The Integration of Fluctuating Renewable Energy Using Energy Storage

by

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Abstract

Energy storage is often portrayed as an ideal solution for the integration of fluctuating renewable energy (RE) due to the flexibility it creates. However, there is uncertainty surrounding energy storage in terms of the technologies that currently exist, the additional RE it enables, and its role in modern electricity markets. These uncertainties have hampered the deployment of large-scale energy storage and hence, this research examined these concerns.

This research began by identifying the most feasible energy storage technology available for the integration of fluctuating RE, specifically for Ireland. Due to its technical maturity and large-scale capacities, pumped hydroelectric energy storage (PHES) was deemed the most viable technology, but the literature outlined a lack of suitable sites for its construction. Therefore, a new software tool was developed in this study to search for suitable PHES sites, which was then applied to two counties in Ireland. The results indicate that these two counties alone have over 15 sites suitable for freshwater PHES, which in some cases could be twice as large as Ireland's only existing PHES facility. Hence, the next stage of this research assessed the benefits of constructing large-scale energy storage in Ireland. To do this, a model of the Irish energy system was needed and so a review of 68 existing energy tools was completed. From this review, EnergyPLAN was chosen and subsequently it was used to simulate various capacities of wind power and PHES on the 2020 Irish energy system. The results reveal that PHES could technically integrate up to 100% penetrations of fluctuating RE if very large capacities were used under certain operating strategies. However, the economic assessment indicates that this would cost more than the reference 2020 scenario. In addition, alternatives were identified which could offer similar savings as PHES, while also being more robust to changes in fuel prices, interest rates, and annual wind generation, but they did consume more fossil fuels. Finally, a new practical operating strategy was created for energy storage while operating in a wholesale electricity market. Results indicate that approximately 97% of the maximum feasible profits are achievable. However, the annual profit could vary by more than 50% and hence, energy storage will need more profit stability to become feasible for investors.

To summarise, this work concludes that PHES is the most promising energy storage technology for integrating fluctuating RE. More sites do exist than previously expected and constructing them will enable higher penetrations of fluctuating RE. However, based on predicted 2020 costs, using PHES is more expensive than the reference scenario and alternatives could be more cost-effective, which really need further analysis. Finally, if energy storage is required, electricity markets will need to create more certainty surrounding their potential profits.

Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the University or other institute of higher learning, except where due acknowledgment has been made in the text.

David Connolly David Connolly 10/DEC/2010

This is to certify that the thesis entitled “The Integration of Fluctuating Renewable Energy Using Energy Storage” submitted by David Connolly to the University of Limerick for the award of the degree of Doctor of Philosophy is a bona fide record of the research work carried out by him under our supervision and guidance. The contents of the thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any other degree or diploma.

Martin Leahy, University of Limerick, Ireland 20/01/11

Henrik Lund, Aalborg University, Denmark 19/JAN/2011

Brian Vad Mathiesen, Aalborg University, Denmark 20/1/2011

Dedication

To Kieran

For your unwavering support

…

Til Danmark

For alt

Preface

My first interaction with energy storage came during a module I completed as part of my undergraduate degree in Mechanical Engineering in the winter semester of 2006 called "Energy Management". I can still remember the day when our lecturer, Tony Kay, explained the concept of energy storage. We discussed Ireland's enormous and freely available wind resource, which could, if harnessed, transform Ireland into a renewable energy goldmine. However, not long after this thought had sparked a few big ideas in my head, I was brought back to reality by the sound of that frightful word: intermittency. Unfortunately, we cannot rely on wind power to meet our energy demands because there are times when it doesn't blow. We subsequently discussed a range of potential energy storage devices that could solve this problem, focusing primarily on Ireland's only existing pumped hydroelectric energy storage facility, Turlough Hill. As a naive student, the concept seemed so simple. When there is too much wind, store it; when there isn't enough, use the stored energy. However, as we proceeded through the details of the problem, the complexity of the challenge became all too apparent. Energy storage is difficult to construct, expensive, and limited. Even so, it was from that day onwards that my fascination with energy storage began, and so I investigated how I might gain a greater understanding of this area.

After completing my undergraduate degree, I began my PhD in October 2007 under the Charles Parsons Initiative at the Department of Physics, University of Limerick. This thesis documents over three years of investigation into the role of energy storage, focusing specifically on the integration of renewable energy. The thesis structure reflects my learning process throughout the PhD, thus taking the reader along the same path I have also followed. I hope that it informs the debate surrounding energy storage and renewable energy, particularly in Ireland.

