MSc Program
Environmental Technology & International Affairs

Renewable Energies in Scotland and Energy Storage Possibilities: Building a Theoretical Black Box Model in a Closed Hybrid Energy System

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **MARIA-SALUA GASAN ABHARI, MA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "RENEWABLE ENERGIES IN SCOTLAND AND ENERGY STORAGE POSSIBILITIES: BUILDING A THEORETICAL BLACK BOX MODEL IN A CLOSED HYBRID ENERGY SYSTEM", 95 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Recent years have seen the rise of renewable energy and the use of alternative energy resources. This comes as the solution to the use of fossil fuels – a finite resource with immense adverse effects on the environment. The global effort for climate change mitigation needs immediate action and genuine commitment, if it is to succeed, and hence, the share of renewables into the energy mix should be continuously increased. Scotland is a northern country, part of the UK, which has built itself a reputation of an innovative nation with strong ambition and desire to develop and grow their renewables' potential. The country has some of the world's most ambitious targets and an electricity demand almost completely met by renewables. Innovative projects in the fields of low-carbon technologies and energy storage are developed across the entire country, with hydrogen being one of the main focuses of R&D. Energy storage is not a new concept and yet, in the context of renewables it acquires a new meaning with its capacity to bridge the gap between the intermittent nature of most renewable sources and the varying consumers' demand. Adopting a multi-layered approach, both social sciences and technical analysis of the topic are presented and build up the argument that innovative and creative thinking are needed for the successful implementation of renewables into the energy grid. A case study based on a closed system black box model explores to possibility for developing a hybrid energy system, comprised of on- and offshore wind, tidal power, and hydrogen, in the city of Aberdeen, Scotland. The technological advancements are present, it is only a matter of configuring them in such way that they maximise the efficiency and accelerate the energy transition. And for that, it is only needed to think outside the box.

Table of Contents

List of Abbreviations

AREG – Aberdeen Renewable Energy Group

BERD – Business Enterprise Research and Development

EIS – Energy Investment Fund

EOWDC – European Offshore Wind Deployment Centre

GDP – Gross Domestic Product

GHG – Greenhouse Gases

HES – Hybrid Energy Systems

IEA – International Energy Agency

IRENA – International Renewable Energy Agency

MSIP – Michelin Scotland Innovation Parc

NIMBY – Not in my Back Yard movement

NO_x – Nitrogen Oxides

PM – Particulate Matter

PtG – Power-to-Gas

R&D – Research and Development

REIF – Renewable Energy Investment Fund

RSE – Royal Society of Edinburgh

SDGs – Sustainable Development Goals

SDI – Scottish Development International

STP – Standard Temperature and Pressure

UK – United Kingdom

UNEP – United Nations Environment Programme

Part I: Introduction, State of Art, and Methodology

1. Introduction

The global energy demand has steadily grown since the Industrial Revolutions and has experienced a drastic increase in recent decades. Truth to be said, energy is a multi-faceted concept, which in one way or another is part of every aspect of our lives. This could be interpreted on a very literal level, in the sense that energy in the form of food is needed to sustain life itself. However, it can also be construed as the driving force of a country's or, in fact, world's economy as well as a strategic area of focus in global politics. Furthermore, energy is inseparable part of science, technological advancement, and innovation. Yet, with globalisation and industrialisation, there is one very huge hiccup along the way of energy production and use that is the way in which energy is obtained. Nowadays, fossil fuels are the most affordable and accessible energy source. They are also a finite resource though, meaning that their exploitation and use is only possible up until the reserves are depleted, after which the industrial reality of today will be at a dead-end. Another issue that comes along the extensive use of fossil fuels and their sub-products is the negative impact on the environment of the planet Earth, which encompasses ecosystems, wildlife, climate, and human beings.

In order to avoid a climate change catastrophe and detrimental and irreversible effects to the environment, there is a dire need for alternative energy sources and even more so, a need for innovation and technologies, through which these alternatives can be implemented into the current state of matters. Those alternatives, such as the sun, wind, and water are all natural resources classified as infinite and hence, can be used as a source of renewable energy to replace the energy from fossil fuels. In reality, humans are no strangers to these (alternatives) and have long benefited from their use, e.g. wind power for maritime travel or windmills for grinding grain. The technologies for harnessing the energy of these infinite resources are present, some are already put in place and operational, and new ones being continuously developed. What is needed nowadays, however, is a large-scale, active implementation and adoption of renewably generated energy. This transition should be endorsed by states worldwide and included into national and international policies and strategies for development. Renewables should be part of the everyday agenda and a global push in that direction should be made.

With this thought in mind and because of personal interest of the author, renewables, specifically wind and tidal power, have been chosen as the main point of focus for the present master thesis. The objective is to offer a comprehensive study in the field of renewables and their implementation by focusing on the advancements made in a particular country. What the master thesis hopes to achieve is to provide an inter-disciplinary overview of renewables' potential in Scotland by exploring a number of differently-oriented areas, namely politics, socio-economics, technological and project development, in specificity – energy storage, as well as future possibilities for growth of the renewables sector. A further expected outcome is to present insights about green energy transition, based on a case study of the city of Aberdeen and its current performance.

The first part of the master thesis starts off with an introductory part, which presents the reader with a brief overview of the energy topic and the exact spot where renewables come in. It also specifies the key research question, area, aim, and expectations of the study as well as the structure that this work will follow. After the introduction, the analysis continues with a State of Art chapter, which will look in detail into the academic debate that surrounds renewable energy sources, exploitation, drives, and technologies. Additionally, this part will explore the global trends of development of renewable energy, resting on energy generation statistics and figures and adding up data about national and foreign investment into this field. A Methodology chapter will outline what analytical tools will be used to transfer the main ideas and findings into the most comprehensive way, which can serve both academics and non-professionals. As the research is based on an inter-disciplinary approach, a mix of research methods will be applied.

Having defined the field of study and the academic means to conduct said study, the second part of the master thesis will dive into the specifics from a social science point of view. As

Scotland will be the main research area, this part, comprised of four chapters, will look into the impact that renewables have on the state and its people. The areas that are of consequence and will be thus discussed are the political context, the socio-economic implications, the available technologies and project development, and finally how all of this impacts the life of Scots.

The third part will be on the technical side of the topic and it will expand the argument to energy storage possibilities, in particular hydrogen storage. One of the issues with renewables is that there are big fluctuations in the generation of energy based on time scale (day/night cycle for solar energy, inter-seasonal changes for wind, tide for water movement, etc.). For this reason, exploring energy storage is crucial to support the argument that innovative thinking is needed when it comes to the successful implementation of renewables. This part will begin with the theoretical background of energy storage and it will then continue with the mechanism of hydrogen as a means to store energy generated from renewable sources. Finally, it will look into a range of hydrogen storage/usage projects already developed and in operation across Scotland.

The fourth part of the thesis is dedicated to the specific case study of Aberdeen – the third biggest city in Scotland, previously known as the petrol capital of Europe, and now with a clear vision for energy transition. The first chapter of this part will give information about the city – its oil industry and the sustainable projects that are currently in development or already up and running – and will set up the boundaries for the research area of the case study. Afterwards, it will proceed with the discussion of the city's energy needs and the plausibility of establishing a hybrid renewable energy system, based on on- and offshore wind power, tidal power, and hydrogen storage/usage. With this possibility defined, the last chapter will seek to build a theoretical black box model for a green city that explores the energy demand for electricity, heating, and transport and whether that can be met wholly from renewables. The model will look into the existing infrastructure and what additional efforts should be made to achieve this green energy supply. Reference projects and initiatives will be given as rough estimates for the funding that has to be invested into such endeavour. The chapter will then present the findings as well as the limitations of such model.

The final part of the thesis will summarise the most crucial facts and findings, on which a conclusion will be drawn of whether the potential of renewables is enough to completely replace fossil fuels in the current structure of the system. Another objective expected especially from the case study is to demonstrate whether thinking outside of the box and constructing a hybrid system with energy originating from a mix of renewable sources can serve as a successful strategy to complete a green transition.

2. *State of Art: Transition to Renewables in the World*

Energy is invested in every part of goods production processes and provision of services and it can be argued that energy is at the very core of life, both on existential and material level. Energy is an important element defining world's economies, political action, academia, and technological development. The development of renewables has largely increased in recent years and their implementation into the national girds has been on the rise. The present Chapter offers on overview of the global trends for energy generated from renewable sources. Firstly, it examines the negative side of fossil fuels and explains why there is a need for alternative energy sources. Secondly, it will look into the various types of renewable resources, the current trends, the geographical locations, and the degree to which they are developed, in terms of political, economic, social, and technical aspects. Then, it will expand to a discussion of the world leaders in terms of investment and renewable energy generation, before it continues with an outline of the development of renewable resources in the United Kingdom, and specifically Scotland, in the next part.

At present, fossil fuels are the main source of energy and account for more than 80% of the global energy consumption, with oil in the lead, followed by coal and gas (Ritchie, 2021a; Rapier, 2020). However, the use of fossil fuels comes with a price. They are a finite resource and considering the trend of sharp increase of their use in the last half a century – *"around eight-fold since 1950, and roughly doubling since 1980"* (Ritchie and Rosen, 2021), a string of doubt arises regarding how much longer the available repositories can sustain the ever growing demand. Oil is the primary source of energy from fossil fuels and according to Selin (2020) confirmed reserves are to suffice the global demand until the middle of the century. This raises a key question: What is next? Given the fact that the global population is growing, there is a strong urbanisation trend, industry and transport are also further expanding, and simply based on historical evidence, it follows that the energy demand will only increase. Basically, the first and most apparent issue with fossil fuels is the fact that reserves are limited and not nearly enough to uphold the raise in demand.

A second and far more problematic issue stemming from the use of fossil fuels is their negative impact on the environment. The entire Earth system and its subsystems – Lithosphere, Hydrosphere, Biosphere, and Atmosphere, are being affected. For example, the mining and extraction of fossil fuels, regardless of whether it is coal, oil, or gas is changing the upper layer of the lithosphere, known as Earth's crust, and it further brings water (pollution with heavy metals) and air pollution (dust and particles carried by wind) as well as a potential danger for local communities (Bian et al., 2010). The hydrosphere and the water quality are negatively impacted as a result of the acid rain phenomenon, which is directly linked to the burning of fossil fuels and particularly to the SO_2 emissions in the atmosphere. As a consequence, water bodies such as lakes and rivers suffer from acidification (lower pH level, meaning a higher acidity), which then leads to detrimental effect on the aquatic life. (Likens and Butler, 2019). Plastics, as a sub-product of fossils, are also notably damaging the hydrosphere through the raising levels of plastics pollution in the ocean (Eriksen et al., 2014). The atmosphere and air quality are affected by the burn of fossil fuels for industrial and private use. Polluters such as particulate matter (PM), nitrogen oxides (NO_x), sulphur oxides (SO and SO_2), toxic chemicals, which contain heavy metals, carbon oxides (CO and CO_2) are all a consequence of the use of fossil fuels either in power plants or transport. Among these polluters, there are also gases (CO_2) contributing to the greenhouse effect, raising temperatures, and climate change. Ritchie and Roser (2021) claim that *"three-quarters of the global greenhouse gas emissions come from energy production",* whereas the figure given by the International Renewable Energy Agency (IRENA) is two-thirds (2018:3). Another process observed in the atmosphere is the formation of smog, either London- or Los Angeles type, which is also directly linked to the burned petrol/diesel from vehicles or from sulphur-containing coal in power plants (Britannica, 2019a).

The burning of fossil fuels also takes its toll on the biosphere. For instance the above mentioned phenomenon acid rain affects vegetation by damaging tree leaves and also degrading soils' composition and characteristics. A further impact from acid rain, which is more on an anthropological level, is on buildings where calcium-containing materials have been used for construction and which experience faster decay (Likens and Butler, 2019).

Humans form part of the biosphere as well and, aside from being indirectly affected by all of the above mentioned processes, there are also direct harms on human's health and well-being. These are manifested mainly in the respiratory and cardiovascular system of people and often lead to excess mortality (WHO, 2016:19; Landrigan et al., 2018:10; Lelieveld et al., 2019:7192). For example, the number of deaths caused by $PM_{2,5}$ has increased by 20% in the period between 1990 and 2015 (Landrigan et al., 2018:12). The same research also points out that in 2015 around half of the deaths due to chronic constructive pulmonary disease are to be attributed to all pollution combined (2018:10). Other studies show that air pollution has also grave neurological effects on the brain. For instance, an epidemiological research has found that PM could be potentially related to Alzheimer's disease and Parkinson's disease pathogenesis (Heusinkveld et al., 2016:94). Scholars like Payne-Sturges et al. (2019) also explore the topic and identify that combustion-related air pollutants and exposure to them can have harmful effect on the development of the brain, which is then linked to deficit in memory, intelligence, and behaviour. Kotcher et al. (2019:2) further the argument about the negative neurological impact by providing concrete examples, such as *"neurological disorders, including neurodevelopmental impacts in children and neurodegenerative effects in older adults"*. A very new research published by Harvard T.H. Chan School of Public Health offers quite a dark picture, claiming that one in five early deaths in 2018 were due to the burning of fossil fuels (Vohra et al. 2021). With their findings the authors also show that PM pollution from fossil fuels is more easily controlled than from other PM sources (dust) and with this they underline the need to shift towards clean energy sources. It is undeniable that fossil fuels have been a drive of the industrial expansion and economic growth. However, this has come at a very high price, which has already rendered almost impossible to cover as the negative effects from fossil fuels are so vastly observed and experienced. The previous paragraphs have briefly outlined the most notorious impacts from the burning of fossil fuels, yet the list is in no way exclusive, and only serves as a ground for building the argument that renewable energy sources are a much needed and viable way forward.

Renewable energy refers to energy that originates from infinite natural energy sources and is then transformed into a useable type of energy, i.e. heat, electricity, power, or fuel. There is a number of sources of renewable energy – the sun, wind, water (rivers and tidal power), geothermal, and biomass (Selin, 2020). Reports from international consultancy companies and organisations study the global trends in renewables and establish that their share has experienced a rapid growth and has even enabled the renewable sector to compete with conventional energy sources (KPMG, 2016; Deloitte, 2018, IEA, 2020a). Frankfurt School of Finance & Management together with the United Nations Environment Programme (UNEP) have also studied the global trends in the field and point out that *"renewable technologies (excluding large hydro) raised their share of global generation to 13.4% in 2019, from 12.4% in 2018, and just 5.9% in 2009"* (2020:11). This figure is slightly different than the value given by Ritchie (2021b), namely 15.7% coming from low-carbon energy sources (yet, it has to be said that this figure combines energy generated from both nuclear and renewables). Despite the difference observed, the important element here is the fact that the implementation of renewables and their use is steadily increasing. Further evidence supporting this claim is the fact that many countries worldwide are adopting renewable energy policies to guide and back up their national energy transition.

