. Thus, to comply with the operational conditions established during

literature review that enable the production of Synthetic Natural Gas (SNG) through Power-to-Gas (PtG) technology, yielding in the production of an energy carrier with the suitable quality and similar properties as conventional methane to be further injected in the existing infrastructure of the Scottish Natural Gas Grid, therefore reducing or avoiding emissions from the production and consumption of a certain amount of conventional NG in Scotland, according to the study conducted by Qadrdan et al. the role of power-to-gas in an integrated gas and electricity system in Great Britain (Qadrdan, et al., 2015).

The defined LCA methodology chosen to assist with the addressing of environmental impacts of the objective is that of *cradle-to-gate* analysis. The environmental stressors for requirements of energy, resource consumption, and allocated emissions of all the products and processes related to the manufacture of the technology and infrastructure required for this scaled study have not been specifically considered, as opposed to the study conducted by Spath and Mann 2004 regarding the LCA of renewable hydrogen production from wind power electrolysis (Spath & Mann, 2004). Subsequently, the emissions and environmental impacts of end-use of the products and by-products of the proposed system are not accounted for either, as proposed by Uusitalo et al., Reiter and Lindorfer, as well as Stemberg and Bardow in their comparative LCA study for environmental impacts of different PtG systems and pathways compared to conventional production methods (Uusitalo, et al., 2016; Sternberg & Bardow, 2016; Reiter & Lindorfer, 2015). However, the latter referred have been rather considered in the LCA model on a qualitative basis, as a relative percentage on the potential reduction of the statistical total domestic consumption of natural gas for the defined scenarios.

For reasons of appropriate and sufficient quality data available from reliable database and official government sources, the figures belonging to year 2015 have been chosen. Additionally, due to that, statistically, 2015 hold a record year for surplus electricity production from renewable sources for Scotland in terms of electricity produced from wind (Scottish Government, 2018; Department of Business, Energy & Industrial Strategy (BEIS), 2018).

Product utilization from end-consumer is not specifically evaluated in this study. However, it is rather considered in the LCA model, on a qualitative basis, as a relative percentage on the reduction potential from the statistical overall demand/consumption of natural gas for the year defined.

After developing the calculations for the following reactions (Eq. X and X), the results yielded in an approximation of conversion factors consistent with the ones reviewed from literature on LCA of PtG pathways , GWP of wind electrolysis, LCA of carbon capture, and in order to ensure the required consistency for inputs, outputs, and calculations of the chemical conversion of each of the systems products, the assumption of utilizing the production conversion factors according to Uusitalo et al., which are also consistent with those from Stemberg and Bardow, used for calculations in their respective LCA studies on PtG (Uusitalo, et al., 2016; Sternberg & Bardow, 2016). The respective efficiencies of conversion for each unit process were assumed within achievable parameters according to literature review. The detailed parameters, factors, inputs and outputs of each of the unit processes created for the GaBi model will be described further in this section.

Therefore, the following conversion factors, considered from Uusitalo et al., and Sternberg and Bardow, where assumed to be adequate for carrying the calculations of the created unit processes for electrolysis, methanation and carbon capture, since these regards the production of the required inputs and outputs based on 1 MJ units of electricity. Which is presumed mathematical correct for the scaling-up of the processes calculations regarding the PtG scenarios proposed (Sternberg & Bardow, 2016; Uusitalo, et al., 2016).

Table 5. Conversion factors applied for calculations of the created unit processes.

Conversion factors and specifications applied for Electrolysis and Methanation processes (Source: (Uusitalo, et al., 2016))			
Electrolysis			
	Unit	Input	Output
Efficiency of electrolyzer	%	0	72
Electricity	MJ	1	0
Hydrogen (H2)	kg	0	0.0052
Water (H2O)	kg	0.046	0
Oxygen (O2)	kg	0	0.041
Methanation			
	Unit	Input	Output
Efficiency of CH4 conversion	%	0	95
Electricity	MJ	1.19	0
Heat	MJ	0	10.53
Methane (CH4)	kg	0	1
Hydrogen (H2)	kg	0.53	0.03
Water (H2O)	kg	0	2.25
Carbon dioxide (CO2)	kg	2.89	0.14

Construction of the GaBi 6.0 model for the LCA

A basic layout of the LCA-GaBi 6.0 model showing the material and energy flows implicated in the processes is shown in Figure 18. A defined amount of surplus renewable electricity from wind power produced in the North-East of Scotland is the Functional Unit and assigned as a Global parameter to the model.

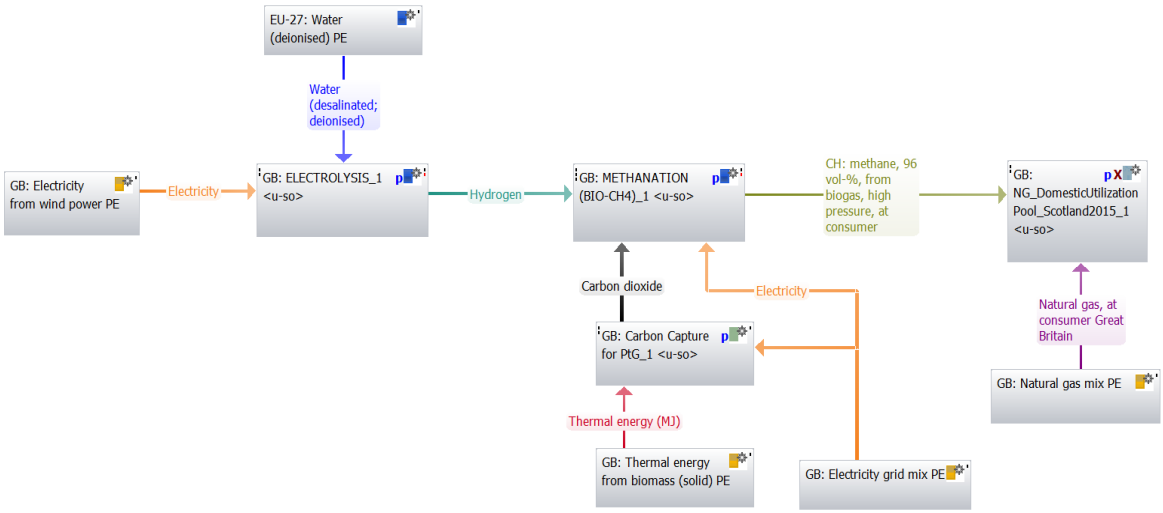

Figure 18. Basic layout of the proposed GaBi model for LCA study.