This work would never have been possible without the help and inspiration of many people along the way. I wouldn't have the space to thank them all, but there are a few people I would like to mention in particular. Firstly, I would like to thank my father, Kieran, for being a constant source of encouragement throughout my time as a PhD student. Also, thanks to Anna, and my sister Maria, for all your help and support over the last three years. To Martin Leahy, the staff in CPI/Department of Physics, and my PhD colleagues for all your help during my time at the University of Limerick. A special thanks to Henrik Lund and Brian Vad Mathiesen for your hospitality, patience, guidance, and inspiration, and also to the staff at Aalborg University, particularly in the Department of Development and Planning, for my wonderful stay during this work. I would also like to thank Shane MacLaughlin from Atlas Computers Ltd, Amanda Barriscale from the Sustainable Energy Authority of Ireland, and Margaret McCarthy from EirGrid. Thanks to the Irish Research Council of Science, Engineering, and Technology (IRCSET) for funding my PhD over the last three years. Last, but not least, thanks to all my friends, especially the lads in number 1 The Birches and those from AAU!

Finally, thank you to anyone I may have omitted and I hope you enjoy reading my thesis.

David

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Nomenclature

Symbol, description, and unit	
A_L	Polygon area for lower reservoir, m^2
A_U	Polygon area for upper reservoir, m^2
CEEP	Critical excess electricity production, TWh/year
C_{Pump}	Capacity of the PHES pump, MW
$C_{Storage}$	Capacity of the PHES storage, GWh
$C_{Turbine}$	Capacity of PHES turbine, MW
E_L	Max excavation volume for lower reservoir, m^3
E_U	Max excavation volume for upper reservoir, m^3
FFD	Fossil fuel demand, TWh/year
FR	Grid search interval for lower reservoir, m
PES	Primary energy supply, TWh/year
$P_{Capacity}$	Power capacity of a PHES facility, W
Q	Discharge through the turbines, m^3/s
H	Head of PHES facility, m
I_{Annual}	Annual repayment costs, €M
I_P	Investment cost of PHES pump, €M/MW
I_T	Investment cost of PHES turbine, €M/MW
I_S	Investment cost of PHES storage, €M/GWh
$O\&M_{Fixed}$	Fixed O&M costs, % of total investment
s_{PHES}	Hourly energy stored in the PHES facility, GWh
SR	Radial search interval for upper reservoir, m
SV	Vertical search tolerance for flatness, m
V	Volume of water between PHES reservoirs, m^3
d	Maximum acceptable horizontal separation, m
e_{CEEP}	Hourly critical electricity production, MWh
e_{PP}	Hourly power plant electricity production, MWh
e_{Pump}	Hourly PHES pump electricity consumption, MWh
$e_{Turbine}$	Hourly PHES turbine electricity production, MWh
g	Acceleration due to gravity in m/s^2
i	Interest rate, %
n	Lifetime, years
η_{PHES}	Round-trip efficiency of PHES, %
η_{Pump}	PHES pump efficiency, %
$\eta_{Turbine}$	PHES turbine efficiency, %
ρ	Mass density of water, kg/m^3

Energy, economic, and other units	
W	Watt
kW	Kilowatt (1000 W)
MW	Megawatt (1000 kW)
GW	Gigawatt (1000 MW)
TW	Terawatt (1000 GW)
kWh	Kilowatt hour
MWh	Megawatt hour (1000 kWh)
GWh	Gigawatt hour (1000 MWh)
TWh	Terawatt hour (1000 GWh)
ktoe	Kilo ton of oil equivalent
Mtoe	Million ton of oil equivalent
GJ	Gigajoule
PJ	Petajoule
kg	Kilogram
Mt	Megaton
Gt	Gigaton
m	Metre
km	Kilometre
s	Second
h	Hour
€(M)	(Million) Euro
$	US Dollar