From a global political perspective, as of 2019, a total of 158 countries had put such policies in place, for comparison in 2005 only 48 countries had frameworks regulating the renewables sector (REN21, 2020). Without these supportive policies as well as investment and funding, the renewable sector would not have been able to grow and compete with the conventional energy sources the way it does nowadays (Ciarreta et al., 2017:396). Furthermore, when supporting the development of renewables, states attract foreign investors, which can then serve as an improving factor for national welfare (De Arce and Sauma, 2016; Yang et al., 2018) and with this their own economic development is also stimulated. Additionally, the implementation of renewables brings a number of positives on societal level, such as reduced emissions, which benefit the health and well-being of people. Besides national level policies, there is also a number of international incentives and targets related to the climate change mitigation strategy, the most remarkable current examples being the Paris Agreement and the Sustainable Development Goals (SDGs). With the former, the envisioned reduction of GHG emissions and the global temperature, both a result of the use of fossil fuels, cannot be achieved without the endorsement of alternative energy sources and renewable energies are the most suitable tool for the achievement (Pursiheimo, 2019:1119). With the latter, *"a powerful framework for international cooperation to achieve a sustainable future for the planet"* is established (Gielen et al., 2019:38). SDG 7 is the one that focuses on ensuring access to affordable, reliable, sustainable, and modern energy for all (UN, 2015). As energy is an intricate matter it is also covered in targets and incentives for the other 16 SDGs. In order to ensure a successful energy transition, the measures and strategies adopted should be quite ambitious and adapted to the changing circumstances of the global context. On one side, an example for the ambition of the climate change mitigation efforts is the target provided by the roadmap of IRENA, which states that the share of renewable energy in the energy mix should increase to two-thirds by 2050 (IRENA, 2018:9). On the other side regarding the changing circumstances, the past year and the global pandemic of COVID-19 have shown how much the energy sector can be affected. According to the International Energy Agency (IEA) in 2020 the energy demand declined by 4%, which is *"the largest decline since World War II and the largest ever absolute decline"* (IEA, 2021a:6). However, what the Agency remarks is that renewables are more resilient to the global health crisis than other energy sources and in 2020 have actually experienced an increase of 3%, with a further increase across all sectors – power, heating, industry, and transport expected in 2021 (IEA, 2021a:3). This figures only back up the idea that renewables should have their place in the energy reality of today, even if the transition process is not that easy and straightforward. In his study based on empirical research, Sovacool (2016:202) demonstrates that energy transition occurs over time and sometimes it can take decades or even centuries to occur. However, he also argues that future energy transition can be accelerated because of a political or societal drive behind, as opposed to previous transitions which have more or less happened in an accidental or circumstantial way (Sovacool, 2016:210). Based on the argument that has been presented so far, it follows that the transition towards renewables can be accelerated for a number of reasons, such as the limited resources of fossil fuels or the adverse effect of their use on the environment.

In terms of economic context, it is worth saying that renewables bring a significant change as well. In their article, Yazdi and Shakouri (2017) study the correlation between economy and renewables consumption in Iran. They establish that that there is a two-way causal relationship between economic growth and renewable energy. And even though, their research is based on Iran, the claim itself can actually be applied to every country. This is due to the fact that from one side the renewables sector nowadays brings a lot of investments and its development can contribute to a national's economy growth. From another side, countries which develop their renewable sector are more attractive opportunity for foreign investments as they give a safer ground to put money into. In other words and also as put by Masini and Menichetti (2012:37), it is important and also beneficial to develop the potential of renewable energy sources as the performance of the portfolio attracts more investors. Data from the KPMG report (2016:2) shows that between 2004 and 2015 there has been an 18% increase of new investment in renewables, with a higher share in developing countries. At the same time, Deloitte's report (2018:16) elaborates on the fact that emerging energy markets are becoming the leading markets in the renewables field. The following table extracted from the Global Status Report (REN21; 2020:36) demonstrates the top five countries and the different renewable energy sources, in which they invest.

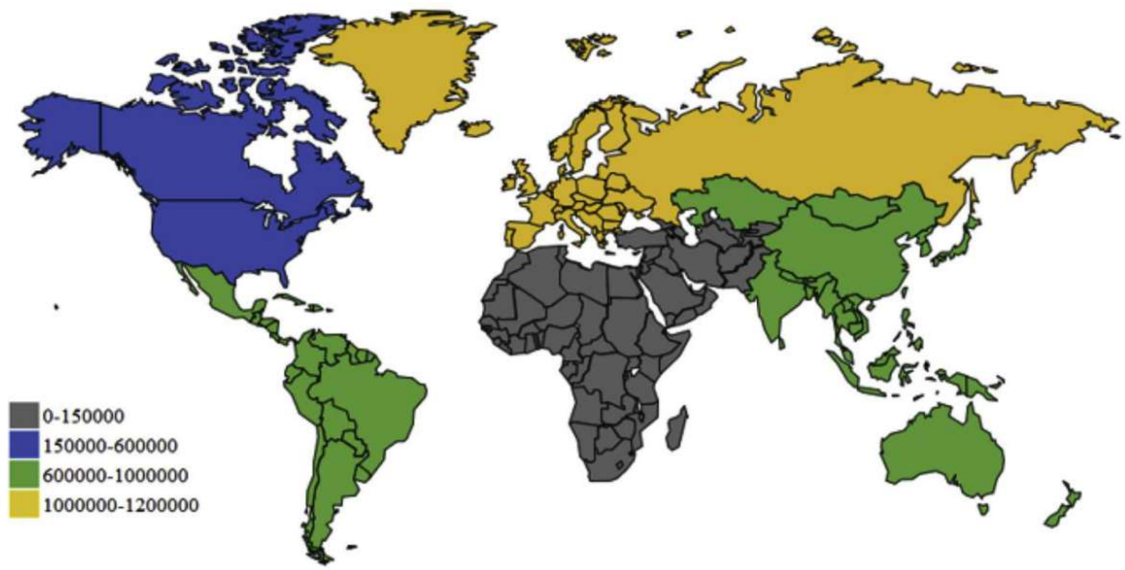
Table 1: Top 5 Countries Investing in Renewables

Annual Investment / Net Capacity Additions / Production in 2019
Technologies ordered based on total capacity additions in 2019.

	1	2	3	4	5
Investment in renewable power and fuels capacity (not including hydropower over 50 MW)	**China**	United States	Japan	India	Chinese Taipei
Solar PV capacity	**China**	United States	India	Japan	Vietnam
Wind power capacity	**China**	United States	United Kingdom	India	Spain
Hydropower capacity	**Brazil**	China	Lao PDR	Bhutan	Tajikistan
Geothermal power capacity	**Turkey**	Indonesia	Kenya	Costa Rica	Japan
Concentrating solar thermal power (CSP) capacity	**Israel**	China	South Africa	Kuwait	France
Solar water heating capacity	**China**	Turkey	India	Brazil	United States
Ethanol production	**United States**	Brazil	China	India	Canada
Biodiesel production	**Indonesia**	United States	Brazil	Germany	France

What is clearly seen from that table is that predominantly developing and emerging economies are on the lead of global investment in the renewables sector. The report further specifies that *"Investment in renewable power and fuel capacity accounted USD 282.2 billion"* – an increase of 1% from the previous year (REN21, 2020:165) and, yet, another confirmation that the growth in renewables continues.

Renewable energy is basically energy obtained from infinite natural sources like the wind or the sun and that has been turned into a useable form of energy, namely heat, electricity, and fuels. That is why, it is important to underline that the renewable energy generation is geographically defined and somewhat limited to local availability and capacity. The following map shows renewable energy generation by region in 2016 (extracted from Xu et al., 2019:4).



Map 1: Renewable energy generation by region in 2016

It is noticeable that Europe and Asia are the two regions with most substantial energy generation from renewables. They are followed by Latin America, where hydro power covers around 50% of the demand, and the Asia-Pacific region where solar capacity is large. North America is in the middle and Africa and Middle East region have a relatively low percentage of renewably generated energy. When looking into the geography of renewables, it is important to also mention the world leader in energy production and consumption – China. From its leading position and as a highly industrialised country, China has a crucial role in the global energy transition process. The country has set targets to increase the share of renewables and thus, satisfy its growing energy demand as well as to reduce industry related air pollution. In the 13th Five-Year Plan for Energy Development from 2016, China has committed to decrease carbon emissions by 60-65% per unit of GDP by 2030. By the same year, non-fossil fuel energy sources should reach 20% (Gielen et al., 2019:39).

Aside from the geographical characteristic, renewable energy capacity is also defined by the availability of technology, which can harness the energy and meet the demand (Østergaard et al., 2020:2430). New technologies are constantly being developed and improved, so that the highest possible efficiency and outcome can be achieved. A very recent example for a new technology in the field of renewables is the new type of bladeless wind-generating turbines that have been developed by a Spanish company (Ambrose, 2021). In their article, Rexhäuser & Löschel (2015) argue that the improvement of renewable energy technologies is crucial for a cost-effective, competitive, and sustainable energy supply. A further argument offered by Dincer (2001:83) is that the development of technologies actually reduces maintenance costs, it betters the reliability, and improves the efficiency of energy generation and conversion. The IRENA report (2018:33) offers an overview of a wide range of technologies, for example new energy sources like batteries and fuel cell in combination with information and communication technologies (ICT) can alter the transport industry. Another figure provided by the report is an over 90% reduction of energy-related CO_2 emissions that can be achieved through technologies together with improved energy efficiency and implementation of renewables (IRENA, 2018:9).

In terms of benefits for the society that stem from the use of renewable energy, in first place come the health-related improvements. As already discussed, the burning of fossil fuels and the exposure to the pollution has a number of adverse effects – from cardiovascular and respiratory problems to neurological impact and carcinogenic potential (Kirk, 2020). Thus, implementing renewable sources of energy reduces the emissions and the health risks that they bring. In the second place, societal benefit from the adoption of renewables is that they can become a key factor against climate change by decreasing the GHG emission levels in the atmosphere (REN21, 2020:58, IRENA, 2021). Other important element underlining the relationship between society and renewables is in fact the society's awareness of renewable energy. The understanding of the field by the public influences the behavioural trends in the community. This basically means that the more aware and informed the public is, the easier it is to implement renewable energy projects. Such conclusions are also reached by Mirza et al. (2009:931) in their study of the sector in Pakistan. In their study on The Netherlands Flacke & De Boer (2017:2) discuss the limited capacity of local institutions in terms of decision-making powers for renewable's project implementation as well as the phenomenon of Not in my Back Yard movement (NIMBY). For this reason and as the authors stress, it is really important to raise the awareness of the people about the benefits of a given renewable project and also to put the given project in the bigger picture of the renewables' reality (Flacke & De Boer, 2017:13).

3. *Methodology*

The master thesis is based on a multi-disciplinary approach and a combination of social sciences aspects and technical elements are to be discussed. For this reason, the methodology and tools of analysis will also comprise a mix of research instruments. Each following part of the thesis will adopt a specific approach, which has been selected as best suited to serve the purpose of the respective part. In this Chapter, the methodology applied to each part will be discussed in detail and reasoning for the selection of the given method will be given.

However, one more additional remark should be first made. The present master thesis in its integrity has been based on a top-down approach, which is building the argument towards the final part where a case study is presented. The discussion preceding the last chapters is quite important for the wholesome understanding of the topic and the proposed model. The benefit of the top-down approach is that it first allows a look at the 'big picture'(Hayes, 2021), namely the global and then Scottish trends of renewable energy transition as well as energy storage technologies before diving into hydrogen technology and the hybrid energy system concept. Just as in investment theory, where the top-down approach originates, this master thesis initially focuses on global level, continues with national scale and sector analysis (both renewables and energy storage), and finishes up with a specific case study that encompasses all of the above elements.

Part II: Renewables in Scotland – figures, policies, economy, and society, presents the topic of renewable energies in Scotland from a social science perspective. That is to say that two crucial areas will be studied – politics and socio-economics. The analysis of the overview Chapter 1 will be based on statistical datasets and comparisons of the figures. Chapter 2 will combine historical analysis, aimed at establishing the process of political evolution in the UK, and a comparative analysis of a series of legal documents, national policies and strategies. The comparative analysis of the legal and policy documents allows tracing the transition process and the evolution of a given area, in this case – energy. Chapter 3 will keep the same analytical framework but will instead focus on the economics and project development of Scottish energy transition. Chapter 4 examines and presents the social impacts that the green energy transition has. This comparative research method and the underlying historical and statistical analysis were chosen as the most suited tool for the construction of an integral analysis of various official sources from different social sciences areas. Furthermore, this method enables the reader to acquire a deeper understanding of complex legislative and political matters in Scotland. One of the issues that comes with the study of legal documents specifically is the fact that often the language and structure of speech are professionalised and thus, sometimes result difficult to comprehend. Another aspect in terms of difficulty when studying political documents is that the UK has a very specific system of governance. Due to this fact a very wide range of bills, acts, plans, etc. are produced and each has a differing degree of authority. Hence, this is discussed in detail in this part. Another challenging factor is that even though the policy documents (especially Plans and Reports, are not primary law) have been written by the same legislative body, the figures and statistics are often measured in different units. To avoid big discrepancies in the data presented in the thesis, a thorough research of the documents has been conducted and same value sets have been used.

Part III: Energy Storage Possibilities covers the more technical side of the master thesis, by exploring energy storage technologies as a complementary means to render renewably generated energy as a viable way towards decarbonisation. This part in itself also adopts top-down approach by starting with analysis of energy storage as a whole. Chapter 1 presents a comparative technical discussion of the various types of most commonly applied storage technologies. Chapter 2 submerges into the specifics of hydrogen storage and usage technology as it is to serve as a foundation of the case study in the following part. In this Chapter 2 hydrogen usage is compared to the use of fossil fuels and aspects such as pros and cons of the two energy sources are examined. Chapter 3 is based on a profile building of hydrogen in the Scottish context. This is achieved through presentation of the most notorious projects in the sphere of hydrogen that are developed and operational or currently under construction across the entire country. The research methods selected for this part are considered fitting as they enable the presentation of complex concepts and technological mechanisms in a simple and comprehensive way. This is particularly important as one of the aims of the present work is to be accessible for academics and non-professionals alike. Additionally, the profile building method allows the structure of the chapter to be slightly more different, namely the projects are to be presented in a table format. This will facilitate the reader and it will also provide for a quick and easy reference tool.

Part IV: Aberdeen – A Case Study on Renewables Potential and a Green City Model is the final and most specific part of the present work. It presents a case study on the city of Aberdeen which in itself is also divided into a social science part that is based on the economic and general social performance of the city in the context of renewable energy transition (Chapter 1), and a technical part, which discusses the possibility for developing a hybrid energy system in the city that is set upon the existing energy infrastructure and projects (Chapter 2). Chapter 3 develops a black box model in the context of a closed system (i.e. the city) as a representation of the hybrid energy system that combines on- and off-shore wind power, tidal power, and hydrogen. The idea behind a black box model is that it allows seeing the structural characteristics of a system in terms of level of detail, linearity/non-linearity, and the dynamics of said system. The areas which are scrutinised in this model are electricity, heating, and transport. Additionally, as a way to integrate the model into the actual development of the energy sector in the city, a conceptual framework has been extracted from Powering Aberdeen – an action plan published by Aberdeen City Council (2016). The proposed hybrid energy system will be observed in light of the framework below.

Figure 1: Powering Aberdeen Five Themes Framework

The advantage of using a case study as a research method is that it allows the transfer of all accumulated theoretical elements discussed into the previous parts in a concrete example of how they fit a real-life context. The black box modelling serves as a simple tool to illustrate the flows of energy through the system and the conceptual framework of Powering Aberdeen offers a possibility to put the theoretical model of a hybrid energy system up against the actual expectations. Of course, such modelling has its limitations and cannot provide an integral instrument for real project implementation. However, it offers a starting point and a consideration of an alternative low-carbon energy technology that has not yet received the due attention from the R&D and industry sectors. Finally, the case study also serves the purpose of the argument that is – in renewable energy transition it is not only about the technology availability, but also about the innovative thinking that can make this technology work.

Part II: Renewables in Scotland:

figures, policies, economy and society

1. How far is Scotland in its Transition to Renewables' Journey?

In the past 20 years Scotland has become a country with a very strong development of the renewables' sector and some, including former Scottish first minister Alex Salmond and the current UK Prime Minister Boris Johnson, even compare it to Saudi Arabia in terms of renewables' potential (Diamond, 2020). Considered as the windiest country in Europe, Scotland holds 80% of the total wind generation in the UK (Department for Business, Energy and Industrial Strategy, 2021). Hence, wind, both on- and offshore, is the main renewable source for energy generation but others such as solar, tidal, hydro, etc. are also being developed (BBC, 2015; Scottish Government, 2020a; i.d., 2021a). The pie chart below extracted from Scottish Renewables (2021) represents the renewables energy portfolio of the country in terms of electricity generation, once more demonstrating wind is largely dominating. A percentage share has been calculated and added to the figure for each renewable energy source.