The following unit processes, listed in Table 6, were considered from the datasets available through the extended database of GaBi 6.0 software given the ease brought to the process of Life Cycle Inventory Analysis. These are assumed to be accurate due to the nation-specific allocation of the available database.

Table 6. Datasets applied from the GaBi 6.0 extended database for the LCA model.

Datasets considered from GaBi 6.0		
Product	**Name of data set**	**Database**
Electricity	"GB: Electricity from wind power PE"	GaBi ts
Water	"EU-27: Water (deionised) PE"	GaBi ts
Heat	"GB: Thermal energy from biomass (solid) PE"	GaBi ts
Electricity	"GB: Electricity grid mix PE"	GaBi ts
Natural Gas (Methane)	“GB: Natural gas mix PE”	GaBi ts

Additionally, in accordance to Sternberg and Bardow (Sternberg & Bardow, 2016), the reason for choosing to use these LCA databases to model is the opposite to their comparative LCA performed for a case of Power-to-SNG pathway against the respective conventional production methods of natural gas.

Table 7. Unit processes created for LCA modelling with GaBi 6.0

Unit processes created for LCA modelling with GaBi 6.0	
Product	**Name of unit process**
Hydrogen	"GB: ELECTROLYSIS <u-so>"
Synthetic Natural Gas (96% Methane)	"GB: METHANATION (BIO-CH4) <u-so>"
Carbon Dioxide	"GB: Carbon Capture for PtG <u-so>"
Natural Gas (Methane)	"GB: NG_DomesticUtilizationPool_Scotland2015 <u-so>"

The assumed potential for a relative decrease in the annual consumption of natural gas from the grid, is not the objective nor has the highest relevance to this conducted study. However, it is presented in the section for results and assessed in a rather quantitative basis of energy units of net calorific value (MWh) obtained in terms of the results from the normal subtraction of the total amount of MJ of SNG produced in the methanation process, from the figure taken from statistical report on sub-national annual natural gas consumption selected for the study case. These numbers were taken directly from the calculations by the model and presented in conclusions as an additional argument to promote the PtG system for Scotland.

"GB: ELECTROLYSIS <u-so>"

According to literature review, for the case of the PtG system to be a feasible alternative for the potential reduction of environmental impacts, the use of surplus renewable electricity is imperative. In order to maintain the consistency of our LCA model based on the assumptions for calculation the potential amount (kg) of required inputs and produced outputs for the methanation process, we decided to refer to Uusitalo et al. and Sternberg and Bardow (Sternberg & Bardow, 2016; Uusitalo, et al., 2016) for the selection of the conversion factors for the production of hydrogen and methane from Table 5. Thus, assuming that the scaling up to our required inputs and outputs for the calculations is feasible by referring to maintain the similar specifications and conditions of their original processes for maintaining coherence of our calculations, and assuming a value of 72% for the efficiency of conversion of the PEM electrolyzer, which is a valid parameter for this technology, according to literature review (Buttler & Spliethoff, 2017; Barbir, 2004). No long-term hydrogen storage is considered, because of direct utilization for conversion to methane at close range (Uusitalo, et al., 2016).

Table 8. Electrolysis unit process for modelling with GaBi 6.0.

Unit process: "GB: ELECTROLYSIS <u-so>"			
Inputs			
Flow	**Quantity**	**Unit**	**Tracked flows**
Electricity [Electric power]	Energy (net calorific value)	MJ	X
Water (desalinated; deionised) [Operating materials]	Mass	kg	X
Outputs			
Flow	**Quantity**	**Unit**	**Tracked flows**
Hydrogen [Inorganic intermediate products]	Mass	kg	X
Oxygen [Inorganic emissions to air]	Mass	kg	X

The oxygen produced as output is disregarded and emitted to the atmosphere in the model

The model was constructed with the purpose of maintaining entire system dependent on the FU and kept throughout all the created unit processes. To comply with the assumptions established to maintain coherence with the modelling for the assessment of environmental impacts of the system depending on one variable global parameter, which will dictate the structure of the up-scaling of the model.

"GB: METHANATION (BIO-CH4) u-so>"

For the methanation process, 95% efficiency of conversion is assumed for the amount of kg of H_2 received as input, the calculations are done using data from Table 5. In addition, for the total amount of electricity input, electricity required for the compression and distribution of methane at 55bar is taken from Uusitalo et al., using 0.71 MJ_{el} / kg_{CH4} (Uusitalo, et al., 2016). This total electricity required for the methanation process is modelled coming from the GB electricity grid mix PE.

The output of the process is required in units of energy (MJ), therefore, to yield this, the final amount of kg of CH_4 produced from this process, is then multiplied by the high heating value of hydrogen: HHV_{H2} = 50 MJ/kg_{H2}, according to literature (Reiter & Lindorfer, 2015)

Table 9. Methanation unit process inputs and outputs for modelling with GaBi 6.0.

Unit process: "GB: METHANATION (BIO-CH4) <u-so>"			
Inputs			
Flow	**Quantity**	**Unit**	**Tracked flows**
Electricity [Electric power]	Energy (net calorific value)	MJ	X
Hydrogen [Inorganic intermediate products]	Mass	kg	X
Carbon dioxide [Inorganic intermediate products]	Mass	kg	X
Outputs			
Flow	**Quantity**	**Unit**	**Tracked flows**
CH: methane, 96 vol-%, from biogas, high pressure, at consumer [fuels]	Energy (net calorific value)	MJ	X
Waste heat [Waste for recovery]	Energy (net calorific value)	MJ	X
Carbon dioxide [Inorganic intermediate products]	Mass	kg	
Hydrogen [Inorganic emissions to air]	Mass	kg	
Water (waste water, untreated) [Production residues in life cycle]	Mass	kg	

"GB: CARBON CAPTURE FOR PTG <u-so>"

For modelling the "Carbon Capture for PtG <u-so>" unit process, for example, conversion factors for the required inputs and outputs of the process were calculated following the CO_2 Absorption process found in literature, once again holding a dependency on the amount of kg required for the methanation process based on the Electricity available, and simply scaled from the conversion factor of Uusitalo et al., to our required inputs and outputs for the carbon capture unit process (Uusitalo, et al., 2016).