Abbreviations	
ACTES	Air-conditioning thermal energy storage
Bbl	Barrel (of oil)
BES	Battery energy storage
BES	Biomass energy system (chapter 11 only)
BEV	Battery electric vehicle
BP	British Petroleum
CAES	Compressed air energy storage
CCGT	Combined cycle gas turbine
CHP	Combined heat and power
COMBO	Combination energy system
DSM	Demand side management
DTM	Digital terrain model
EES	Electricity energy system
EU	European Union
EV	Electric vehicles
EA	Ex-ante (electricity market prices)
EP	Ex-post (electricity market prices)
FBES	Flow battery energy storage
FES	Flywheel energy storage
GDP	Gross domestic product
GHG	Greenhouse gases
GIS	Geographic information system
HES	Hydrogen energy system
HESS	Hydrogen energy storage system
HP	Heat pump
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land-use, land-use change, and forestry
MFWP	Maximum feasible wind penetration
O&M	Operation and maintenance costs
OECD	Organisation for Economic Co-Operation and Development
OCGT	Open cycle gas turbine
OSI	Ordinance Survey Ireland
PHES	Pumped hydroelectric energy storage
pop.	Population
PP	Power plant
Ref.	Reference (citation)
RE	Renewable energy
REF	Reference energy system
REF2020	Reference energy system for the year 2020
RES	Renewable energy system
RD&D	Research, demonstration and development
SCC	Survey control centre
SCES	Supercapacitor energy storage
SEAI	Sustainable Energy Authority of Ireland
SEM	Single Electricity Market
SEV	Smart electric vehicle
SMES	Superconducting magnetic energy storage
SMP	System marginal price
TES	Thermal energy storage
TESS	Thermal energy storage system
TFC	Total final consumption
TIN	Triangulated irregular network
TSO	Transmission system operator
UPHES	Underground PHES
US(A)	United States (of America)
V2G	Vehicle to grid

Chapter 1

1. Introduction

"So this is a wish, it's a very concrete wish, that we invent this technology. If you gave me only one wish for the next 50 years, I can pick who's president, I can pick a vaccine, which is something I love, or I could pick that this thing that's half the cost with no CO_2 gets invented, this is the wish I would pick, this is the one with the greatest impact."

Bill Gates, Chairman of Microsoft, February 2010 [1].

This research will contribute towards this wish by identifying if and how large-scale energy storage can unlock the potential within fluctuating renewable energy resources. Such a broad and global issue incorporates a very wide range of technologies, resources, issues, and assumptions. As a result, each chapter in this dissertation covers a unique challenge encountered during this research and hence, they contain an independent background, literature review, discussion, and range of conclusions. Therefore, this introduction is a signpost towards the chapters of most relevance to the reader.

In chapter 2, a broad background relating to the major concerns of global energy supply and demand is provided, while also outlining the consequences of burning fossil fuels. During this process, chapter 2 illustrates why fluctuating renewable energy is a resource which must be utilised for a sustainable energy supply and reveals how energy storage can unlock its potential. To some, these issues may be common knowledge and if so, then chapter 3 may be a more suitable starting point where the objectives of this study are discussed in detail, including the motivation behind this research and its primary focus points.

In chapter 4, Ireland[1]'s energy system is discussed in detail to outline why it is a suitable case study for analysing the role of large-scale energy storage when integrating fluctuating renewable energy. To illustrate this, chapter 4 discusses the structure of the Irish energy system, its renewable energy potential, and the targets included within current energy policies. It is evident from this breakdown that wind energy, which is the most economical fluctuating renewable energy technology, will play a pivotal role in a sustainable energy future for Ireland. Therefore, to complete this chapter, a thorough review of the current wind energy research being carried out in Ireland is provided, to illustrate how this thesis will complement existing work.

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[1] Ireland refers to the Republic of Ireland only, unless otherwise specified.

After establishing Ireland as a suitable case study, chapter 5 discusses the type, capacity, cost, and potential of all large-scale energy storage facilities identified during this work. The aim here is to identify what energy storage technology would be most suitable for integrating wind energy in Ireland and based on the evidence presented, it was concluded that pumped hydroelectric energy storage (PHES) is the most attractive large-scale energy storage option for Ireland at present.

Thus, chapter 6 provides a detailed overview of how PHES operates, the mathematical equations governing is capacities, its current role within energy systems around the world, the typical costs to construct it, as well as a detailed review of existing literature relating to PHES and the integration of wind energy. Based on this investigation, the most concerning issues facing the development of PHES are identified and hence, these become the primary focus within the remaining chapters.

In chapter 7 a software tool is developed which can identify suitable locations for the construction of PHES, along with a complimentary spreadsheet tool for estimating the cost and capacity of the sites identified. Subsequently, these tools are applied to a 1 km^2 artificial terrain for testing, an 800 km^2 site for an initial search, and a 3150 km^2 county in Ireland. The results from each of these applications are displayed, analysed, and discussed throughout chapter 7, where it is concluded that Ireland has a significant freshwater PHES resource.