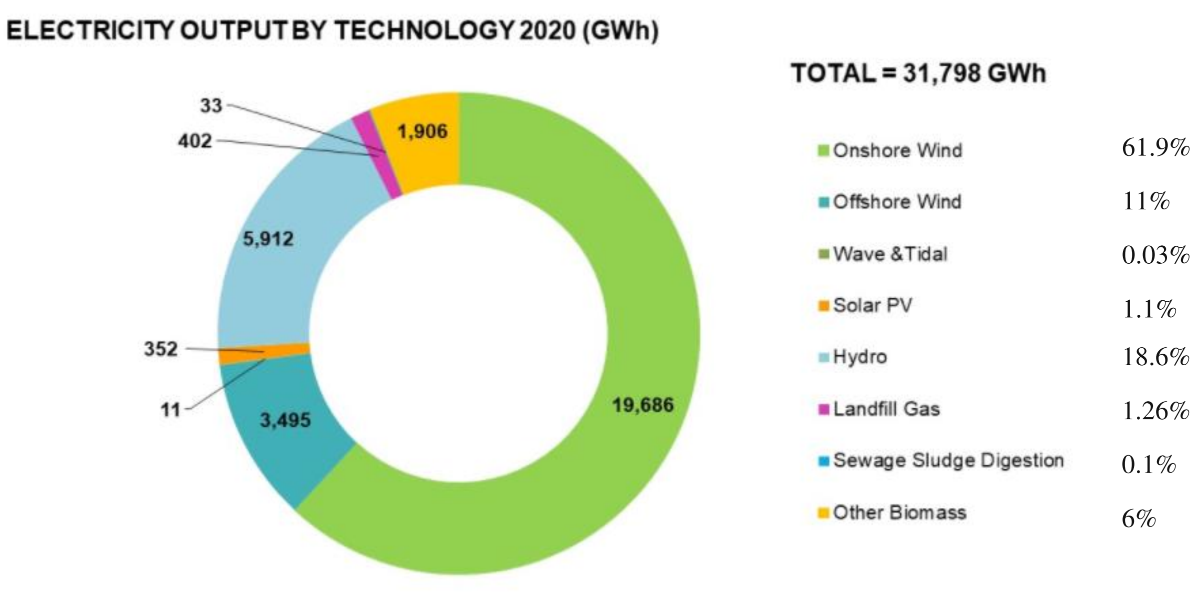


Figure 2: Electricity Output by Technology 2020 in Scotland

A bit over a decade has passed since 2009 when renewables accounted for only 27.2% of Scotland's electricity and the progress made has been exceptional (Elliot, 2019). 2020 has seen a record number registered for renewably generated electricity – 97.4% or else 31 798 GWh, which narrowly missed the ambitious target of 100% electricity generation from renewables (BBC. 2021, Scottish Government, 2021b). The next figure taken from the Q4 Energy Statistics report puts that number – 97.4% of electricity generated from renewables in a bit more practical context (Scottish Government, 2021b).

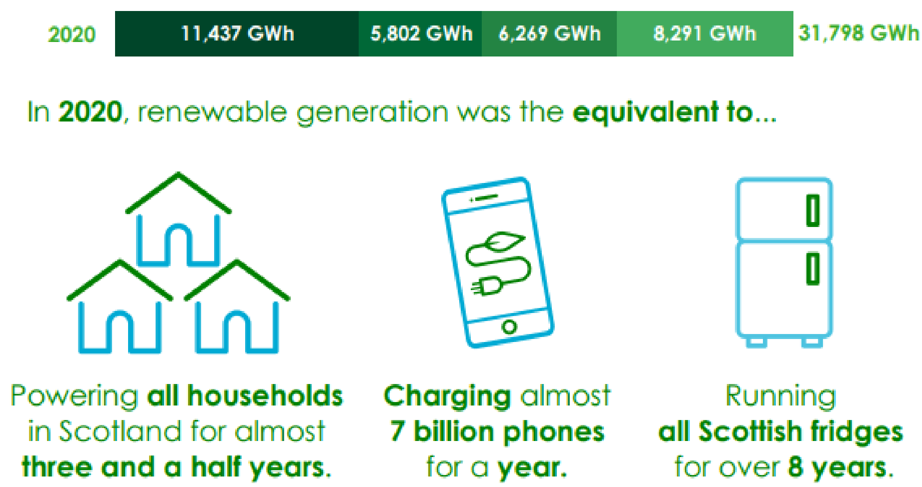


Figure 3: 2020 Electricity Generation and Possible Practical Applications

The Scottish Government has set itself and the country a number of ambitious targets, which would lead the way towards reducing emissions, offsetting the use of fossil fuels, and eventually reaching a net-zero. In a national review related to the SDGs, the Scottish Government (2020b:86) attests: *"We believe Scotland should be a world leader in affordable and clean energy. This ambition is shared across the public, private and third sector, and is being advanced through legislation, local and central government policy, community action and a focus on corporate sustainability"*. The figure presented below indicates the targets in a couple of key areas and measures their progress (Scottish Energy Statistics Hub, 2021). The results are showing that in general terms the country is well on track of achieving the set targets and in some areas it is in fact outperforming the expectations.

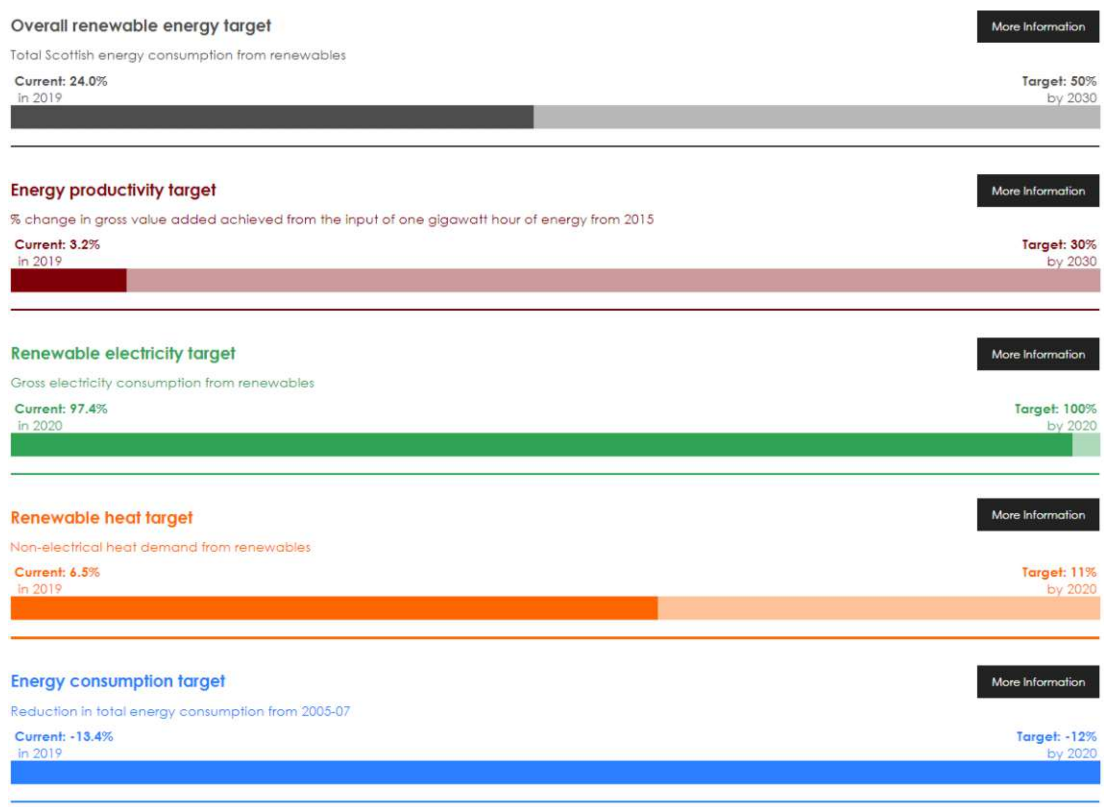


Figure 4: Overall Renewable Energy Target

The energy transition in the country is indeed well supported by the legislative and policy frameworks. It is evident that Scotland has a strong commitment to the development of the renewable energy sector, which would benefit first, the state itself and second, the global efforts to reduce the use of fossil fuels and to tackle climate change. The legislation is being continuously developed and updated based on performance. The Government poses challenging expectations and targets, but it also provides for funding and investment opportunities that can support the green energy transition. The following Chapters study in detail the political context of Scotland and focus on energy legislation as well as the socio-economic impact that the development of the renewable industry has on the life of Scots.

2. *National Energy Policies and Legislation*

Before diving into the specific Scottish legislation related to energy policy and strategies, it is very important to define and explain the nationwide political context of the UK, namely the devolution principle. Devolution becomes a reality in 1998, when referendums were held in Scotland, Wales, and Northern Ireland. The word 'devolution' finds its roots in Latin and more or less indicates the action of 'rolling down'. In politics, the concept does not change much and it means that a certain degree of power has been transferred from the central government to subnational authorities (Hauss, 2020). There is one very important remark that has to be made here in regards to the difference between devolution principal and federal or con-federal system of governance. In a federal context, all parts have their sovereignty and are autonomous from the central federal entity. In a devolved context, the system is uniform with the central governing body having the last word on matters, meaning that the powers conceded to the devolved institutions can be reversed (Torrance, 2019:4). The United Kingdom (UK) and its devolved institutions are established with an UK statute and are not a consequence of constitutional amendments. The devolution in the UK is characterised by an asymmetrical structure, which grants varying level of power to the three devolved states, namely Northern Ireland, Wales, and Scotland (Torrance, 2019:4). As the last one is actually the subject of this master thesis, it is also important to mention that the Scottish Parliament (Holyrood)[1] as a devolved institution has mandate over both primary and secondary legislation. With this mandate Holyrood has power over a range of areas and can both introduce (new) laws and act upon them. The areas where the Scottish Parliament can act freely are referred to as 'devolved matters'. Yet, there is still a number of spheres, which are known as 'reserved matters' and which are only governed by the UK Parliament (Westminster)[2]. Additionally, the UK Parliament as the highest

[1] Scottish Parliament and Holyrood (the building where the Scottish Parliament is based) are to be used interchangeably.

[2] UK Parliament and Westminster (the building where the UK Parliament is based) are to be used interchangeably.

authority and sovereign entity of the UK can legislate on any matter, even on those that normally fall under devolved matters. However, it is worth mentioning that this is not a usual practice of Westminster (Scottish Parliament, 2021a). Schedule 5 of Scotland Act 1998 – the document that introduces the devolution principle – is where reserved and devolved matters are defined. Under devolved matters fall the following categories[3]: *health and social work, education and training, local government and housing, justice and policing, agriculture, forestry and fisheries, the environment, tourism, sport and heritage, economic development and internal transport* (UK Government, 2019). The spheres that are classified as reserved matters are predominantly those that are of consequence for the national interests of the entire United Kingdom, namely *the constitution, foreign affairs, defence, international development, the Civil Service, financial and economic matters, immigration and nationality, etc.*[4] (UK Government, 2019). Since 1998, the Scotland Act 1998 has been updated and thus, some amendments to the devolved and reserved matters have been made.

In the context of devolved institutions, energy has a very specific place as only some energy-related aspects fall under the reserved matters category, e.g. electricity, coal, oil and gas, and nuclear energy. Even though, the UK Parliament can legislate on these, the Scottish Parliament holds the mandate over environment and planning (UK Civil Service). This leads to some discrepancies between the two Parliaments, as based on environment and planning grounds Holyrood can interject decisions taken by Westminster. The most suited example that can represent this conflicting context dates back to 2009 and is related to the construction of a new power plant in Scotland (decision taken by UK Parliament under the right to legislate on reserved matters). However, Holyrood intercepted the development of the plant based on their devolved authority in environmental protection and planning of energy infrastructures (Little, 2009:37). Based on the asymmetrical devolution, the way decision-making power is attributed to one or the other in different areas that are

[3] This is not a complete list of the devolved matters.

[4] This is not a complete list of the reserved matters.

directly linked to energy though, and the sometimes differing interests on UK-wide and Scottish level make the energy a somewhat problematic field of the political debate. Another good example presenting this controversial nature of energy in the devolved context is the Scottish independence referendum from 2014. At the time, one of the pillars on which the independence movement and claim were built, were the North Sea extensive oil and gas reserves as well as the renewables potential of the Scottish land (Goodall, 2014). Even though, the independence referendum has been unsuccessful, the stance made indicates the mighty energy capacity that Scotland has and also reiterates the dependence of the rest of the UK on energy imports from Scotland. Nonetheless, according to some academics the achievement of Scottish independence would have meant a loss of subsidies and funding from the UK budget and consequently, a loss of competitive advantage in terms of renewables development and implementation (Toke et al., 2013:4). Since the referendum, the renewable capacity of Scotland has grown significantly. Taking that into consideration some scholars claim that, either accidentally or on purpose, the UK has stopped some of its funding and subsidies for carbon capture and energy storage technologies (Little, 2016:394). This can also be seen as a way to prevent a second Scottish Independence Referendum and in a way to keep the energy-rich country that Scotland is, within the borders of the UK.

Even with the energy controversy, resulting from the devolved political system, Scotland has an outstanding performance in terms of energy generated from renewable sources. Ellis et al. (2013:403) point at the aspirations of the Scottish Government *"to generate an equivalent of 100 per cent of Scottish demand for electricity from renewable energy resources by 2020"*. When consulting the present figures it is evident that Scotland has been very close to achieving that rate. In 2019 around 90% of the total electricity generation has been from renewables (Frangoul, 2019; Webster, 2020) and in 2020 the country fell behind its 100% goal with just a bit over 3%, recording a rate of 97.4% of renewably generated electricity (BBC, 2021a; Scottish Government, 2021b). This has all become a reality due to a series of Scottish national policies, strategies, and packages for renewable energies. The devolved powers in planning and environment have allowed the country to more or less shape and guide its own energy development, despite the fact that energy in itself is a reserved matter. It is important to underline the fact that the renewable energy transition in Scotland has an early start back in 2004, when there has been a push for the development of 'fully fledged' energy policy. A further development has been the introduction of the junior ministerial position of 'Minister for Enterprise, Energy and Tourism', which was filled by Jim Mather in 2007, when the then new Scottish National Party (SNP) created the role (Scottish Parliament, 2021b).

The next big step in the Scottish energy development is marked by the Climate Change (Scotland) Act 2009. Based on a Bill accepted by Holyrood in June 2009 and with the Royal Assent obtained a month later, the Act aims at setting up a gas emission target for 2050 with an interim target for 2020. The values given to the two milestone years are defined into Part 1, Section 1(1) and Section 2(1). The former establishes that by 2050 the emissions target should be at least 80% lower than the baseline level. The latter indicates that the interim goal of 2020 is to be at least 42% lower emissions than the baseline value (Climate Change Scotland Act 2009)[5]. Said baseline values are to be set on different years depending on the type of gas that is emitted and are defined in Section 11 and 12 of the Act. For example for CO_2, CH_4, and N_2O the baseline is 1990, whereas 1995 is set as a baseline year for hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride (Climate Change Scotland Act 2009). In a report from 2018 presented by the Committee on Climate Change (CCC) is shown that the performance in regards to the achievement of the interim goal outlined in the Act 2009, namely 42% lower emissions, is very good. This is argued in the light of the fact that *"Emissions on the net basis in 2016 were 45% below 1990 levels. Scotland is currently outperforming the interim target for at least a 42% reduction in net emissions by 2020"* (CCC, 2018:7). Because of the recorded figures and the UK commitment under the Paris Agreement, the Climate Change (Scotland) Act 2009 has been revised and more ambitious goals have been set. In May 2018 a new Climate Change Bill has been introduced before the Scottish Parliament. The most significant change proposed is related to the final value of 90% reduction of gas emissions from the baseline year 1990

[5] Source: The National Archive

(a 10% increase of the value set in the Climate Change (Scotland) Act 2009). Another amendment made is about methods through which gas emissions are measured (CCC Report, 2018:6). Based on the progress made, the Bill undergoes a revision the following year and offers even more ambitious targets than the previous policies. It envisions a net-zero emissions by 2045, 5 years earlier than the initial plan, and it also establishes a system of more frequently monitored interim targets, i.e. 56% reduction by 2020, 75% by 2030, and 90% by 2040 (Scottish Government, 2021c). A Royal Assent to the Bill is given in October 2019 and a second Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 is presented. The objective of this more ambitious policy is not only to drive the national interests of climate change mitigation and renewables' development, but also to contribute to the achievement of the Paris Agreement goals. The Scottish Government (2021d) identifies low-carbon energy solutions and renewable energies as the main element needed for establishing a low-carbon economic model. Based on the challenging nature of the new Act 2019 and the international commitments, it can be claimed that the renewable sector is a crucial tool in the climate change mitigation efforts.