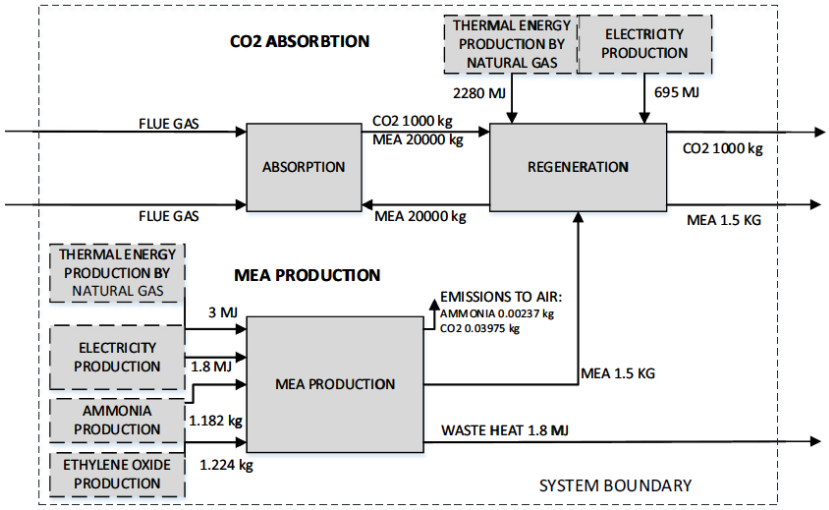

Figure 19. Absorption process followed for CO2 capture unit process, taken from (Uusitalo, et al., 2016).

5.1.4 Life Cycle Impact Assessment

Results from the GaBi 6.0 model for Global Warming Potential for 100 years

Baseline Scenario 2015: NO PtG system

According to the model, the Baseline Scenario for the complete consumption of NG is met from the grid due to the absence of a PtG system for Aberdeen City and Aberdeenshire. The Balance results weighing method for the environmental impact category of GWP100 was "CML2001 - Apr. 2015, Global Warming Potential (GWP 100 years)"

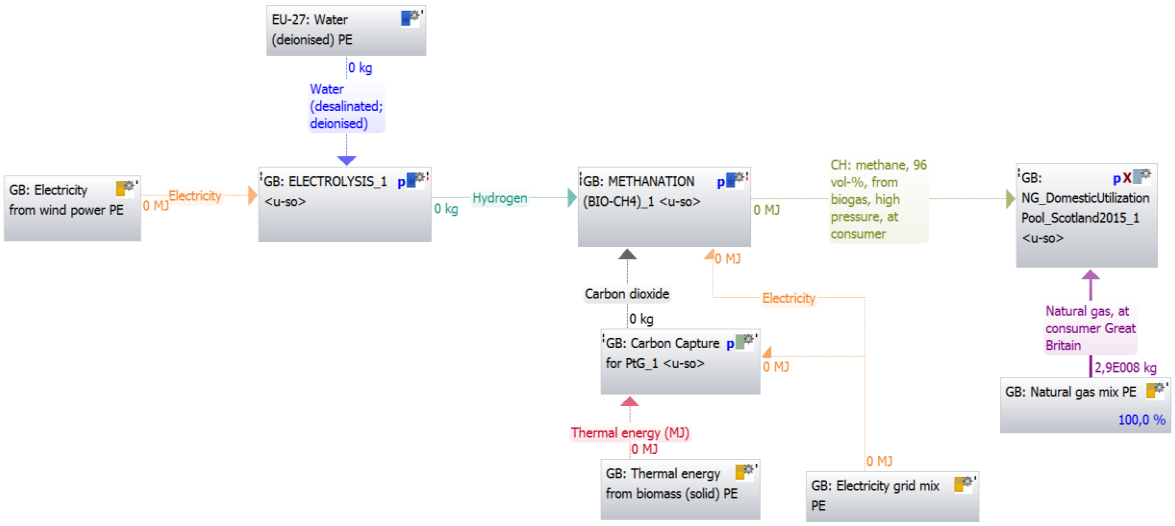

Figure 20. Baseline Scenario GaBi 6.0 model layout. Including relative contribution views for GWP100. No PtG system available.

From the DB Balance we get that, from a total amount of 3 623 GWh of natural gas obtained from the GB: Natural gas mix, to total GWP100 yielded in a grand total 7.71E+07 kg $CO_{2\text{-eq}}$ brought to the system. Thus, getting the highest impact on GWP as it is the only unit process affecting it, this is the reference value to which the subsequent results of the added unit processes will be compared. In Figure 19 is illustrated the GaBi model layout for an overall appreciation of material and energy flows.

Scenario 1: PtG 2015 from Hywind Offshore Windfarm (30MW)

With the established conditions when the PtG is introduced, assuming a total amount of 84320 MWh is available as surplus electricity for SNG production and assuming the direct carbon capture and storage facility located in Peterhead only a slight reduction from the relative contribution to GWP100 is achievable. A layout of the model showing GWP100 relative quantities for S1 is provided at Figure

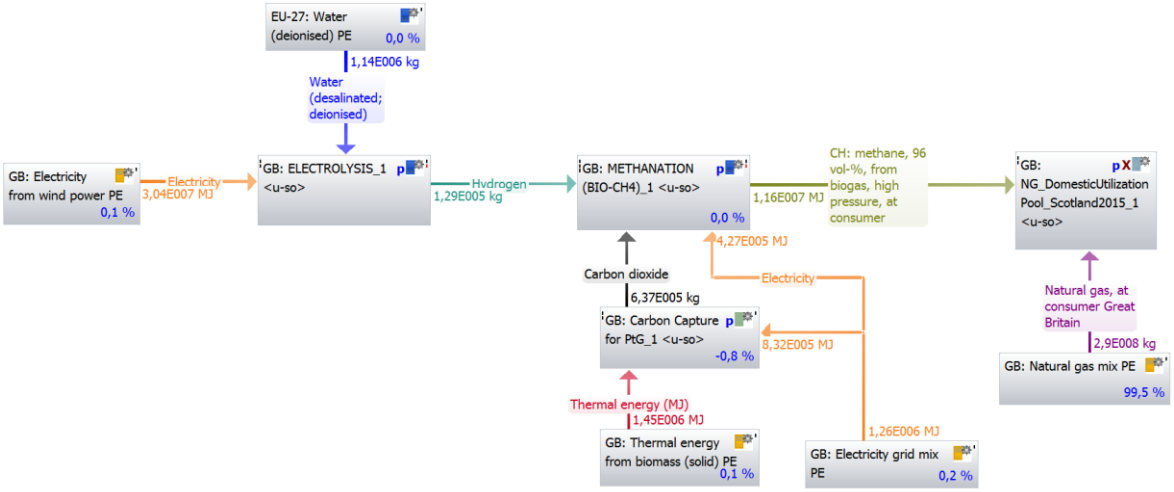

Figure 21. GaBi model lay out for S1 when PtG 2015 is modelled.