After concluding that numerous PHES sites exist in Ireland, chapter 8 then assesses the technical and economical implications of constructing PHES. To do this, the literature indicated that a detailed model of the Irish energy was required and hence a review of 68 existing energy tools is carried out in chapter 8. The primary purpose of the review is to identify an existing energy tool which can be used to develop an accurate and detailed model of the Irish energy system. After concluding that the energy-systems-analysis tool, EnergyPLAN, is the most suitable for this research, it is subsequently used to create a model of the 2020 Irish energy system. For the technical analysis of PHES, the maximum wind penetration which can be achieved on the 2020 Irish energy system with the introduction of PHES is identified. Initially, a metric is developed to define a maximum feasible wind penetration and then, different PHES operating strategies and capacities are analysed for wind penetrations of 0-100% of electricity demand on the 2020 Irish energy system. Results reveal that PHES can enable wind penetrations of up to 100% on the 2020 Irish energy system, but it requires very large PHES capacities. Hence, an economic assessment was also carried out in chapter 8 to identify if the economic savings from the additional wind power feasible due to PHES, were greater than the initial investment costs required. In addition, the economic savings from PHES are compared to those from alternative technologies in the form of heat pumps and district heating. Here it is concluded that PHES will most likely increase the costs of the Irish energy system, but the additional socio-economic benefits may be worth this additional cost. Also, the results demonstrate the importance of assessing alternatives across any energy system, especially through the integration of the electricity, heat, and transport sectors.

Chapter 9 examines the structure of the existing Irish electricity market and examines how energy storage could make a profit on wholesale electricity markets using electricity price arbitrage. A new practical operating strategy is developed for energy storage and then assessed on 13 different electricity markets. The results illustrate how an energy storage facility could operate to achieve approximately 97% of the profits feasible when taking advantage of electricity price arbitrage, but conclude that the uncertainty in annual profits from one year to the next could be a significant deterrent for investors.

To finish, chapter 10 discusses the key conclusions from this work and chapter 11 outlines the immediate objective of the work to follow this study. Overall, it is evident that this dissertation provides a wide range of various analyses, investigations, methodologies, and conclusions. As a result, this thesis is divided so that each topic is discussed independently, but structured so they can also be read progressively. Therefore, the reader can decide where to introduce, focus, and conclude in this thesis, based on topics which are most relevant to them.

Chapter 2

2. Contextual Framework

This chapter explains the background of this research and outlines its context relative to the global energy challenge. After an overview of the problems relating to global energy production, the discussion concentrates on the role of renewable energy as a solution for the future. Subsequently, the function of energy storage in conjunction with renewable energy is illustrated, thus refining the objective of this particular research.

2.1. Global Energy

Overall, the push towards renewable energy in any nation is typically driven by three main concerns: climate change, security of supply, and job creation. Although the significance of these issues changes from one country to the next depending on their natural resources, political stability, and demand for energy, the world as a whole will need to overcome two of these if it will ever achieve a sustainable future: climate change and energy security.

Climate change is caused by a change in the balance between the short-wave solar radiation coming into the earth’s atmosphere and the long-wave solar radiation leaving the earth’s atmosphere, which is displayed in Figure 2-1. As the proportion of greenhouse gases within the earth’s atmosphere increases, the ‘absorbed by atmosphere’ and ‘back radiation’ depicted in Figure 2-1 also increases. This subsequently alters the earth’s solar radiation balance: there is now more solar radiation entering the earth’s atmosphere than there is leaving it, which is called radiative forcing.