Another instrumental tool, which helps enact the provisions of the Climate Change Scotland Act (both 2009 and 2019) are a series of Climate Change Plans. These are to be presented every five years and their purpose is to offer a range of proposals and policies, which can help achieve the targets set out in the Act. Truth to be said, in the first ten years since the Act 2009 was adopted, three supporting Plans have been published, the most recent version dating from 2018 and updated at the end of 2020. This latest version of the Plan covers the newly established targets from the Climate Change (Scotland) Act 2019 and the period between 2018 and 2032 (Scottish Government, 2020). A further insight brought up by the 2020 update of the Plan is in regards to the global COVID-19 pandemic as it sets out a green recovery strategy. The Plan from 2018 has been built on three pillars: 1) the climate change proposals and policies, 2) the Scottish Government and its statutory duties, and 3) trajectories for emission reduction in each sector (Scottish Government, 2018a). The 2020 update is more or less based on the same ideas, but with the more ambitious targets for a net-zero emissions by 2045 in mind, it also offers a strategy to *“maximise the opportunities to deliver a thriving, sustainable economy”* after the pandemic (Scottish Government, 2021d).

3. *Economic Impact and Project Implementation*

It has already been established that investment into the renewables has been substantial and gradually increasing, with USD 282,2 billion invested in 2020 (REN21, 2020:165). Scotland has also attracted a fair share of investments into the sector, with both national subsidies and direct foreign investment streaming into the country. According to the official records, Scotland's goal is to invest into low-carbon technologies, such as hydrogen storage and usage, harnessing renewables such as wind or tidal power, etc. (Climate Change Plan – Update, Scottish Government, 2020c). The country has put in place a number of national funds, which are to serve this purpose. For example, funding (both debt and equity funding) is provided by the Energy Investment Fund (EIS), which is available to projects that are already partially funded. The EIS is to succeed the Renewable Energy Investment Fund (REIF) and the available funds account for £20 million, which can benefit both community and commercial projects. Another important aspect is that Holyrood is looking into diversifying the renewables portfolio of the country and establishes that 'most of the low carbon economic activity in Scotland so far has been associated with the provision of renewables and low carbon electricity, but there is significant economic turnover for some other sectors, including provision of energy efficiency products and low carbon services' (Scottish Government, 2021d). Funding in this area comes from the Low Carbon Innovation Fund, which provided £60 million to support renewables as well as the building of a low carbon infrastructure (Scottish Government, 2018a). There are also a number of other funding opportunities[6], for example the Energy Efficiency Programme (£500 million for low carbon heating and energy efficiency measures), the Renewable Energy Scheme (£45 million for 600 local energy projects), and the Wave Energy Scotland (£38.6 million for 86 projects) (SDI; 2021a). Other possibilities for funding come as a consequence of the Climate Change Plan Update (Scottish Government, 2020c) and these are: a £180 million Emerging Energy Technologies Fund, £120 million for Zero Emission Buses, £50 million to transform Vacant and Derelict Land, and £50 million to create active Freeways (i.e.

[6] The examples given here provide only partial funding.

sustainable links between cities). The varying range of funds is established to support Scotland on the path of achieving net-zero emissions. However, it is also important to underline that those financial means also help small businesses across Scotland that are willing to engage and thus, *"benefit from engaging in climate change mitigation through energy efficiency and low carbon heat and by promoting sustainable practices"* (Scottish Government, 2021d).

Due to its promising renewable capacity, Scotland is also a prime location for foreign investment in the sector, a claim that is also made by the Scottish Government, which says that Scotland is *"a highly attractive key location for investment in renewables"* (Scottish Government, 2020d:48). Scottish Development International (SDI) is one of the governmental agencies which identifies Scotland as a 'world leader' and establishes that the renewables industry is the best ground for investment opportunities (SDI, 2021a). So, aside governmental funds, the country also has a number of projects developed with funding from foreign investors. Dickie (2020) argues that Scotland has been *"one of the most successful parts of the UK outside London for attracting foreign investment"*. The figures given in his article and relevant for 2019 demonstrate that the share of foreign direct investment projects in Scotland has been higher than the share recorded for the entire UK – 7.2% as opposed to 5,2% (Dickie, 2020). The northern country has also worked on developing an inward investment strategy, in which nine strategic areas are defined and in relation to which Scotland should *"identify and proactively target 50 leading global companies"* that can respectively invest in one of the nine (Scottish Government, 2020d:8). Good examples that demonstrate the foreign investment in the renewables field are the Michelin Scotland Innovation Parc (MSIP) and Amazon, which invests in wind capacity projects, both on- and offshore (SDI, 2021b; Glover, 2021). MSIP is a partnership project developed in cooperation with the Dundee City Council, Michelin, and Scottish Enterprise. The Parc is located in a now closed Michelin Tyre Factory and its aim is to address the global climate emergency through focusing on decarbonistation technologies and sustainable mobility (MSIP, 2021a). The second big investor Amazon already has its share in the Scottish wind industry, namely the onshore wind farm at Kennoxhead in South Lanarkshire. The project has been *"the largest single site corporate power purchase* *agreement in the UK"* at the time of signing (Walker, 2020). As of April 2021, Amazon has announced another investment on Scottish land, this time in the North East. The new project investment is for the development of an offshore wind farm that is to be located off the coast of St Andrews (Glover, 2021).

The growing renewables sector has also seen for the development of many diverse projects in the field, all of which aimed at supporting the transition to net-zero emission system. Since the implementation of all this projects has an impact on the Scottish population, Holyrood engages in quite a few different incentives and activities, all while keeping people informed and where possible also making room for public participation. For instance, the Energy Efficiency Scotland Programme (EESP) is built on the ambitious goal to *"transform Scotland's buildings to be warmer, greener and more efficient"* (Scottish Government, 2018b:2). A Route Map – the main instrument of the programme – determines the action plan for the next 20 years which is to work towards a net-zero carbon buildings. In other words, the EESP is aimed at improving the energy efficiency of buildings (where feasible) both in the public and private sphere. It is expected for the EESO to attract between £10 and £12 billion of investment into energy efficiency measures (Scottish Government, 2018b:23). Another advantage of the programme is that through the improved building energy efficiency, there will be a reduction in the heat demand and thus, a reduction of GHG emissions and fuels used will be observed. Another added value is that better buildings' energy efficiency will also lead to a decrease of energy poverty levels (Scottish Government, 2018b:5). Furthermore, the implementation of the programme itself serves as tool for promoting sustainable life culture and as it aims at a nearly net-zero carbon buildings in 20 years, it also means that it will reach out to the larger public and potentially will have the power to make a difference in the lives of Scots, particularly in remote and rural areas.

A more local example for the development of a project, which has a direct positive impact on the community, is the H2 Aberdeen. This is a project developed in the field of green transport implementation that forms part of the Aberdeen Hydrogen Strategy (2015-2025). H2 Aberdeen started operation in 2015 with a fleet of 10 hydrogen fuel cell buses and the cost for the project development has been reported as £19 million, which were provided from Scottish, UK, and European partners (Fuel Cells Bulletin, 2015:13). Aside from the hydrogen bus fleet, which has since 2015 grown and even included double-deckers in October 2020, the project has also built two hydrogen fuel stations that are with an open access for the public (Aberdeen City Council, 2020). The H2 Aberdeen has brought a series of benefits for the city and its people. From one side, this green transport alters the nature of public transportation as well as the environmental perceptions and experience of the general public. From the other side, it also changes the health impact that the conventional public transport has. Busses running on fossil fuels produce emissions through which they contribute to air pollution and climate change. Hydrogen technology and thus, hydrogen fuel cell buses, however, only emit water vapour. This automatically implies a reduction of the CO_2 emissions in the city. For example, the 15 double-deckers added to the fleet have been operational since January 2021 and until April 2021 they have prevented an estimate of 170 000 kg of CO_2 to be released in the atmosphere, which is the equivalent of 42 cars being stopped from running for a year (Wood, 2021). This reduction of emissions also means a reduced exposure of the local community to harmful compounds and particles and is of added value for the human respiratory and cardiovascular system. The developers of the project have not limited themselves only to hydrogen buses, but have also introduced other hydrogen vehicles and offer two hydrogen fuelled cars for hire (Aberdeen City Council, 2019). With this project it is really important to point out that it is a pioneer in the commercial use of hydrogen for public transportation and it also has quite a few positives for Aberdonians.

4. *Scots and Renewables*

The example of H2 Aberdeen demonstrates how low-carbon technologies become an inseparable part of the lives of locals. Yet, there are many other aspects of the everyday life that are influenced by the growth of the renewables sector. In order for renewable projects to be welcomed and better accepted by the society, information is really crucial. Holyrood has researched the behaviour of the general public in regards to climate change and emission reduction. What has been found as a result is that when implementing renewables projects an integrated approach should be taken. This should rest on engagement and communication with the public as well as programmes that are combining together a number of energy related aspects (Scottish Government, 2013). Eventually, it can be argued that information is key for project development. However, projects cannot be completed without a workforce and here comes one of the biggest advantages for Scots. The ambitions of the national policies, the international commitment, and the increasing share of investment are all factors that contribute to the growth of the renewables' sector. With this employment rates are also positively influenced and growing. In their report to the House of Commons on the Renewable Energy Sector in Scotland, the Convention of Scottish Local Authorities argues that *"renewable energy schemes alleviate fuel poverty in remote and rural communities across Scotland, and also offer significant opportunities for job creation and economic growth in these areas"* (COSLA, 2016). This trend of growing employment rates is shown by Scottish Renewables, which between 2013 and 2014 discerns an increase of 5% in the number of people employed in the sector (Scottish Renewables, 2014). In more recent years that growth has been sustained, with 70 000 employees in renewables – a number which does not take into consideration the supply chain workers and yet, accounts for 2,7% of the total employment (RSE, 2019:41). For that statistic of 2016, a further figure is provided by the Climate Change Plan 2018, which determines that a bit less than 50 000 jobs were in the field of low carbon technologies and renewable energy industry (Scottish Government, 2018a:46). Employment in the renewables sector is also supported by a governmental initiative which has been introduced by the Climate Change Plan update. A Green Jobs Fund based on an investment of £100 million has been created (Shreshta, 2020). The aim of the fund is to help businesses adopt sustainable, low carbon products and services (Scottish Government, 2020e). This fund is created under the strategy for green recovery proposed by the 2020 update of the Climate Change Plan and is envisioned as a tool for achieving a multi-dimensional impact in the business fields. First and foremost, the fund will help companies adopt sustainable practices and where feasible become carbon neutral. As a consequence more job opportunities will be created as those businesses will need manpower to lead them on the way to sustainability. Secondly, the fund will provide support training and education of qualified and skilled workers, who can more successfully contribute and effectively develop the path towards a net-zero system. Additionally, it will fund the retraining of workers from industries that are largely incompatible with a renewable strategy, such as oil and gas. Lastly, but also very importantly, a proportion of this fund will be directed towards the creation of so called 'youth job opportunities' in land-based or nature jobs and with this it will not only support the professional development of young individual, but will also raise environmentally aware people (Scottish Government, 2020e).

Another field where renewables have a significant impact is the academia and research and development (R&D). The practical side of project implementation is undoubtedly important and is defined by factors such as policies, investment, and workforce. However, the technological advancement, based on academic research and a number of R&D trials, are of as much importance as the above mentioned. For this reason, it can be argued that Scotland is also experiencing an increase of investment into the academic field. For instance, the Royal Society of Edinburgh (RSE) studies the R&D aspect in light of renewables development. The recommendations made by RSE are that on one side, R&D should go in line with the national policy targets and on the other side, that the legislation should be more aware of the R&D needs. A further recommendation emphasises the need for attracting more investment to R&D as well as the need to educate a skilled workforce (RSE, 2019:114). Despite the fact that RSE recommends the strengthening of the relation between policies and R&D, there are already examples for investments in the research field. In 2019, Scotland has spent 12.7%, equal to £179 million, of its total Business Enterprise Research and Development (BERD) in the energy growth sector (Scottish

Government, 2021e:4). In terms of academia itself, Scottish universities have a strong presence in the world's top universities, with 5 in the top 200 list (SDI, 2021a). This indicates the high quality of higher education in the country. Additionally, in the context of the UK, Scotland is leading in *"university spinouts and investment in higher education R&D"* (SDI, 2021a). According to SDI (2021a) *"there are over 700 renewable energy engineers, scientists, and academics, who represent the 'world's largest energy research group"*. The strength of the academic field serves as a ground for Action 13 of the Inward Investment Plan, which envisions to *"support stronger ties between academia and industry in Scotland"* (Scottish Government, 2020d:9). A great example for the creation of such bond is present at the MSIP, which has been developed as a working space where academia can meet the industry and the two can collaborate together – for instance connecting students and academics from Scottish Universities and the Michelin working professionals. MSIP is a facility with complementary advantages such as the Innovation Labs and Innovation Hub, the Skills Academy, the MSIP Accelerator (16-weeks programme that gives access to skills, knowledge, networks, and advice) (MSIP, 2021b).

Part III: Energy Storage Possibilities

1. Energy Storage – A Viable Way Forward?

Energy storage is not a revolutionary idea that has recently come out of the blue and shocked scientists and policy makers alike. It has in fact been around for quite a while and even used in the form of battery since the early 19th century and since the 1920s it has been applied to a large-scale pumped-storage of hydropower in the United States (Zabloki, 2019:1). Antoine Laurent de Lavoisier is one of the founding fathers of modern chemistry and he developed the principle of mass conversion, which can also be applied to energy storage. In his own words Lavoisier says *"Rien ne se perd, rien ne se crée, tout se transforme"*[7] (Wagner, 2014:613). Basically, from that it follows that the energy in a system stays constant; it cannot be created, nor destroyed, but it can be transformed from one form of energy to another (e.g. kinetic to electric energy). This idea is also valid for the energy storage technology and it means that the energy generated can be stored when the demand is lower and then at a peak demand, it can be discharged into the grid (Kalaiselvam & Parameshwaran, 2014:21). In terms of the academic fields, a more scientific definition of the energy storage technology would be: *"the storage of some form of energy that can be drawn upon at a later time to perform some useful operation"* (Wagner; 2014:613).

In the past decade the growing concerns over ecological impact of fossil fuels as well as the matter of depleting reserves, has turned the focus towards more innovative solutions, such as renewably generated energy complemented by energy storage solutions. In most cases, energy from renewable sources is generated regardless of the demand, but it also has time scale limitations, which are in the very nature of most renewable energy sources, e.g. solar energy fluctuating due to day/night cycle, wind power dependent on wind availability, etc. As Burheim (2017a:2) has put it, our society has transitioned from *"supplying energy on demand to supplying energy when energy is present"*. And here is where the energy storage

[7] Translation of the phrase: Nothing is lost, nothing is created, everything is transformed.

solution comes in as it can bridge that gap between temporal fluctuations of renewable energy generation and demand. This claim is further confirmed by Whittingham (2012:1519), who argues that *"renewable energy sources cannot be the sole provider of energy without an associated energy storage facility"* and that even if *"plugged into the grid, a storage device is required to smooth the output"*. Renewables are entering more and more into the energy mix and with their varying nature, the energy system itself will require a greater flexibility (IRENA, 2017:10). For this reason, another very important point that has to be made in regards to energy storage is on the multiple advantages and the fact that these can enable the development of a more flexible and responsive grid. In Ch. 27 of 'Future Energy', Wagner (2014:629) offers an overview of the benefits that stem from the adoption of energy storage technologies:

1) Serve as a safety net against long outages and grid overloads,
2) Meet demand from peak shaving customers,
3) Serve as a complementary mechanism for the successful implementation of renewables into the energy grid,
4) Have a favourable life-cycle cost, which includes capital and installation cost, operation and maintenance cost, and disposal cost,
5) Serve as a possible mechanism to diversify micro-grids and decentralised systems.