This due to the vast difference in comparable quantities, considering the 3 623 GWh of natural gas obtained from the GB: Natural gas mix, as the largest contributor to GWP, with a remaining 99.5% was again awarded to this unit process, for a total yield of 7.67E+07 $kg_{CO2\text{-}eq}$ for the

The amount of CO2 produced in the CCunit process: -6.37E+05kg_{CO2} is shown in the balance as a negative (-) relative contribution equivalent tp -0.831% of total GWP yielding from the to the substraction of CO_2 from the categorie of inorganic emissions to air.

The Electrolysis process if considered to not have any emissions nor impacts. The methanation process has a relatively low contribution to GWP of 3.09E+04 $kg_{CO2\text{-}eq,}$ given the small amount of available prodcuded SNG against the considerably higher impact on GWP brought from the GB Natural gas mix to fulfill the supply for consumption.

5.1.5 Sensitivity Analysis

Scenario 2: Expanded wind offshore installed capacity for PtG by 2030

For the sensitivity analysis we assumed a substantial increase of the potential amount of surplus renewable electricity from offshore wind power integrated to the system and available by year 2030. All these wind farm projects are currently under construction and are expected to be fully operational in the upcoming years (Beatrice Offshore Windfarm Ltd., 2017; 4C Offshore Ltd., 2018; Equinor ASA, 2018; Scottish Government, 2012; Vattenfall, 2016). Thus, all these are considered to be fully operational generating the of Scenario 2 by 2030. Therefore, substantially increasing the amount of available surplus electricity for the PtG process compared to 2015 Scenario with PtG implementation. In Table 10 below, the specifications and outputs of the wind farms to be added to the installed capacity of the Scottish Renewable Energy Mix by year 2030 are presented. Followed by Figure 22 illustrating the respective locations of the mentioned sites, across the shoreline of Aberdeen City and Aberdeenshire council areas.

Table 10. Data for sensitivity analysis.

Scenario 2030: Assumed available surplus electricity from expanded installed capacity of neighboring sites by 2030.				
Wind farm @2030	Capacity **[MW]**	Expected Electricity Generation / year **[MWh]***	Energy output (Surplus Electricity Available) **[MJ]**	Expected CO2 saved per year by replacing Natural Gas use **[tonnes CO2/year]***
Beatrice	588	1.6527E+06	5.9497E+09	6.2637E+05
Hywind Scotland Floating Pilot Plant	30	3.8432E+05	3.0355E+07	3.1957E+04
Aberdeen Offshore (EOWDC)	93.2	2.6196E+05	9.4304E+08	9.9281E+04
Kincardine Offshore Wind Farm	48	1.3491E+05	4.8569E+08	5.1132E+04
North East Site 3 (NE3)	100	2.8107E+05	1.0118E+09	1.0653E+05
TOTAL	**859.2**	**2.7149E+06**	**8.4206E+09**	**9.1526E+05**

***These accurate figures were obtained using the *'Renewable Electricity Output Calculator'* tool, made available by the Scottish Government (Scottish Government, 2017). It includes statistical, standardized data to calculate the estimated actual generation for one-year, annual load factors, average wind speeds, generation technology segregation, and network transmission and distribution losses in Scotland.**

Therefore, the new assumed amount of renewable surplus electricity that could be brought to the future scenario, when the installed capacity of the Scottish offshore wind is expanded, shows an increase from the 84 320 MWh, or 3.0355E+07 MJ_{el} available for the Scenario 1 where the PtG is introduced to a limited scale by 2015; to the assumed forecasted increase to 2 714 938 MWh or 8.429E+09 MJ_{el}.

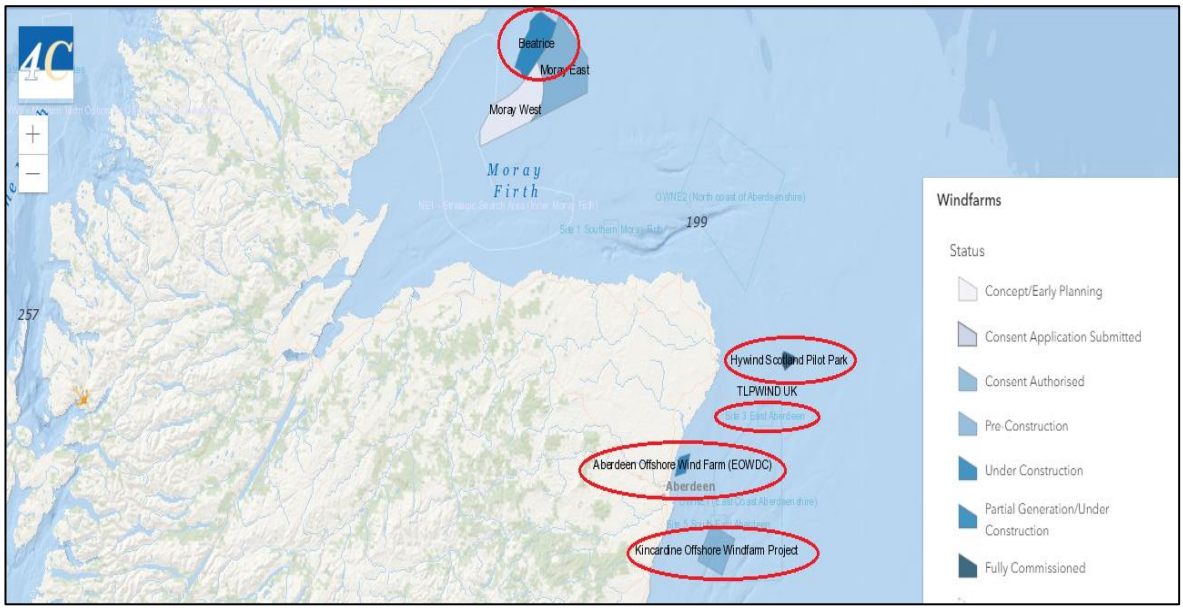

Figure 22. Windfarm projects for Scenario 3 modelling (Source: (4C Offshore Ltd., 2018)).

For purpose of consistency with previous scenarios, and for illustration of the context modeled, in Figure 23 is presented a layout of the GaBi 6.0 modelled parameters, material an energy flows, and GWP relative figures for Scenario 2.