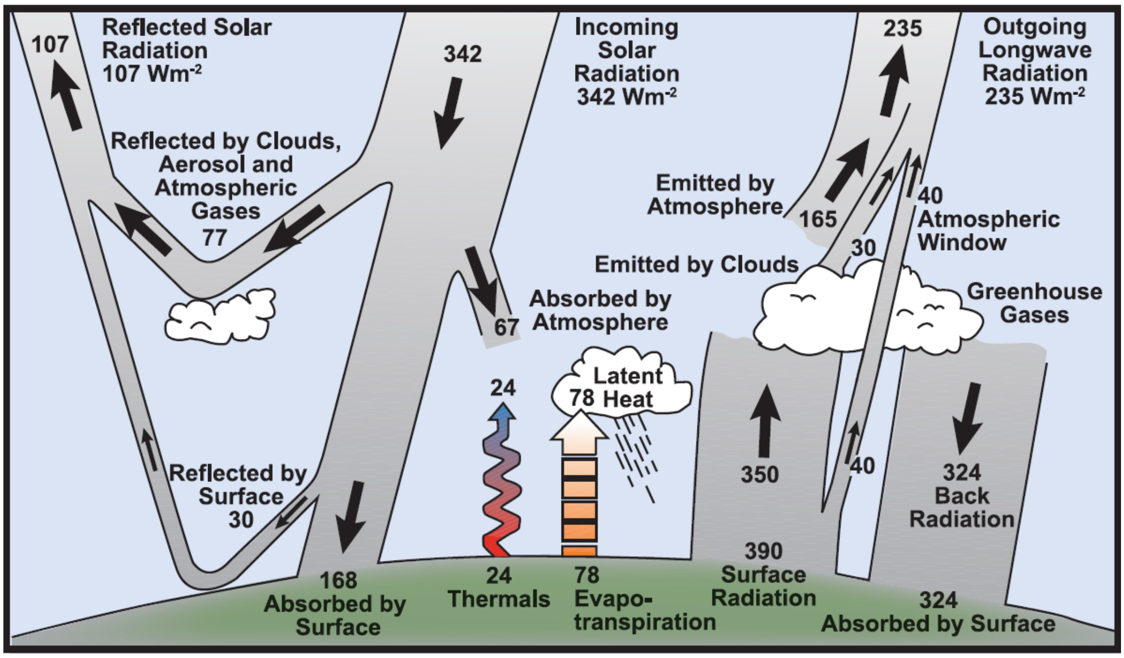
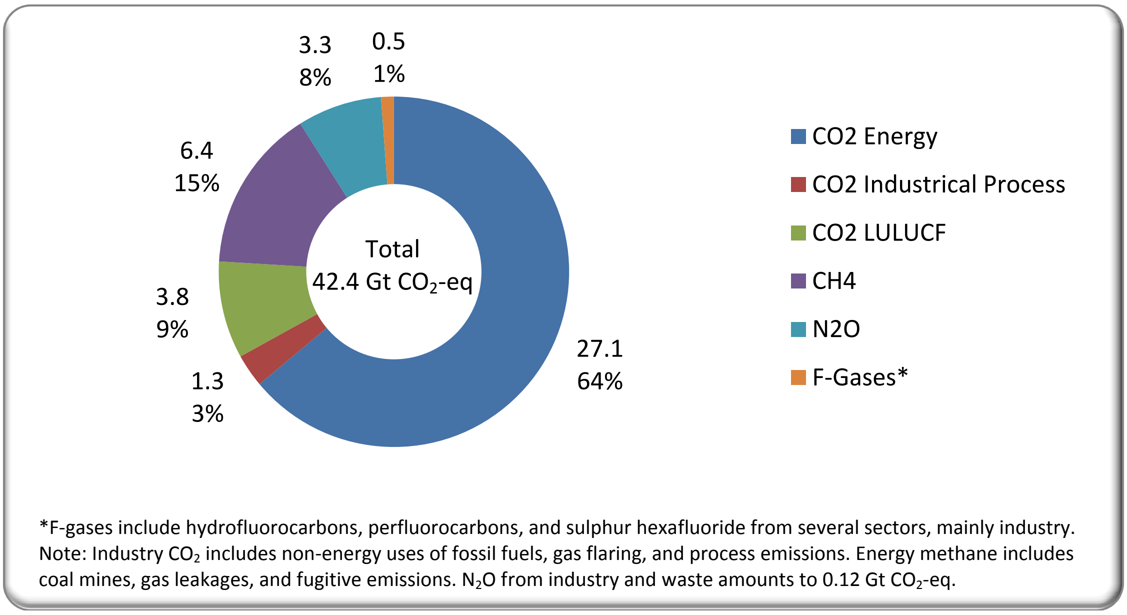


Figure 2-1: Estimate of the earth's annual and global mean solar radiation balance [2].