Based on these points, it can be argued that energy storage can indeed provide a viable way forward, especially when combined with renewable energy. However, what should not be forgotten is the fact that a number of energy storage technologies exist and that a very careful selection should be made on a case-by-case principle. The following paragraphs briefly present the different types of storage technologies

There are quite a few different types of energy storage technology based on the type of energy itself; they are further distinguished dependant on the specific storage mechanism that is used. A distinction is made between:

1) Electrochemical energy → batteries

   This type of energy storage is based on the transformation of chemical energy into electric energy. The main building elements of batteries are the anode, the cathode, and an electrolyte; their properties are defined by their chemical nature (Wagner, 2014:619)

2) Electrostatic energy → capacitors

   The electrostatic energy storage is working on the principle of storing energy as electric charges that result from applied voltage. As a mechanism capacitors have two metal or conductive plates that are separated by an insulating medium, where in fact the electric charges are stored (Kalaiselvam & Parameshwaran, 2014:31)

3) Electromagnetic energy → superconducting magnets

   In an electromagnetic storage system, the energy is stored within a magnet, which releases megawatts of power and is a mechanism to secure a sudden loss in line power (Wagner, 2014:622)

4) Kinetic energy → mechanical flywheels

   The essence of the flywheel is in a rotating motion and an electric motor, defined by storage phase when the system rotates, and discharge phase when the kinetic energy is used to regenerate the motor, which then functions as an electric generator (Kalaiselvam & Parameshwaran, 2014:23)

5) Potential energy →pumped-storage hydropower, compressed air, springs

   Example for widely applicable potential energy storage system is the pumped-storage hydropower. The mechanism is very straightforward with low demand periods used to pump up the water to a higher-ground reservoir and during peak demand use the gravitational force and turbines to generate energy (Wagner, 2014:625)

6) Thermal energy → ice, molten salts, steam

   Thermal energy storage is referred to the process of *"storing thermal energy in the form of sensible heat, latent heat, and reversible thermochemical reactions"* (Kalaiselvam & Parameshwaran, 2014:37). Based on the specific technology used, there is varying mechanisms.

Energy storage technologies and their effectiveness are measured through a couple of different parameters, namely time responsiveness to changes in the demand, the percentage of energy lost during the storage process, the storage capacity, and recharge timing (Zabloki, 2019:1). The following table extracted from a report of the World Energy Council presents the different types of energy storage technology and compares their technical characteristics (World Energy Council, 2016:872).

Table 2: Comparison of Major Energy Storage Technologies by Technical Characteristics

WORLD ENERGY COUNCIL | E-STORAGE

	Power rating (MW)	Discharge time	Cycles, or lifetime	Self-discharge	Energy density (Wh/l)	Power density (W/l)	Efficiency	Response time
Pumped Hydro	100 – 2500	4 – 16h	30 – 60 years	~ 0	0.2 – 2	0.1 – 0.2	70 – 85%	10 s – min
Compressed Air	10 – 1000	2 – 30h	20 – 40 years	~ 0	2 – 6	0.2 – 0.6	40 – 70%	min
Flywheels	0.001 – 20	sec – min	20000 – 100000	1.3 – 100%	20 – 80	5000	70 – 95%	< sec
Li-ion battery	0.05 – 100	1 min – 8h	1000 – 10000	0.1 – 0.3%	200 – 400	1300 – 10000	85 – 95%	< sec
Lead-acid battery	0.001-100	1 min – 8h	6 – 40 years	0.1 – 0.3%	50 – 80	90 - 700	80 – 90%	< sec
Sodium-sulphur battery	10 – 100	1 min – 8h	2500 – 4500	0.05 – 20%	150 – 300	120 – 160	70 – 90%	< sec
Flow battery	0.1 – 100	hours	12000 – 14000	0.2%	20 – 70	0.5 – 2	60 – 85%	< sec
Superconducting Magnetic	0.1 – 1	ms – sec	100000	10 – 15%	~ 6	~ 2600	80 – 95%	< sec
Supercapacitor	0.01 – 1	ms – min	10000 – 100000	20 – 40%	10 – 20	40000 - 120000	80 – 95%	< sec
Hydrogen	0.01 – 100	min – week	5 – 30 years	0 – 4%	600 (200bar)	0.2 – 20	25 – 45%	sec - min
Synthetic Natural Gas	1 – 100	hour – week	30 years	Negligible	1800 (200bar)	0.2 – 2	25 – 50%	sec - min
Molten Salt (latent thermal)	1 – 150	hours	30 years	n/a	70 – 210	n/a	80 – 90%	min

Excludes technologies with limited experience to date from multiple sources. Sources: Bradbury, K. (2010), "Energy Storage Technology Review"; IEC (2011), "Electrical Energy Storage. A White Paper"; Schlumberger Business Consulting (2013), "Leading the Energy Transition: Electricity Storage." Schlumberger Business Consulting Energy Institute, FactBook Series, World Bank ESMAP Technical Report 006/15 'Bringing variable renewable energy up to scale: Options for grid integration using natural gas and energy storage', and contributions from WEC Energy Storage Knowledge Network participants.

The energy storage technology that is of interest for the present work is hydrogen storage, which falls in the electrochemical energy storage category. However, the reason for which the different mechanisms are presented above is because of the fact that this is an overview chapter which studies the potential of energy storage as a whole in the context of the ongoing energy transition. With the increasing energy demand and with the more wide-scope implementation of renewables, the need for energy storage facilities will also increase. Sagadevan et al. (2021:2) argue that *"no single technology meets all large-scale* *grid performance storage demands and metrics"*. This argument further supports the claim that the energy transition should be supported by creative and innovative thinking. As a consequence, in terms of energy storage technologies, it follows that a mix of multiple technologies should be used – a fact that falls well with the innovative thinking framework. Zabloki cites IEA, which has estimated that to meet the target of keeping the global warming below 2° C, the storage capacity needed by 2030, should be 266 GW, which is a 100 GW more than the figure obtained in 2017 (176.5 GW) (Zabloki, 2019:2). Furthermore, as a complementary to renewables, the energy storage sector is also attracting more and more political and economic attention. A report from BloombergNEF (2018) has presented a forecast that the *"global energy storage market will grow to a cumulative 942 GW/2,857 GWh by 2040, attracting $620 billion in investment over the next 22 years"*. Additionally, having well-developed and efficient energy storage systems can ensure the sustainability of the energy sector, bringing positives from an environmental perspective as well (Burheim, 2017a:6). It also plays a critical role in terms of *"energy security of the current energy networks"* (Sagadevan et al., 2021:18). Lastly, if the energy storage sector develops well, this will also benefit the supply chain of the renewable sector, as it will allow for future expansion (Stevens et al., 2019). With all these arguments in mind as well as the brief technical analysis of the energy storage possibilities, it can be concluded that energy storage as a solution to some of the hindrances of the energy transition, particularly fluctuations in renewable energy, is a viable way forward.

2. *Hydrogen Storage and Use Technologies*

Hydrogen is the most abundant element in the universe and is characterised by the lightest molecular mass and the highest calorific value. In the nature it is most often found in the form of water, H_2O, a result of the high affinity between hydrogen and oxygen (Burheim, 2017b:147). Abe et al. (2019:15074) identify the large energy storage capacity of the element and explain that 1kg of hydrogen equals about 120MJ, which is double to the energy contained value of conventional fuels. For this reason, the IEA (2021b) has defined hydrogen as a *"versatile energy carrier, which can help to tackle various critical energy challenges"*. This idea for hydrogen storage capacity is explored by Burheim (2017b:147) as well and he argues that in this regard hydrogen is *"the most flexible energy storage medium available"*. However, hydrogen has a downside as it has a very low energy density, meaning that if compared to fossil fuels, then hydrogen definitely proves more challenging to be stored and transported. Yet, this is not a reason to give up on this promising element and technologies for hydrogen-based fuels can be used instead (IEA, 2019a:55). Under such form, the hydrogen can be utilised in a number of important sectors, namely in transport with hydrogen as fuel, in industrial and private buildings with hydrogen used for heating, and with hydrogen power supporting the responsiveness of the energy grid towards the shifting demand. Furthermore, hydrogen is identified as a very promising option for storage and distribution of large (in the scale of GWh or TWh) amounts of energy (Preuster, 2017:445). Another very important aspect with hydrogen use, especially in terms of transport but also industry, is that, regardless of whether it is burned or reacting with air in a fuel cell, the only by-product is water/water vapour (Abe et al., 2019:15074). This means that through the implementation of hydrogen storage/usage technologies, the air pollution emissions can be effectively reduced and with this, bring a series of health improvements.

In terms of storage technologies, hydrogen can be stored in the three physical states. In other words, it can be stored as compressed gas also known as Power-to-Gas (PtG), as a liquid or else, cryogenic hydrogen, or as a solid also referred to as metal hydride. The first technology – compressed hydrogen – is a process which requires a certain degree of work in order to be completed. The compression is achieved through the use of several compressors and with an optimum rate of compression around 700 bar, which allows a driving range of more than 450km and short refuelling timing of less than 3 minutes (Burheim, 2017b:169). PtG is intricately related to the compressed hydrogen storage technology as hydrogen is a product of an electrolysis process (World Energy Council, 2016:869), which transforms the energy generated into compressed hydrogen. Important remark that has to be made here is in regards to the electrolysis process. The principle behind it is the introduction of water to the reaction environment, where because of the electrical current occurs dissociation. The reaction products are hydrogen and oxygen atoms which are accumulated in different physical streams, after being put through ionic transfer mechanism (National Research Council and National Academy of Engineering, 2004:98). Advantages and applications of the PtG technology are that it allows storing energy generated from renewable sources and then using it when demand is high. A further application is in the transport sector with hydrogen-based fuel cells. The PtG can also be applied to industrial uses or it can be used as a means to satisfy the heating demand, for example replacing natural gas and pumping hydrogen into the existing networks (World Energy Council, 2016:869). PtG can also be stored at caverns, similarly to the compressed air energy storage, and it would be even more efficient, but such technology is still not commonly used (Burheim, 2017b:174). The second technology is known as cryogenic hydrogen, or even simpler – liquid hydrogen. The important element needed for this process to take place is the temperature. Liquefaction occurs at very low temperatures and proper medium should be present in order to avoid heat leakages (Abe et al., 2019:15076). However, this energy storage technology has its limitation, namely the fact that liquefaction of hydrogen is a very energy demanding process (Abe et al., 2019:15076) and as of now it would not prove economically promising and benefiting is applied to a large-scale dimension. The third technology for hydrogen storage in the solid phase is based on the formation of chemical bonds between the hydrogen and the metal hydrides. Due to the strong nature of the bonds, larger amount of energy (heat) is needed to release the hydrogen. On one hand, this process has the advantage to store more hydrogen at high density even at standard temperature and pressure (STP), yet, on the other, the release of hydrogen is more energy demanding (Andersson & Gronkvist, 2019:11905). An application of this method is when low-grade waste heat capacity is used to compress hydrogen in a process known as thermal swing adsorption (TSA), which is identified as one of the most promising markets for the use of metal hydride technology (Burheim, 2017b:174).

The technology that is of interest for the present work and in the context of renewable energy is in fact hydrogen as a means to store energy, i.e. the PtG technology. In order for hydrogen to become a storage medium the following sequence of events is needed. Firstly, energy is generated from a renewable source – the sun, the wind, tidal, etc. Then, there are two possible scenarios depending on whether the renewable facility is connected to the gird or not. If connected and demand is low, then any excess energy can be redirected to a hydrogen storage facility. If it is not connected, then all the energy generated goes to the facility for storage and transformation for later-use availability. Secondly, hydrogen is produced by the electrolysis process. Thirdly, it is stored in gaseous phase and when needed distributed into the network. Another possible use is in fuel cells, which can then be used for transport as well. This scenario is very well represented by the following image extracted from Burheim (2017b:148). What this image also adds is a comparison between the specific storage technologies and the conditions needed for optimum operation.

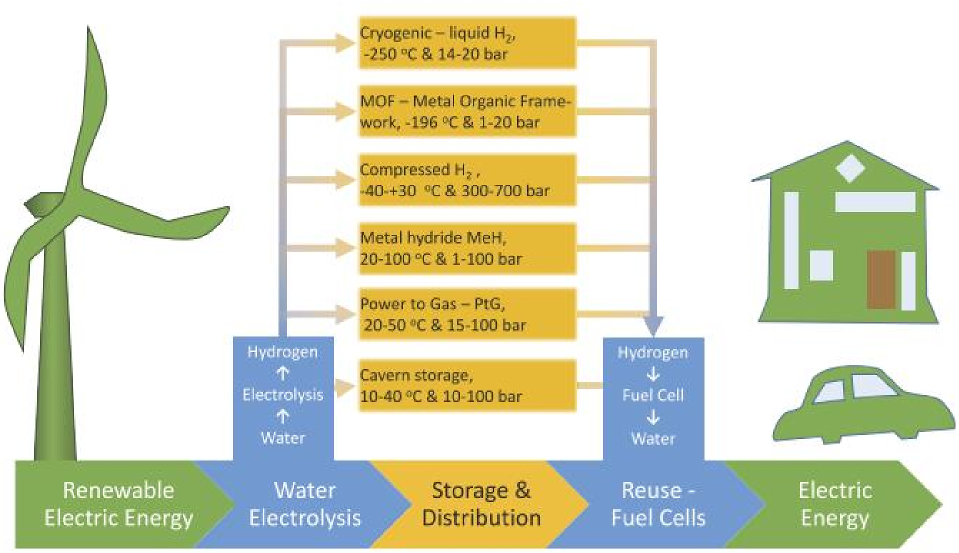


Figure 5: Hydrogen as an Electric Energy Storage Medium

Hydrogen has a very large potential to enter the energy mix and there are quite a few opportunities for its use in industry, transportation, infrastructure (buildings), and power (IEA, 2019a:123). The demand for pure hydrogen has been steadily growing since the 1970s and is represented in the following chart from IEA (2019b).