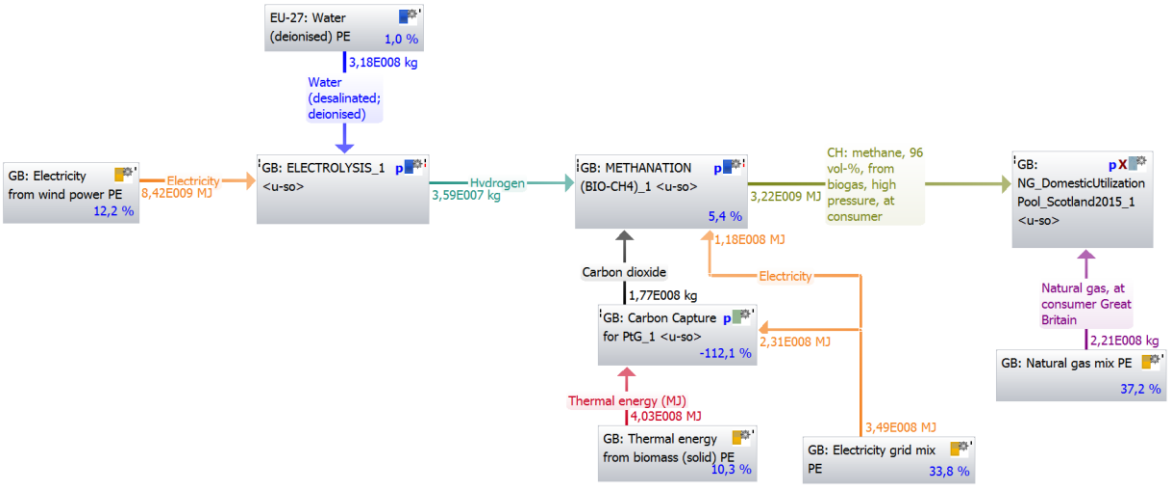

Figure 23. GaBi 6.0 model lay out for S2 when PtG 2030 is modelled.

5.1.6 Life Cycle Interpretation of results

Scenario 2: Expanded wind offshore installed capacity for PtG by 2030

This scenario shows the greatest potential for CO_2 reduction from GWP. Relevance for the study case is shown when an abundant quantity of renewable surplus electricity is available for the process, in this case it scales up to 2 714 938 MWh. For the CO_2 capture unit process, the GWP (CML2001, GWP) was of -1.77E+08 $kg_{CO2\text{-}eq}$ for the added capacity, awarding a considerably high relative contribution to GWP reduction of -128% when compared to the -0.4622% obtained from Scenario 1, as shown in Figure 23, the relative contributions to GWP from each unit process regarding this scenarios balance is appreciate it in Figure 24.

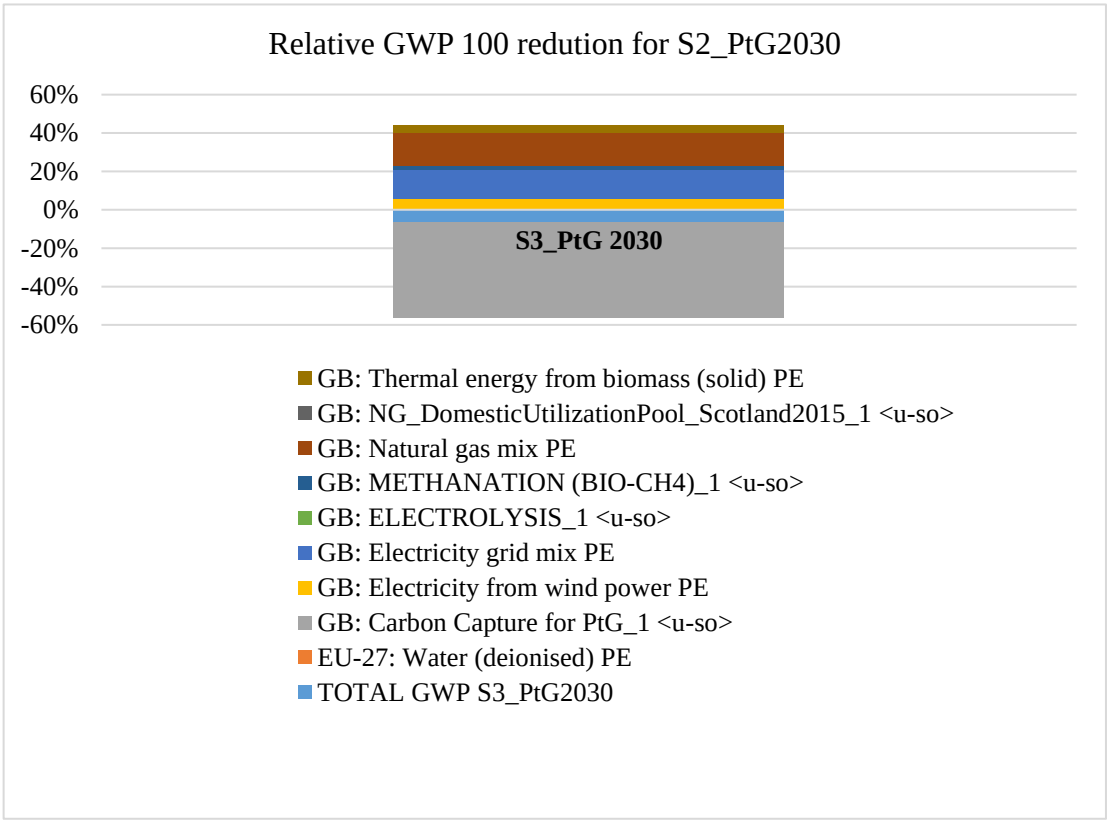

Figure 24. Relative contribution to GWP by unit process to S2_2030

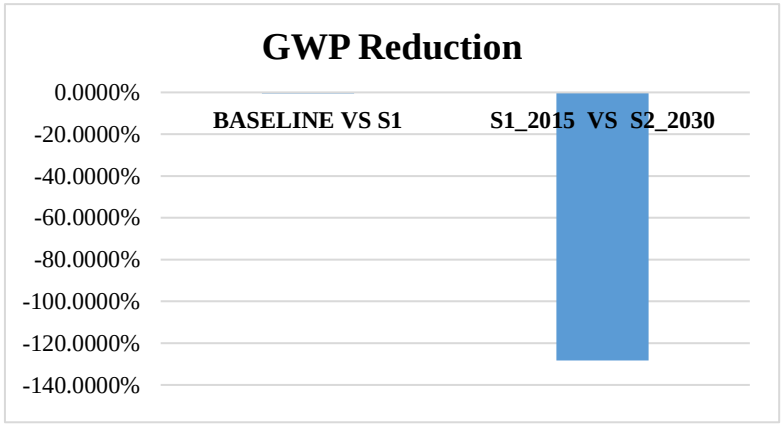

Figure 25. Comparative results for GWP100 reduction potential from sensitivity analysis

This scenario is assumed feasible could potentially be achievable from the assumption of direct CCU from CCS Peterhead facility, hence, extending its potential shown in the results.

6. RESULTS AND DISCUSSION

After modelling the implementation of the proposed PtG system for this study case, the evaluation of results of the performed LCA for the reduction of GWP are presented in a quantitative measure. Thus, comparing the avoided difference units of kilograms of CO_2-Equivalent ($kg_{CO2\text{-}eq.}$) obtained, to the levels obtained as reference from the baseline scenario.

$$GWP_{reduction} = \frac{Reference\ quantity - Scenario\ X\ quantity}{Reference\ quantity} \qquad \text{(Eq. 9)}$$

6.1 CO_2 reduction potential from utilization of PtG technologies

The wrongful, yet deliberate, assumption to consider the National gas consumption remains steady from 2015-2030 was considered to be modeled as such due to the lack of reliable and accurate data regarding the decrease of natural gas demand by 2030. Regardless of its mentioning in the latest releases by Scottish Government Energy Trend reports and statistical records of an annual decreasing tendency for natural gas consumption every year, still a high portion of the Sottish energy mix remains dependent on NG (Scottish Government, 2017).

The LCA-GaBi 6.0 modelling was carried as such, and after modeled and compared to the different scenarios and specifications, Scenario 2 yielded in the most promising results, given the key role to play of the substantial increase of available surplus electricity for the process. The results for the PtG scenario 2030, the total potential reduction of GWP in the magnitude of -2.1745E+07 $kg_{CO2\text{-}eq}$. These can be appreciated in a comparative graph in Figure 26

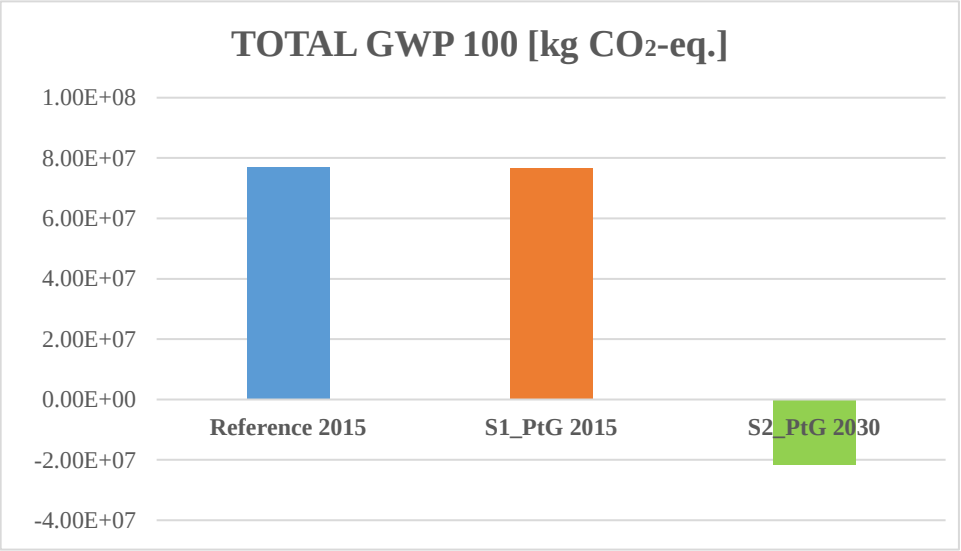

Figure 26. Total global warming potential (GWP) for 100 years of the three scenarios from GaBi 6

- UTILIZATION OF BY-PRODUCTS OBTAINED FROM THE SYSTMEM:

The influence of environmental indicators and impacts brought to the overall GWP by the production and end-use phases of the by-products produced in the system, were purposely left un-tracked in the delimitation of the system boundaries for the proposed study case. However, this does not mean that these have no impact or influence in the environmental impact category assessed.

The potential of utilization for the O_2 produced in the electrolysis process has been previously discussed in the literature review. Establishing that oxygen is a valuable fuel with a great demand for utilization in the metallurgic industry, as chemical feedstock or for aeration in waste water treatment processes (Lehner, et al., 2014; Uusitalo, et al., 2016).

7. CONCLUSIONS

The PtG concept proposed for this study complies with all of the characteristics outlined by Lehner and the German Energy Agency ((DENA), Deutsche Energie-Agentur GmbH. German Energy Agency, 2015). Therefore, fitting the adequate criteria for the supposed implementation of this technology in a specific location: at close range to Peterhead CCS plant for CO_2 availability. Electricity supply coming initially from 30MW floating offshore Hywind Scotland Pilot Plant, which was assumed to be operational by 2015, even though It began operations in October 2017. Is at close range for delivery outputs of H_2 and SNG to the grid at St. Fergus gas terminal. Both heat from methanation and from Peterhead power plant CCS facility could be used for the regeneration of MEA in the CO_2 capture process or derived to the district heating network. Lastly, maintaining proximity to potential buyers, as Aberdeen City and Aberdeenshire hold great demands for natural gas that could potentially be replaced, to an extent, by renewably produced SNG as illustrated in literature and in Figure 27.

Figure 27. Illustration of the potential location for proposed case of PtG in North-East Scotland (Source: (Equinor ASA, 2018)

Some of the drawbacks or constraints to this theoretical proposition for the implementation of a PtG system to reduce GWP from use of conventional natural gas, could be the sizing of plant for electrolyzer stacks, methanation reactors, capital expenses are not considered

within this study but most likely would play a role of high relevance to the give decision making of this proposes study case. However, as concluded, the highest GWP reduction potential was achieved when the case of the PtG for 2030 is available yielding in -2.1745 $kg_{CO2\text{-}eq}$. for the 2 714 938 MWh (8.42E+09 MJ_{el}) introduced in the system. This is a possibility due to the several increase in the upcoming offshore wind installed capacity. The yield for potential GWP reduction could be substantial if coped with direct generation of hydrogen to methane and direct utilization of CO_2 available from the CCS facility.