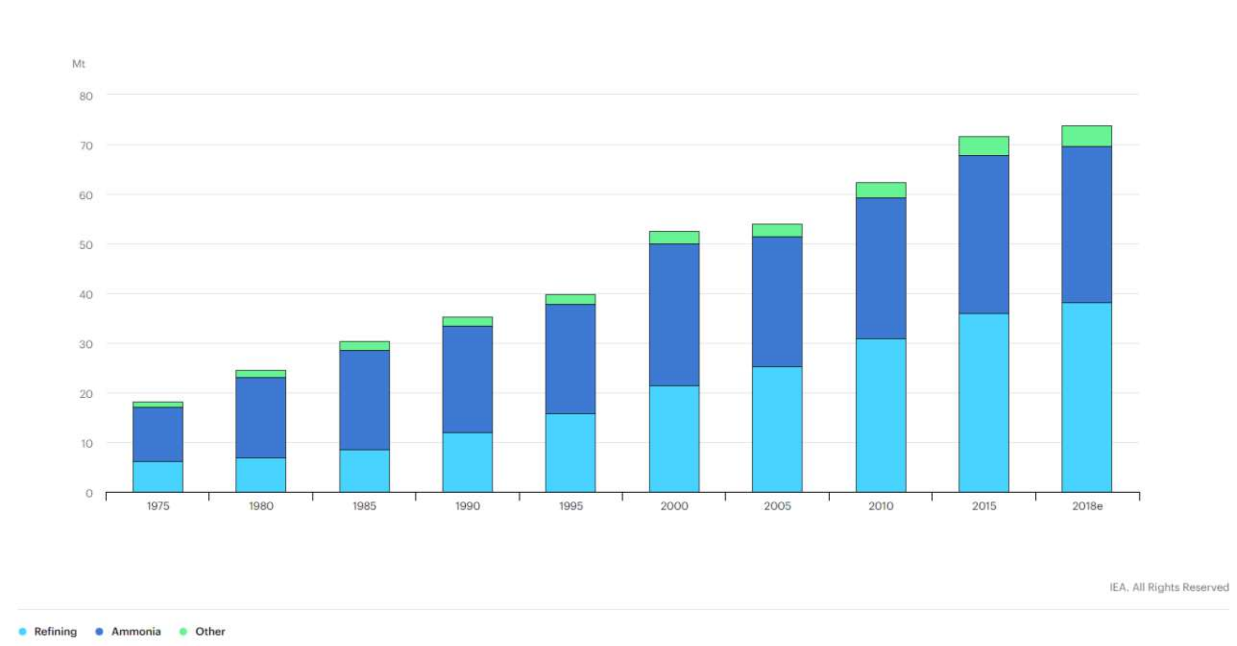


Figure 6: World Demand for Pure Hydrogen

Another figure, which also confirms this growth trend, is the added electrolysis capacity in 2019 which accounted for 25,4 MW/yr. as compared to less than 1 MW in 2010 (IEA, 2020b). However, what has to be mentioned is that nowadays most of the hydrogen production comes from fossil fuels, mostly natural gas (6% of global use), followed by coal (2% of global use) (IEA, 2021b). This method for hydrogen production is not environmentally friendly and in no way sustainable considering the large amount of CO_2 emissions as a result – 830 million tonnes per year (IEA, 2021b). This means that despite its potential, if hydrogen continues to be produced from fossil fuels it will only become a contributor to the global climate change crisis, and not the solution, which it is needed to be. If speaking metaphorically hydrogen can be either with the 'bad guys' or it can be one of the ‘good guys’ that enhances the sustainable development and makes an effort to mitigate a climate change catastrophe. That’s why efforts to promote hydrogen technology for storage and use as a complementary to the renewables sector are needed. Hydrogen can provide a bridge between the energy generated from intermittent resources and the energy demand and through this make the grid more flexible and responsive to changes and fluctuations. Currently, there is a significant difference in the price of hydrogen production from fossil fuels – between \$1-\$1.8/kg, and from renewables – in the range between \$3-\$6/kg (Bennett, 2020). On this ground and because the possibility for broad application of hydrogen across different sectors is quite plausible, it can be argued that more investment as well as R&D should be directed in the area of green and sustainable hydrogen. Hydrogen can be used as a medium for electricity storage or replace natural gas into heating networks, it can be further utilised in transport with fuel cells and only water vapour as an emission or it can be stored and used when needed. So eventually, it turns out that the technologies and the possibilities are there, the only thing that has to change is the focus and the way we implement said technologies, as in order to be successful, it is needed to think outside the box.

3. Hydrogen Projects across Scotland

The following Chapter focuses on precise examples of the application of hydrogen storage and usage technologies. It provides an overview of a series of projects developed across the entire country, which all have a different focus and application of the technology. The projects are presented in a form of table which helps the reader obtain the most important facts and figures at a glance.

Table 3: Overview of Hydrogen-Related Projects Developed across Scotland

Project[8]	Location	Overview	Costs
HyFlayer I[9]	Orkney	The HyFlyer I project has already been developed and saw the launch of the world's first commercial flight powered on the basis of hydrogen-electric principle. The aircraft used for that pioneering project was 6-seat Piper Malibu M350 using a ZeroAvia hydrogen fuel cell powertrain.	£5.3 million
HyFlayer II[10]	Orkney	The HyFlyer II project will have ZeroAvia develop the first certifiable hydrogen-electric powertrain, which can be used to power an aircraft capable of transporting up to 19 passengers. The culmination of the project is expected in 2023 with another world-first hydrogen-electric flight	£12.3 million

[8] H2 Aberdeen has not been included in the list as it is already discussed in Part II, Ch.4.

[9] Source: EMEC, 2021a

[10] i.d.

		with a distance of 350 miles.	
Dolphyn project[11]	Aberdeen	Aberdeen has attracted yet another very innovative hydrogen project and has been selected as a location for the 'world's first' hydrogen producing offshore floating facility. Based on electrolysis, the facility is expected to use the wind-generated energy to dissociate seawater that will first be desalinated. The prototype is scheduled to go live in 2024 with a capacity to supply a third of the city's hydrogen needs. The hydrogen will then be transported to the shore, nearby the new port extension, where it is expected to power buses, ferries, and potentially a hydrogen train.	Not Available
H100 Fife[12]	Fife	The aim of the project is to make use of the 7 MW offshore Levenmouth wind turbine, which will generate electricity that will then be used for the production of 100% green hydrogen. The expected result of the outcome is to provide carbon-free heating and cooking for around 300 homes by the end of 2022.	£25 million[13]
HySpirits[14]	Orkney	At the present moment the project is at the	£148 600

[11] Source: Thomas, 2020

[12] Source: SGN, 2021

[13] Source: SDI, 2021c

[14] Source: Orkney Distillery, 2019

		feasibility study stage, which looks into developing a technology that will allow the Orkney Distillery to use hydrogen as a fuel for the distilling process. The technology that is explored is thermal fluid heater system that can be operated with hydrogen as a combustion fuel within the process. Such system will enable the decarbonisation of the Distillery's work as the hydrogen will replace fossil fuels such as kerosene and liquid petroleum gas (LPG) that are currently used for the process.	
Glasgow Fleet[15]	Glasgow City	As part of the preparations for the COP26 meeting that will take place in November 2021, the city is getting a fleet of 19 refuse trucks which are to be the world's largest fleet of hydrogen refuse vehicles. As part of the project green refuelling station will also be developed in the city.	£6.3 million
Surf 'N' Turf[16]	Eday (Orkney)	Surf 'n' Turf is a community project in Orkney which uses wind and tidal power to produce green hydrogen. Based on a 500 kW electrolyser the EMEC's tidal test site on Eday harnessed tidal energy from the EMEC's Fall of Warness tidal test site and	£1.46 million

[15] Source: BBC, 2020

[16] Source: EMEC, 2021b

		from the community owned wind turbine. The world's first tidal-powered hydrogen was generated at the installation in August 2017. The produced hydrogen it stored and then transported to Kirkwall in a fuel cell, where it is later converted back to electricity.	
St Andrews Hydrogen Accelerator [17]	St Andrews	A hydrogen accelerator facility will be located at the University of St Andrews, where it will connect expertise of the University with institutions across Scotland to enable the development of innovations in hydrogen technology in the transport sector and encourage knowledge-sharing.	£300,000
Hydrogen-powered train project[18]	Bo'ness and Kinneil Railway	Another project related to the pre-COP 26 preparations is the development of a hydrogen fuel cell electric train, the demonstration of which is planned as a centrepiece of the global meeting. The train that will be adapted to hydrogen fuel cell technology is a ScotRail Class 314 car passenger train. The team working on this project will be comprised by Scottish Enterprise, Transport Scotland, and the University of St Andrew's Hydrogen Accelerator and the aim is to boost	Not Available

[17] Source: Transport Scotland, 2020

[18] Source: The Engineer, 2021

		hydrogen implementation into the railway industry.	
Green Hydrogen for Glasgow[19]	Glasgow	The project envisions the construction of a green hydrogen production facility located outside of Glasgow and will use both solar and wind energy to power a 10MW electrolyser. The aim of the project is to supply hydrogen to the commercial market and ensure zero-emission fuel is available for use from a wide range of sectors.	Not Available
Acron Hydrogen[20]	St Fergus	The St Fergus gas terminal in North East Scotland is one of the most important lines in the natural gas network, through which passes a third of the total natural gas used in the UK. Acorn Hydrogen is expected to take the North Sea natural gas and reform it into clean burning hydrogen. The CO_2 emissions form the conversion process are to be safely removed and stored within the infrastructure optimised during the first stage of the Acron Project – Acron CCS infrastructure.	Not Available

The massages that all of these projects convey are that Scotland is a country where innovation has definitely found its place and feels at home. It is also a country which makes a conscious effort to achieve the targets set under the ambitious national policy, but also those that are part of the international commitments. Similarly, it is a country which

[19] Source: ITM Power, 2020

[20]Source: Acron, 2021

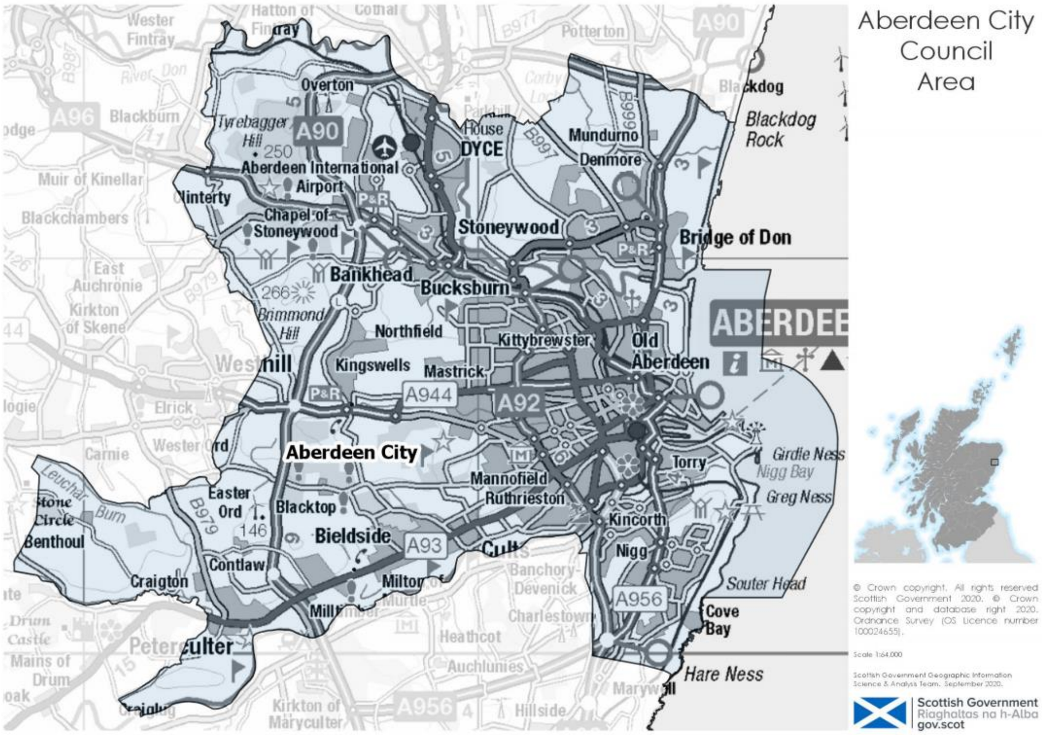
attempts to bring hydrogen to as many industries as possible. Furthermore, the application of hydrogen technology is a step towards the decarbonisation of fossil fuels and the integration of the renewables.

Part IV: Aberdeen –Case Study on Renewables Potential and a Hybrid Energy System

1. Scope and Boundaries of the Researched Area

The last part of the master thesis is dedicated to the case study of Aberdeen City, Scotland. The study offers an overview of the researched area by following a number of parameters. Then it presents a discussion of a hybrid renewable system, based on on- and offshore wind, tidal, and hydrogen power and explains how such system is applicable to the Aberdonian context. Lastly, the case study develops a simple model showing the interlinkages between the various energy sources and key application sectors. The model is based on existing infrastructure and projects but will also attempt to give an estimate of what else has to be implemented. Reference projects will be given in order to cover the financial side of such endeavour. Additionally, it will be discussed how such organisation of the energy sector can fit into the context of the Powering Aberdeen Framework. Lastly, an overview of the findings and limitations of such approach will be offered

Aberdeen is a port city located between the River Don and the River Dee in the North East of Scotland. It is the third biggest in the country stretching on an area of 185.7km^2 on the east coast of the North Sea. Exact location and thus, boundaries of the research area are presented on the following map (Scottish Government, 2020f).



Map 2: Aberdeen City Council Area

The population of the city accounts for 228 670 people equalling to 108 381 households, both values valid for 2019 (Scottish Government, 2021f). Aberdeen City Council is one of the 32 Scottish local government council areas (Aberdeen City Council, 2017:3). Aberdeen has long history related to the sea – first it was fishing, then ship building and trade, and since the 1970s oil industry development. The extensive oil reserves found in the North Sea have contributed to the economic development of the city and have even become the basis for the city to be known as the 'Oil Capital of Europe'. Yet, with the changing energy mix in the past decade as well as the diversification of the industry context of the city with electronic design and renewables (Britannica, 2019b), it is maybe more appropriate to talk about 'Energy Capital' instead (Arnold, 2003; Gomersall, 2017).

In terms of economic performance, in 2012 Aberdeen has been named one of the UK's 'supercities' by HSBC as it is one of the leading hubs for business development (BBC, 2012). More recent articles also identify Aberdeen as 'the wealthiest' city in the UK as *"residents benefit from the biggest disposable income in Britain"* (Buchan, 2019). Furthermore, Aberdeen City Council (2016:15) attests that the city is one of the *"top 20 regions in Europe for the value of economic output per head of the population"*. Most of the city's economic activity is focused on the primary industry, which is expected considering the well-developed oil and gas extraction. MRP estimates that in 2019, Aberdeen has recorded a GDP of £11.4 billion, which is around 17% of the GDP of the entire country (MRP Group, 2019:4). Another important fact presented by the same report is that five of the top ten businesses in Scotland are based in the city and their collective turnover is £14 billion (MRP Group, 2019:4). PricewaterhouseCoopers (PwC) has developed a Good Growth Index which measures the performance of cities based on 10 indicators. In the most recent report, which also studies the impact that the global pandemic of COVID-19 has had on cities' development, Aberdeen has been put under the category of 'High Good Growth Score with Low Economic *Impact' (PwC, 2021:9). A further report from PwC cited in Findlay (2021a) claims that "Aberdeen economy is poised for 4.1% growth in 2021"*. From this strong economic dataset and good performance of the city as a whole, it follows that the employment rate in the city is also really good. According to Matthews & Scherr (2019:14) the *"employment in the energy sector is highly concentrated, with more than half (52.9%) of the jobs located in the North-East: 38.6% in Aberdeen City and 14.3 % in Aberdeenshire"*. This is quite understandable given the fact that the oil and gas industry in Aberdeen accounts for 80% of the UK employment into the sector and as a consequence the city becomes the biggest cluster for subsea business (MRP Group, 2019:4). The total employment rate for people in full-time positions is 73.8% (Scottish Government, 2021f).

As for the energy consumption of the city, the figure given by the statistics portal of Scotland for total energy consumption is 5059.62 GWh, which is only around 3.4% if compared with the total national energy consumption of the country (147 403.16 GWh) (Scottish Government, 2021g).

The city of Aberdeen has been selected for the present case study for a number of reasons. First and foremost, the city has a long history with the energy industry. This means that the city has the knowledge and skills capacities to work on the future development of the energy industry. Secondly, which is a direct consequence of the first is that Aberdeen has not limited itself to the oil and gas reserves in the North Sea, but has instead explored and implemented other options for energy generations, such as wind power. Another important element, which makes the city an interesting ground for research is the fact that there is already a series of green-oriented projects implemented the city, for example H2 Aberdeen which has already been presented in the previous part. Further factor to be taken into consideration is that Aberdeen already has an existing gas network, which can play a key role for the implementation of a hybrid energy system based on the potential of renewables. Overall, the city provides a number of characteristics that are crucial for sustaining a successful energy transition based on existing infrastructure (and not on architectural design of the future) and it also has proved to be a place with many assets where innovation and creative thinking are well accepted.