Lastly, the obtained results were compared to those from Sternberg and Bardow's LCA study to assess the environmental impacts of Power-to-SNG, and these were consistent, as for them, the environmental impacts of the Power-to-SNG assessed, for each 1kWh of electricity, yielded in 8.20E-02 $kg_{CO2\text{-}eq}$. In contrast, after transforming the energy units and quantities obtained by our study and convert them to equivalent units to make the results comparable, the results from the best scenario (S2_2030) yield in 2.43-E02 $kg_{CO2\text{-}eq}$ per kWh of reduction for GWP from our study. Hence, making this a compelling case for promoting the potential for CO_2 reduction via PtG technology utilization for the North-East of Scotland as a suitable pathway to follow towards achieving the ambitious pursued targets for the quick de-carbonization of the current, and future, Scottish energy system.

8. REFERENCES

(BEIS); Department of Business, Energy & Industrial Strategy, 2017. *Sub-national gas consumption data.* [Online]
Available at: https://www.gov.uk/government/collections/sub-national-gas-consumption-data
[Accessed 3 February 2018].

(DENA), Deutsche Energie-Agentur GmbH. German Energy Agency, 2015. *Power to Gas system solution. Opportunities, challenges and parameters on the way to marketability.*, Berlin: Deutsche Energie-Agentur GmbH (DENA). German Energy Agency.

4C Offshore Ltd., 2018. *4C Offshore Ltd. - Kincardine Offshore Windfarm Project.* [Online]
Available at: https://www.4coffshore.com/windfarms/windfarms.aspx?windfarmId=UK2H
[Accessed 3 February 2018].

4C Offshore Ltd., 2018. *Global Offshore Renewable Map - 4C Offshore.* [Online]
Available at: https://www.4coffshore.com/offshorewind/
[Accessed 3 February 2018].

Abu-Zahra, M. R. et al., 2007. CO2 capture from power plants Part I. A parametric study of the technical performance based on monoethanolamine. *International Journal of Greenhous Gas Control*, 18 December, pp. 37-46.

Barbir, F., 2004. PEM electrolysis for production of hydrogen from renewable energy sources. *Solar Energy*, 19 October, Volume 78, pp. 661-669.

Beatrice Offshore Windfarm Ltd., 2017. *Beatrice Offshore Wind Farm Ltd - One of the largest ever private investments in Scottish infrastructure.* [Online]
Available at: https://www.beatricewind.com/
[Accessed 3 February 2018].

Budzianowski, W. M., 2017. Assessment of Thermodynamic Efficiency of Carbon Dioxide Separation in Capture Power Plants by Using Gas-Liquid-Absoption. In: W. M. Budzianowski, ed. *Energy Efficient Solvents for CO2 Capture by Gas-Liquid-Absoption.* Wrocław, Poland: Springer International Publishing, pp. 13-26.

Buttler, A. & Spliethoff, H., 2017. Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, 9 September, pp. 2440-2454.

Carmo, M., Mergel, D. L. F. J. & Stolten, D., 2013. Comprehensive review on PEM water electrolysis. *International Journal of Hydrogen Energy,* 14 March, pp. 4901-4934.

Decourt, B., Lajoie, B., Debarre, R. & Soupa, O., 2014. *Hydrogen-Based Energy Conversion Factbook,* s.l.: SBC Energy Institute.

dena, German Energy Agency, 2015. *Power to Gas system solution: Oportunities, challenges and parameters on the way to marketability,* Berlin: German Energy Agency.

Department of Business, Energy & Industrial Strategy (BEIS), 2018. *Department of Busienss, Energy & Industriak Stratery National Energy Statistics.* [Online] Available at: https://www.gov.uk/government/statistics/energy-trends-section-6-renewables [Accessed December 2017].

ENEA Consulting, 2016. *The potential of power to gas - Technology revie and economic potential assessment*, Paris: ENEA Consulting.

EPA, 2014. *Global greenhouse gas emissions data.*. [Online] Available at: https://19january2017snapshot.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data_.html

Equinor ASA, 2018. *Hywind—the world's leading floating offshore wind solution.* [Online] Available at: https://www.equinor.com/en/what-we-do/hywind-where-the-wind-takes-us.html
[Accessed 3 February 2018].

Eurostat, 2017. *Natural gas consumption statistics.* [Online] Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_consumption_statistics

Ferreroa, D., Gambaa, M., Lanzinia, A. & Santarelli, M., 2016. *Power-to-Gas Hydrogen: techno-economic assessment of processes towards a multi-purpose energy carrier,* Torino, Italy: Elsevier Ltd.

Götz, M. et al., 2015. Renewable Power-to-Gas: A technological and economic review. *Renewable Energy,* 3 August, Volume 85, pp. 1371-1390.

HM Government, 2008. *Climate Change Act,* s.l.: HM Government.

Holopainen, A., 2015. *Carbon sources for Power-to-Gas applications in the Finnish energy system,* Lappeenranta, Finland: Lappeenranta University of Technology.

IEA, International Energy Agency, 2017. *Renewables information: Overview - Statistics 2017,* s.l.: IEA, International Energy Agency.

IIEA, The Institute of International and European Affairs, 2017. *Brexit: A status report,* Dublin: The Institute of International and European Affairs.

IRENA, International Renewable Energy Agency, 2016. *Renewable Energy Statistics 2016,* Abu Dhabi: International Energy Agency (IRENA).

ISO International Organization for Standardization, 2006. *Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006). European Standard EN ISO 14040.,* Geneva, Switzerland: The International Organization for Standardization.

ISO International Organization for Standardization, 2006. *Environmental management - Life cycle assessment - Requirements and Guidelines (ISO 14044:2006). European Standard EN ISO 14044.,* Geneva, Switzerland: The International Organization for Standardization.

Koponen, J., 2015. *Review of water electrolysis technologies and design of renewable hydrogen production systems,* Lappeenranta, Finland: Lappeenranta University of Technology.

Kotowicz, J., Jurczyk, M., We˛cel, D. & Ogulewicz, W., 2016. Analysis of Hydrogen Production in Alkaline Electrolyzers. *Journal of Power Technologies*, pp. 149-156.

Lehner, M., Tichler, R., Steinmüller, H. & Koppe, M., 2014. *Power-to-Gas: Technology and Business Models.* s.l.:Springer.

Leonzio, G., 2016. Process analysis of biological Sabatier reaction for bio-methane production. *Chemical Engineering Journal,* 15 April, Volume 290, pp. 490-498.