2. *Hybrid Energy System (On- and Offshore Wind, Hydro Power, and Hydrogen)*

Hybrid energy systems (HES) are to be studied in the next couple of paragraphs and that is necessary as they are considered a prerequisite for the accurate understanding of the model presented in the following Chapter. IRENA (2017:4) observes the substantial growth of renewables and remarks that *"electricity systems will require greater flexibility"*. In that context come the idea and concept of hybrid energy systems, which are defined as *"the integration of several types of energy generation equipment"* (Nazari-Heris & Mohammadi-Ivatlo, 2018:25). A further definition is given by Berrada et al., (2021:3) and it introduces HES as *"the increasingly frequent coupling of different energy sources at different levels of an energy system"*. In general terms, the hybrid energy system combines energy generated from various sources, such as renewables (like wind and solar), energy storage systems, etc. The HES are a flexible form of energy system, which fits well in the context of the ongoing energy transition. They enable the better integration of renewable energy technologies and ensure a higher reliability. A further advantage of such system is that it allows overcoming the deficiencies resulting from intermittent sources like the wind. Furthermore, if combined with an energy storage technology it can also meet sudden peaks or lows of the energy demand. As Fathima & Palanisamy (2018:147) discuss in their work, such hybrid system can facilitate the delivery of *"quality and reliable power to consumers"*. They also point out the importance for promotion and development of hybrid systems as part of the future energy reality and emphasise the fact that energy storage and renewables should go hand in hand to enable successful implementation of such combined energy systems (Fathima and Palanisamy, 2018:16). Another asset that HES bring forward is that they can be widely applied, meaning that such energy systems can be used as a main grid system or they can be isolated and used at remote locations. The current way of functioning of the energy system is more or less passive, in the sense that the goal is to satisfy the demand. However, a hybrid system will mean a higher degree of interconnectedness, which will involve the control of a couple of power in- and out-flows, and with this its nature can be seen as more active (Ghiani & Pisano, 2018:26).

The hybrid energy system that the present work proposes is based on the Scottish, and more specifically Aberdonian context. The hybrid system is to be entirely comprised of renewable energy sources – on- and offshore wind power, tidal power, and hydrogen.

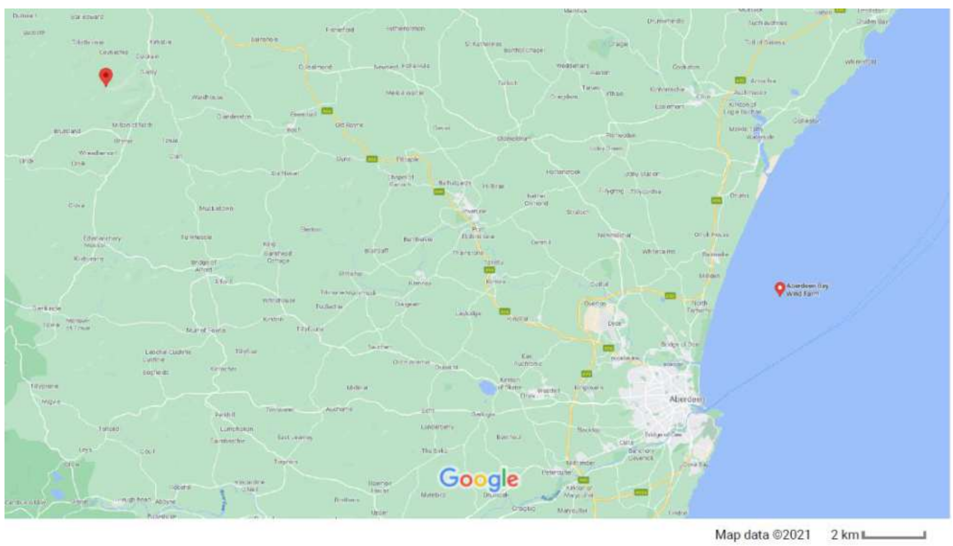
Wind power in Scotland is very promising with large capacities for generation of both onshore and offshore wind energy. This energy generated from wind is a source of green, *"non-polluting electricity"* that can compete with conventional energy sources (Carton & Olabi, 2010:4536). Three wind farms – two offshore and one onshore, will be discussed as part of the hybrid energy system developed in this Chapter.

Aberdeen sports a pioneering project in the field of offshore wind with the European Offshore Wind Deployment Centre (EOWDC), also known as Aberdeen Bay Wind Farm. The construction of this project started in 2011 and the EOWDC has been in operation since 2018. The wind farm consists of 11*8.8 MW turbines of 191 meter height. They are spread along the cost on a distance of 1.5 miles from shore and have a blade rotation diameter of 164 meters (Belfast Telegraph, 2018). The total installed capacity is 96.8 MW and the annual output is 309GWh. This accounts for 70% of the Aberdeen domestic electricity demand and 23% of the total demand of the city (AREG, 2021). The project has been developed by Vattenfall with a cost estimate of £300 million, an average annual homes equivalent of 80 000 homes, and the introduction of suction bucket jacket foundations – *"an industry first"* (Vattenfall, 2021a).

Another very prominent offshore wind farm, currently under development just south of Aberdeen is the Kincardine Floating Wind Farm. The installation will have a capacity of 50 MW coming from five 9.525 MW turbines, installed on semi-submersible floating structures. The annual output is expected to be around 218 GWh, which should be enough to power approximately 55 000 homes (Randal-Smith, 2021). The costs of the projects are reported as £350m (NS Energy, 2020) and the commissioning is expected in the summer of 2021, being delayed from the initial 2020 completion date (Randal-Smith, 2021). In conjunction with the wind farm, a construction of Dolphyn - the 'world's first' hydrogen producing offshore floating facility is ongoing. The first phase of completion is scheduled for 2024, when the 2 MW prototype is expected to supply one third of the Aberdeen's hydrogen needs (Thomas, 2020).

The onshore wind farm discussed here is of consequence for the development of HES system, even if it is not so close to the city itself. The Clashindarroch Wind Farm is in the Aberdeenshire area and is in operation since 2015. This is an onshore wind farm with 18*2.05 MW wind turbines and a total capacity of 36.9 MW. The annual production output accounts for 114 469 MWh, which is the average annual homes equivalent of 27 000 homes (Vattenfall, 2021b).

The following two maps present the location of the EOWDC, Kincardine, and Clashindarroch Wind Farm[21]

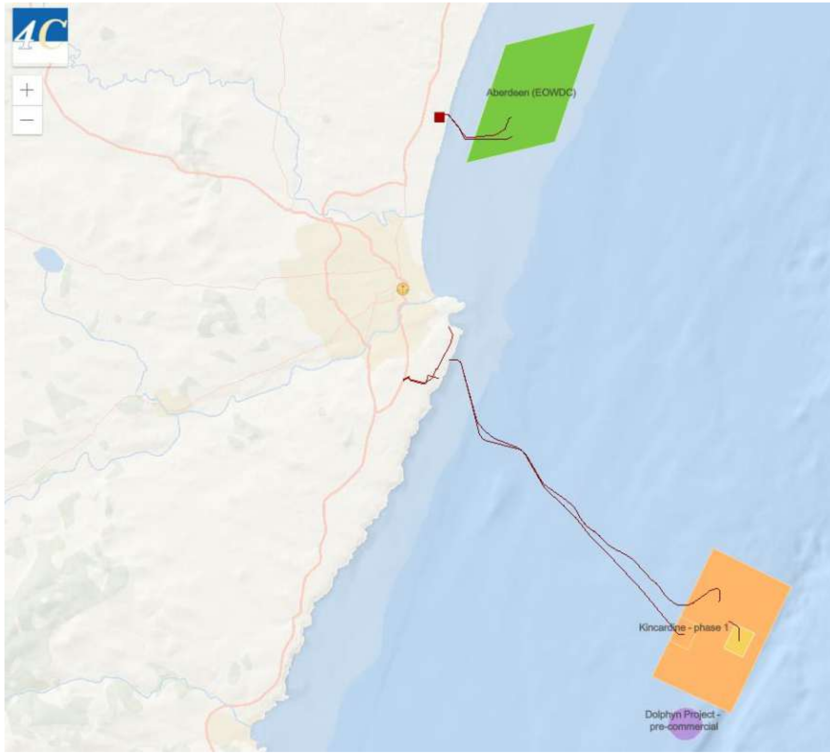


[22]

Map 3: Location of the EOWDC and Clashindarroch Wind Farm

[21] Important note for consideration is that Clashindarroch Wind Farm is located close to Huntley, at the edge of Aberdeenshire and at the distance of 45 miles to Aberdeen.

[22] Source: Google Maps



[23]

Map 4: Location of EOWDC and Kincardine Floating Wind Farm

Based on the information provided in the portfolios of the three wind farms, it follows that they can power an estimate of 162 000 homes. The total number of households in Aberdeen is 108 381, which means that the three wind farms would be capable of covering the household electricity demand and also generate a surplus, which can then be directed towards industry needs or further down the grid. In fact, just EOWDC and Kincardine that are practically in the city would be able to meet that household electricity demand (a total of 135 000 homes together, again registering a surplus). The following graph represents the percentage of Aberdeen households that is covered by each wind farm in terms of electricity generation. However, it should be pointed out that the graph covers only household electricity demand and thus, excludes industry and public electricity demand.

[23] Source: 4COffshore

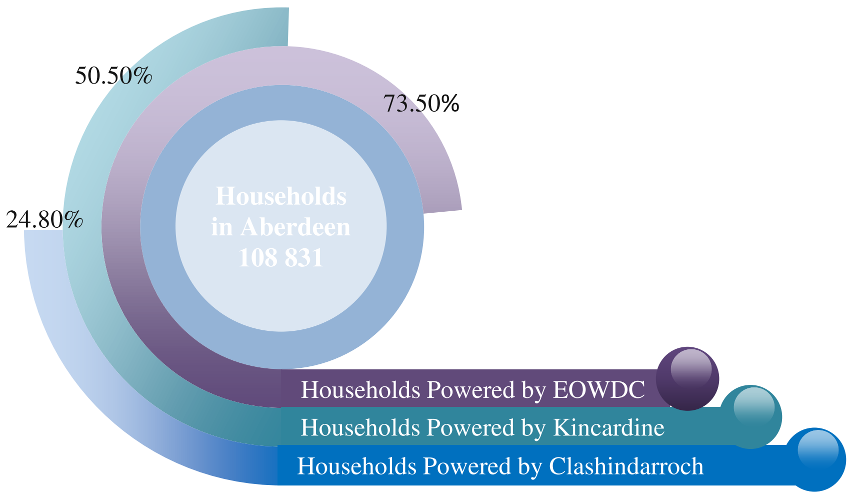


Figure 7: Household Electricity Demand Powered by Each Wind Farm

In terms of wave and tidal energy most of Scotland's potential is concentrated around more remote areas, namely the small islands along the costs in the North, where some of the strongest tidal currents in the world are formed. These are promising locations because mighty tidal currents are present in the channels between the islands, or the islands and the mainland. A particular example is the Pentland Firth, which has been nicknamed *"Saudi Arabia of the tidal power"* (Neill et al. 2017:1). The downside, which also hinders a more large-scale development of tidal power, is that the remote locations often lack proper energy infrastructure. And so, even if substantial amounts of energy can be generated, much of it is lost, due to the inability to use it. When it comes to Aberdeen and its coasts, the city has some tidal potential. Yet, this does not even come close to Pentland Firth *("with peak spring currents of around 0.5 to 1.5 m/s in Aberdeen as opposed to current speeds that exceed 4 m/s in the Pentland Firth")* (Neill et al. 2017:3). Regardless, the area is with strategic potential, due to the experienced workforce from the oil industry that is well acquainted with the working conditions in the North Sea. Further, there is already developed infrastructure which can be in a way adapted to the tidal energy generation technology (Neill et al. 2017:3). Even though, there is not a current project for tidal development in Aberdeen, other Scottish locations are developing the technology – in 2018 a company in Orkney has started work on *"what is described as the world's most powerful floating tidal turbine"*, with 72m length and two 180 degree turbine motors (BBC, 2019). As of 22 April 2021, the O2 tidal energy turbine is in operation. The output is expected to *"meet the demand of around 2,000 UK homes and offset around 2,200 tonnes of CO2 production per year"* (Findlay, 2021b). The development of a similar project off the coast of Aberdeen is envisioned as part of the proposed HES.

The downside of wind and tidal energy generation is that both are dependent on the availability of the resource. In other words, wind energy is defined by significant fluctuations based on the wind capacity and for the tidal power, even if it is more stable than wind, it is not constant. For this reason, energy storage systems should be considered *"to avoid the impact on electricity generation process in the lack of adequate winds"* (Carton & Olabi, 2010:4536) or strong currents. The chosen storage system for the proposed HES is hydrogen, which technological specifics have been discussed in the previous part. Another reason for the selection of hydrogen for the system is the fact that hydrogen is already implemented as fuel in the city's public transport network with the H2 Aberdeen project. The important points to make are that a hybrid system between wind energy, tidal power, and hydrogen can serve as a means to utilise the excess energy "*to decompose water in an electrolyser to produce and store that energy as hydrogen"* (Carton & Olabi, 2010:4539). Through this method of water dissociation, the waste of energy is avoided. Another advantage of such HES is that it provides enough flexibility to shift between meeting the demand and storing energy for later use. It further prevents grid overload and in a way makes the energy network responsive to consumers' need. Additionally, the implementation of a hybrid system can successfully contribute to the achievement of the 'hydrogen economy' model, which according to Carton & Olabi (2010:4538) *"holds great promise of meeting simultaneously concerns over security of energy supply and climate change"*. Furthermore, the hydrogen produced can use the existing electricity or gas infrastructure (Staffel & Dodds, 2017:viii). This makes it a suitable technology for the establishment of HES system in Aberdeen as currently, the city is largely dependent on gas.

The challenges that the development of a HES system can face stem from different areas. For example, there is the economic aspect and the matter of financial constraint. A HES system is a multi-step and multi-component system and consequently requires large amounts of investment and financing to advance. Another possible problem can raise from the lack of consistent low-carbon policies and governmental support for such projects, due to their new and innovative nature in the context of green energy. Also, from a technical point of view and again due to the multi-layered characteristics, there is not a universal controlling mechanism for such HES. This means that for the development of HES in Aberdeen based on on- and offshore wind, tidal power, and hydrogen a specific control configuration is needed. This would translate into additional time needed for first, the control system design and elaboration, then the testing, and finally pre-commissioning phase. It can be argued that hybrid energy system offers a very interesting and innovative solution for reconciling the intermittent nature of renewable energy sources, characterised with peak and off-peak periods, with the energy demand and thus, unpredictable surplus and downfalls of generated energy. In the context of Aberdeen city, such a system is seen as a plausible scenario due to the already well-developed energy sector, the existing infrastructures, and the availability of a diverse range of renewable energy sources. The only remark that has to be made is that such an endeavour would require a significant R&D period on the system itself but also on the specific site that is the city of Aberdeen. The hybrid energy system proposed here and based on wind and tidal power and hydrogen as energy carrier but also energy storage technology is only a starting point, which offers some food for thought, but in no way attempts to be a completely elaborated system model.

3. Building a simple model

The black box model is used here as a tool to investigate the dynamics of a hybrid energy system in the city of Aberdeen (closed system). The model is developed on entirely theoretical grounds as even though the technologies discussed in the HES system exist and are available, they have not been previously combined in such configuration and in a city powering context. That's why, the present work should only be considered as a starting point and innovative proposal, which in no way should be taken as industry and practically applicable. The modelling steps to be followed are: system analysis and data conditioning, key variables analysis, model design, model identification, and finally, model evaluation (SimulateLive, 2020)

a. Steps and Parameters

The system analysis is based on HES on one side and sectors of application on the other. Renewable energies and hydrogen technologies have been largely studied in the previous parts. What has to be further defined here is the inner part of the system, otherwise the consumer side of the energy sector. The three parameters that are to be used for the model elaboration are electricity, heating, and transport.

The only published figure in regards to the energy sector in Aberdeen is in fact the total energy consumption of the city which accounts for 5059.62 GWh. The electricity consumption value has not been made publically available, nor have those for heating and transport. However, an estimate for at least electricity can be drawn from the dataset characterising the EOWDC energy output, namely that it can satisfy 70% of total electricity demand which equals 23% of total energy demand. Assuming these figures as a baseline, an estimate can be made that the total electricity demand is around 1163.71 GWh/yr. From this it follows that the remaining 3 895.91 GWh from the total energy demand are distributed across heating, transport, industry, etc. What has to be mentioned about the heating in the city is that in its larger proportion it relies on natural gas and the gasification infrastructure. Another important remark is concerning the energy efficiency of the buildings. The city is characterised with almost one third of century-old buildings of granite construction and quite poor thermal performance (Aberdeen City Council, 2017:8). In fact upon observation of the Aberdeen Heat Loss map it is clearly visible that buildings' energy efficiency across the city is quite poor with most buildings being 'red' or 'dark red' meaning that heat losses are predominantly large (Geoinformation Group, 2020). As a consequence it is argued that part of the investment attributed to the development of HES, should be directed towards improvement of the buildings' energy efficiency. In terms of transport, two branches are distinguished – public and private. In terms of development of the public transport Aberdeen has already implemented a fleet of buses, refuse trucks, vans, and cars running on hydrogen. As for the private vehicles sector, this is largely dominated by fossil fuels cars. Morrice cites an estimate of 102,929 petrol and diesel cars in the city in 2017. From this number only 0,33% were the recorded electric vehicles, i.e. 349 electric cars (Morrice, 2019).

In terms of the data conditioning of the model, it is important to say that it is grounded entirely on the theoretical possibility of functioning of the system and not on numerical analysis. Thus, the figures provided in the system analysis serve only as contextual frame of the real-time circumstances in the city. The purpose is to demonstrate how the model can fit the current situation based on the available data, but the figures are not to be applied in the model itself.

So far, the key variables have more or less been defined. The inputs to the system will be coming from renewables – wind, tidal, and hydrogen and the outputs of the HES, i.e. energy for heating, transport, and electricity, will be directed towards the three consumer sectors. The system developed for Aberdeen city in this case study is considered to be a closed system, meaning that no inputs or outputs of the national grid are envisioned.

A model structure design has been developed to facilitate the reader's understanding of the system's organisation. The model is based on three pillars, namely renewable energy, consumer profile, and hydrogen economy. Each of them is encompassing the previously presented technologies. The model presents what are the inputs and outputs of such system and how in fact they are closely interlinked and dependent on each other. It further shows how the implementation of one side of the system enables the functioning of the other and vice-versa. As Aberdeen city has been assumed a close system, no external influences or disturbances are shown on the scheme. This part also presents a brief reference table which gives on overview of the development and financing of projects (both those included in the model and reference ones) with the aim of giving a rough estimate of the costs of a HES system implementation in Aberdeen. The model identification and evaluations are discussed in the next two sub-points.

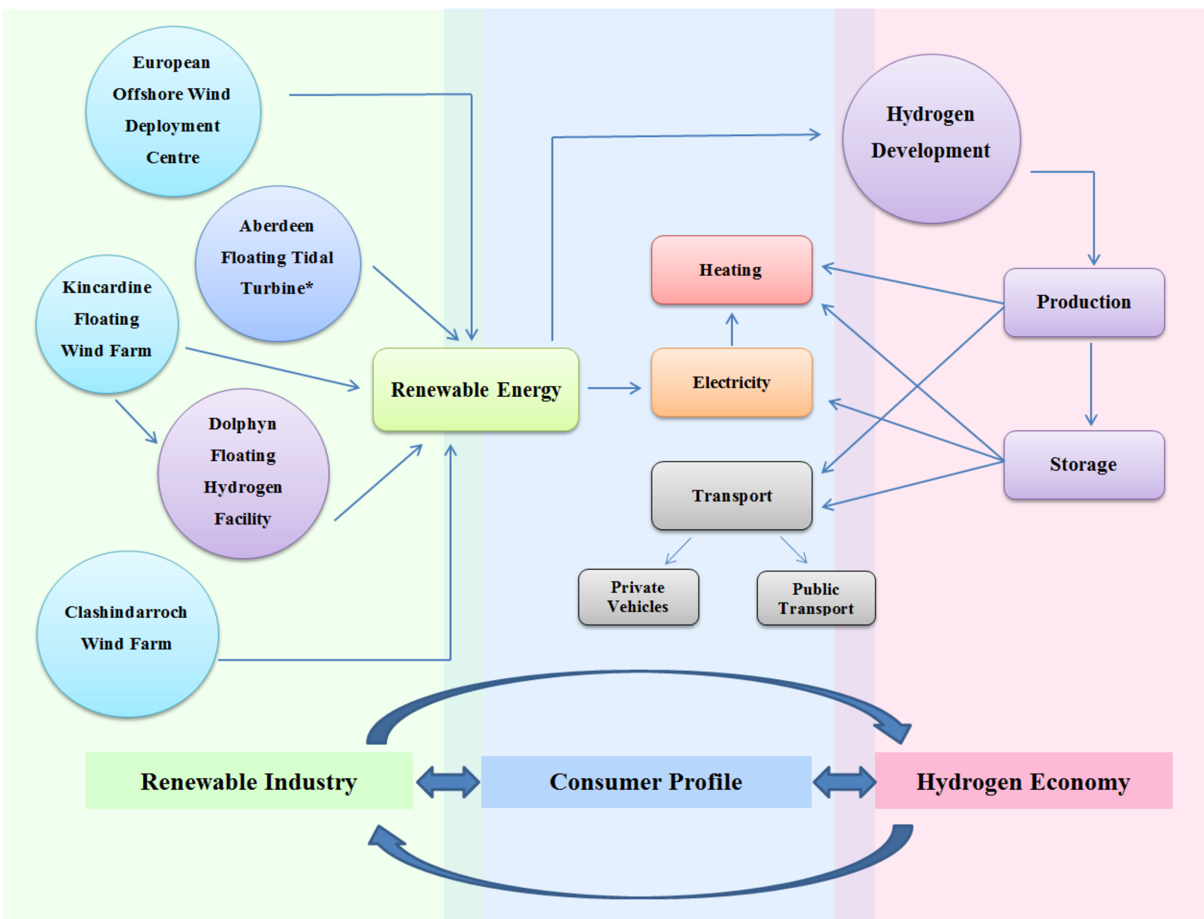


Figure 8: Model of a Closed Hybrid Energy System

Table 4: Projects Overview for the model of HES and Reference Projects

Project	Costs	Status	Comment	Reference Project and Costs
EOWDC	£300 million	In Operation	First off-shore wind farm in vicinity of Aberdeen with a capacity to satisfy 70% of the city's electricity demand.	N/A However, an expansion of the facility can be considered
Aberdeen Floating Tidal Turbine	N/A	A proposal	This is a project envisioned for the development of the present HES and not a project that has been proposed in reality.	O2 Turbine, Orkney £7 million[24]
Kincardine Floating Wind Farm	£350m	In development	Off-shore wind farm 15km south of Aberdeen sporting semi-submersible foundations.	N/A
Dolphyn Floating Hydrogen	Not Available	Awaiting final investment	A hydrogen producing facility that will use the	£10 million trail (in Cumbria,

[24] Source: EMEC, 2021c

Facility		decision (FID)[25]	energy generated from Kincardine wind farm for the electrolysis of desalinated sea water	England) for heating with 100% use of hydrogen trough the existing gas network.[26] This reference project only covers one of the possible applications of the produced hydrogen.
Clashindarroch Wind Farm	£62 million	In Operation	An example for onshore wind farm. However, the wind farm is around 45 miles away from Aberdeen, which might make it not so easy to integrate in the HES	N/A Potentially a project of similar capacity can be developed closer to the city

[25] Source: ERM, 2020.

[26] Source: Prospect

b. Findings

The model shows the interdependencies in a hybrid energy system and confirms the belief that individual parts of that system would not be as efficient just by themselves. Another very important finding that comes from constructing this model is that the energy portfolio should be supported be a wide range of green technologies if the final aim of decarbonisation and climate change mitigation are to be achieved. Aberdeen city has already done quite some progress in that direction with the operational EOWDC, the development of Kincardine and Dolpyn as well as the use of hydrogen as fuel for the growing fleet of vehicles in the public transportation network. The principle on which this model is to work is to have the renewables (on- and offshore wind and tides) generate energy, which will then either be directly released into the city's grid as electricity or will be redirected to a hydrogen technology facility for production or storage. Such mode of operation allows a more efficient use of resources in the sense that if more energy is generated it would not be wasted but instead stored for later. It also covers the opposite scenario with a higher demand than the actual energy generated. At that point, the stored energy in the form of hydrogen comes in and successfully satisfies the consumers' needs. Hydrogen is to be produced through electrolysis and either directly used for heating (through the existing gas infrastructure) and transport refueling or put away in storage. For the storage itself, technologies such as compressed hydrogen or liquefaction (more energy demanding) can be used. The diagram not only reveals the complementarity between renewables and hydrogen, but also shows that the consumer profile is really important for the successful implementation of the two. In other words, if the public opinion and mentality are not favourable to green energy, the transition to low-carbon energy sources would be significantly hindered.

For the model identification and evaluation steps, the developed HES is scrutinised under the framework offered in the city's action plan with five themes of future energy focus. Theoretically, if the model is to be practically applied in the city it is important to know how it fits Aberdeen's strategy and that's why the Powering Aberdeen Five

Themes framework has been selected as a suitable instrument to do so. A brief discussion of how the individual elements of the HES above fit in the context of the five phases will be presented.

1) Energy Efficiency is related to the consumer profile part of the model, more specifically the heating of homes and public buildings across the city. As the thermal performance is generally poor, improvement of the energy efficiency is needed for the successful implementation of the HES model.
2) Resource Efficiency is linked to the idea of circular economy and in the context of a closed system model for the city of Aberdeen, it will be largely related to an efficient harnessing of the renewables' potential. In other words, loss of the generated energy should be minimised and if possible avoided.
3) At that point come the Alternative Technologies, which in the case of the proposed HES is hydrogen storage and utilisation. Hydrogen can bridge the gap between energy generation and demand and can thus improve the demand management flexibility and grid responsiveness. It would also lead to reduced emissions and contribute to climate change mitigation.
4) Low Emission Society is the stage where consumers' behaviour and public opinion are key. In order to implement successfully the HES, there is need to nurture a sustainable lifestyle culture in people. On a micro-scale, everyday small choices have their impact on climate and the environment (e.g. being energy and resource conscious) and on a macro-level the crowd psychology also plays a crucial part in how innovation is accepted and whether it is welcomed or not. For this reason and as pointed out by Powering Aberdeen, educating people about the benefits of a green transition will enable and facilitate the process.
5) Leadership and Behaviour Change phase is with a focus on the governing entity of the city. The decision-making authority is not represented in the model above, yet it is underlyingly there in the sense that without approval and support from the City Council, such hybrid energy system would not be developed in the first place.

As concluding remarks regarding the proposed HES and the Powering Aberdeen Five Phases framework, it can be argued that the former fits well in the context of the latter. It meets all the expectations posed in the phases of the action plan and it also outlines a possible starting point for the future development of the energy transition.

c. Limitations

Unfortunately, such model as the one developed here is flowed on a couple of grounds and as of now, it can only serve as an initial point for consideration in the study of hybrid energy systems. Firstly, there are the limitations related to the availability of information about the city statistics specifically. All of the data collected has been based on what has been published as 'accessible' for the public. Due to the multi-layered research, on quite a few occasions the lack of data and figures hindered the development of the model and thus, a certain degree of reconfiguration of the expected results was needed. For this reason, the model has been developed on entirely theoretical grounds, without fully exploring the full capacity of the HES to satisfy the city needs. Secondly, the model presents a range of technologies as comprising elements of the system. These technologies together with the existing energy infrastructure have been taken as a given, yet a further extensive research is needed in order to deem the model plausible. For example, considerations about the local geological characteristics and possibility to install new facilities (especially, the tidal turbine and an onshore wind farm closer to the city) there are needed. Additionally, the state of the existing infrastructure should be assessed of whether it can support the new load (the case of hydrogen in place of gas in the heating network) as well as a possible need to construct and develop new lines should be envisioned. Furthermore, the model of hybrid energy system only looks into three sectors – electricity, heating, and transport, which in no way represent the wholesome energy demand of the city. Besides, Aberdeen is a busy port city in the North East, it has an airport, and one of the busiest helipads in the UK – aspects of the transport network which are not considered in the model, but are of significant importance in real-life circumstances. Another significant flow is in regards to the limited existing knowledge and technology for implementation of a hybrid energy system fully based on renewables, particularly the lack of a developed control mechanism that can adjust the system operations based on energy generation, demand, disturbances, etc. Finally, the financing estimate has not been very well defined. This is due to the fact that some of the projects from the model are already developed, others are in construction, and others are just theoretically proposed. Lack of information on the reference project funding and the consideration that projects in Aberdeen would have to be adapted to local conditions, needs, and scale have hindered significantly the ability to provide one concrete number for the financing of the separate elements of this HES.

Part V: Conclusion

In recent years renewables have gained momentum and increased their share into the global energy mix significantly. They are fast becoming the solution to the problem with burning of fossil fuels and the resulting emissions. Renewables provide an alternative, infinite resource of energy with lower emission rates, if any, and also a pathway to combat global warming and climate change. The present work submerges into the world of renewables from political, socio-economic, and technical perspective. The analysis is initiated with an overview of the global trends defining the renewables' industry. Firstly, the negative effects of fossil fuels are explored and hence, serve as a foundation for the claims that alternatives are needed. Secondly, the benefits of the use of renewables are presented in the scope of a couple of areas – international politics and economy, technological advancement, locational availability, and societal impact. The second part of the master thesis narrows the context by exploring Scotland and its potential in the field. It has been specifically selected as it is one of the countries with most ambitious targets and legislation linked to low-carbon and green economy in the world. Furthermore, the state has already achieved a remarkable progress of renewable technologies implementation and judging by the ongoing development of a series of projects, encompassing a wide range of alternative low-carbon energy sources, it seems that Scotland is on the way of becoming a world leader in this industry.

Renewable energy is of an intermittent nature and despite being an excellent solution for decarbonisation and climate change mitigation, it would not be able to satisfy the ever changing (predominantly growing) demand just by itself. For this reason storage technologies are needed and they are discussed in the third part. A particular focus has been placed on hydrogen production and storage technology as well as on what projects in the field are ongoing across Scotland. The fourth and last part of the master thesis is based on a case study of the city of Aberdeen in the North East. Aberdeen has committed to transition from the status of 'Oil Capital' to 'Energy Capital' and judging by the present progress, it can be argued that that the city is on a promising path. For this reason, the case study offers an innovative and creative way of thinking that combines a couple of alternative technologies, which potentially can be developed as one whole and then provide the city with green energy. Initially, the concept of a hybrid energy system is introduced – it is not a new concept, yet concerning renewables its development stage is in its beginnings. The study proposes such system with a configuration between on- and offshore wind power, tidal power, and hydrogen to be implemented into the city. By taking Aberdeen as a closed system, a simple theoretical model is developed. It is based on a black box principle with inputs from renewables and energy output into the three main energy consuming sectors, namely heating, electricity, and transport. A diagram of the hybrid energy system is developed and discussion of the findings and limitations of such model is offered.

As a concluding note, it should be said that the research in its integrity together with the case study and the theoretical model (despite its limitations) confirm the argument that the energy transition needs not only technological advancement, but also innovative and creative thinking that can, in fact, enable that advancement. It is already proved that renewables and alternative energy sources are the viable way forward, if a climate and environmental catastrophe are to be avoided. A stable progress has been recorded already, but there is still a long way to go. Further research, development, and testing of untraditional and innovative technologies are of utmost importance for a successful green energy transition.

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List of Tables, Figures, and Maps

- **Tables**

- **Figures**

- **Maps**