Lesnen, A., 2015. Wind power generates 140% of Denmark's electricity demand.. *The Guardian.*

Müller, K., Fleige, M., Rachow, F. & Schmeißer, D., 2013. Sabatier based CO2-methanation of flue gas emitted by conventional power plants. *Energy Procedia*, Volume 40, pp. 240-248.

National Grid, 2018. *National Grid UK.* [Online] Available at: https://www.nationalgrid.com/uk/about-grid/our-networks-and-assets/gas-and-electricity-network-routes
[Accessed 21 October 2017].

Qadrdan, M. et al., 2015. Role of power-to-gas in an integrated gas and electricity system in Great Britain. *International Journal of Hydrogen Energy*, pp. 5763-5775.

Reiter, G. & Lindorfer, J., 2015. Evaluating CO2 sources for power-to-gas applications – A case study for Austria. *Jorunal of CO2 Utilization*, 10(2015), pp. 40-49.

Reiter, G. & Lindorfer, J., 2015. Global warming potential of hydrogen and methane production from renewable electrocity via power-to-gas technology. *Int J Life Cycle Assess*, 20(2015), pp. 477-489.

Rosa, A. V. D., 2013. *Fundamentals of Renewable Energy Processes,* Oxford: Academic Press.

Schiebahn, S. et al., 2015. Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. *International Journal of Hydrogen Energy*, 25 February, Volume 40, pp. 4285-4294.

Scottish Carbon Capture & Storage, 2018. *Scottish Carbon Capture & Storage.* [Online] Available at: http://sccs.org.uk/expertise/global-ccs-map
[Accessed 3 February 2018].

Scottish Enterprise, 2017. *Oil & Gas diversification opportunities: Hydrogen,* Glasgow, Scotland: s.n.

Scottish Government, 2009. *Renewables Action Plan,* Edinburg, Scotland: Scottish Government.

Scottish Government, 2012. *Scottish Government Energy Statistics Website - Part 10 - Draft RLG - Offshore Wind - Deep Water Test and Demonstration.* [Online]

Available at: http://www.gov.scot/Topics/marine/marineenergy/Planning/windrlg [Accessed 3 February 2018].

Scottish Government, 2017. *Energy in Scotland 2017,* Edinburg, Scotland: Scottish Government.

Scottish Government, 2017. *Energy Strategy - Scortland's Energy Efficiency Programme (SEEP),* Edinburgh: The Scottish Government.

Scottish Government, 2017. *Scottish Energy Strategy: The future of energy in Scotland,* Edimburgh: Scottish Government.

Scottish Government, 2017. *Scottish Government Energy Statistics Website - Energy in Scotland 2017 - Data, Charts & Sources.* [Online] Available at: http://www.gov.scot/Topics/Statistics/Browse/Business/Energy/EIS/EIS2017data [Accessed 20 February 2018].

Scottish Government, 2017. *Scottish Government Energy Statistics Website - Reneable Electricity Output Calculator.* [Online] Available at: http://www.gov.scot/Topics/Statistics/Browse/Business/Energy/onlinetools/ElecCalc [Accessed 10 April 2018].

Scottish Government, 2017. *Scottish Greenhouse Gas Emissions 2015,* Edinburgh: Scottish Government.

Scottish Government, 2018. *Energy in Scotland 2018,* Edinburg, Scotland: Scottish Government.

Scottish Government, 2018. *Scottish Government Energy Statistics Website - Energy in Scotland 2018 - Data, Charts & Sources.* [Online] Available at: http://www.gov.scot/Topics/Statistics/Browse/Business/Energy/EIS2018 [Accessed March 2018].

Spath, P. L. & Mann, M. K., 2004. *Life Cycle Assessment of Renewable Hydrogen Production via Wind/Electrolysis,* Golden, Colorado: National Renewable Energy Laboratory.

Sternberg, A. & Bardow, A., 2015. Power-to-What? - Environmental assessment of energy storage systems. *Energy & Environmental Science*, 20 January, Volume 8, pp. 389-400.

Sternberg, A. & Bardow, A., 2016. Life Cycle Assessment of Power-to-Gas: Syngas vs Methane. *ACS Sustainable Chemistry & Engineering*, Volume 4, pp. 1456-1465.

Styring, P., Quadrelli, E. A. & Armstrong, K., 2015. Chapter 2 Carbon Dioxide Capture Agents and Processes. In: *Carbon Dioxide Utilization - Closing the Carbon Cycle.* Amsterdam, Netherlands: Elsevier Ltd., pp. 19-22.

Tagliapietra, S., 2016. A new way to approach Europe's gas security, beyond the usual Russian obsession. *Bruegel*, 3 February.

The Crown Estate, 2015. *Energy and infrastructure key facts 2015-16 - UK Carbon Capture and Storage*, Edinburgh, Scotland: The Crown Estate.

The Guardian, 2016. *The Guardian - Scotland's wind turbines cover all of its electricity needs for a day*. [Online]
Available at: https://www.theguardian.com/environment/2016/aug/11/scotland-completely-powered-by-wind-turbines-for-a-day
[Accessed 30 October 2017].

Tock, L. & Maréchal, F., 2014. *Life cycle assessment based process design of CO2 capture options.* Budapest, Hungary, Elsevier B.V.

United Nations, 2015. *Paris Agreement.* Paris: United Nations.

Uusitalo, V., Väisänen, S., Inkeri, E. & Soukka, R., 2016. Potential for greenhouse gas emission reduction using surplus electricity in hydrogen, methane and methanol production via electrolysis.. *Energy Convertion and Management*, 12 December.p. 9.

Varone, A. & MicheleFerrari, 2015. Power to liquid and power to gas: An option for the German Energiewende. *Renewable and Sustainable Energy Reviews*, 9 February, pp. 207-218.

Vattenfall, 2016. *European Offshore Wind Development Centre (EOWDC) - About the project.* [Online]
Available at: https://corporate.vattenfall.co.uk/projects/wind-energy-projects/european-

offshore-wind-deployment-centre/about-the-project/
[Accessed 3 February 2018].

Wang, M. et al., 2010. Post-conbustion CO2 capture with chemical absoption: A state-of-the-art review. *Chemical Engineering Research and Design*, 5 November, Volume 89, pp. 1609-1624.

Wilcox, J., 2012. Chapter 1. Introduction to Carbon Capture. In: *Carbon Capture*. New York: Springer-Verlag New York, pp. 1-34.