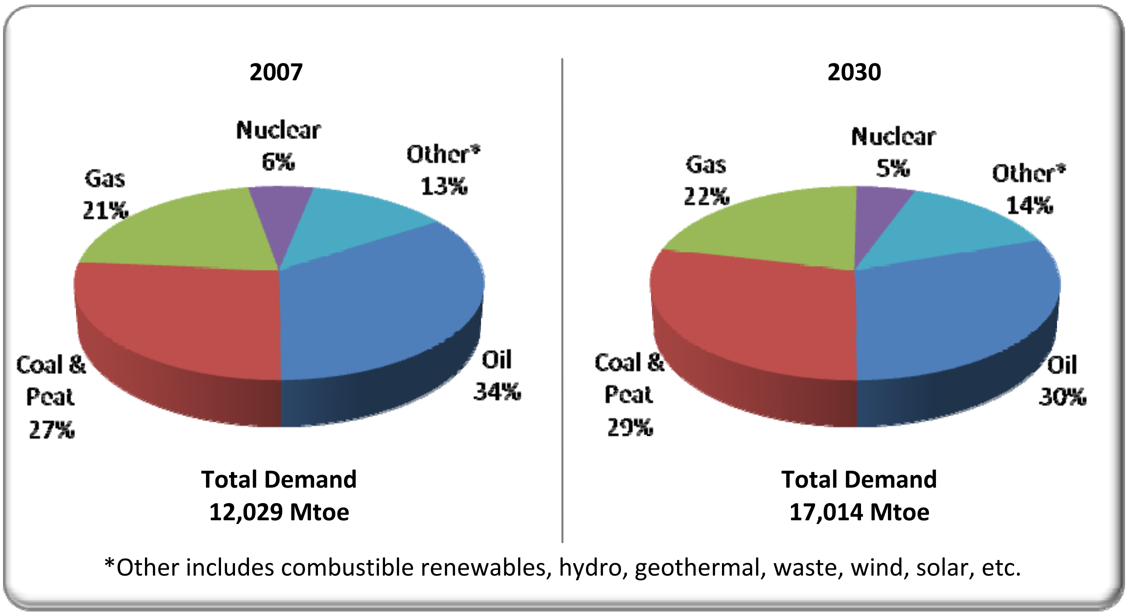
The recorded consequences of radiative forcing over the past two centuries include an increase in global average surface temperatures, an increase in global average sea level, and a decrease in northern hemisphere snow cover [2]. If these trends continue, predictions indicate that it will lead to dramatic changes in the world's climate which will alter water supplies, ecosystems, food supplies, coastlines, and even health. The potential implications are so devastating that the Intergovernmental Panel on Climate Change (IPCC) believes that "unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt" [3]. However, the severity of these changes will depend on the level of greenhouse gases (GHG) which are emitted into the atmosphere in the future. As illustrated in Figure 2-2, CO_2 from energy production creates 64% of the world's GHG emissions alone and hence the IPCC have concluded that "all assessed stabilisation scenarios concur that 60 to 80% of the reductions over the course of the century would come from energy supply and use and industrial processes" [3]. Consequently, to avoid devastating and irreversible changes to the world's climate over the next century, energy production will need to be decarbonised by replacing fossil fuel production with renewable energy.



*F-gases include hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride from several sectors, mainly industry. Note: Industry CO_2 includes non-energy uses of fossil fuels, gas flaring, and process emissions. Energy methane includes coal mines, gas leakages, and fugitive emissions. N_2O from industry and waste amounts to 0.12 Gt CO_2-eq.

Figure 2-2: World anthropogenic greenhouse-gas emissions quantified by CO_2 equivalent and divided by source for the year 2005 [4].

At present the world's energy supply is dominated by fossil fuels. Figure 2-3 indicates that in 2007, 81.4% of the world's energy was produced from fossil fuels, which included 20.9% from gas, 26.5% from coal, and 34% from oil, with almost all of the remainder coming from renewables and waste (9.8%), nuclear (5.9%), and hydro (2.2%).



*Other includes combustible renewables, hydro, geothermal, waste, wind, solar, etc.

Figure 2-3: World's energy supply by fuel from historical data in 2007 and projected for 2030 [5].

Even more concerning however are the current projections for the future of global energy consumption [4]. Using current trends, the International Energy Agency (IEA) expects the world's energy demand to grow from 12,029 Mtoe in 2007 to 17,014 Mtoe (142%) in 2030, with fossil fuels then accounting for 80.5% of supply.

Mirroring this increase in energy production towards 2030 will be an increase in world CO_2 emissions. As discussed previously, further increases in CO_2 emissions will have detrimental implications for the world and hence, future energy production is clearly not sustainable. Furthermore, this increase in energy production and increase in fossil fuel consumption will lead to another major global issue, which is energy security of supply.

The most recent assessment of fossil fuel reserves carried out by British Petroleum (BP) estimated that there is only 46 years of oil, 63 years of gas, and 119 years of coal remaining, which is economically accessible based on 2009 consumption levels [6]. Although it could be argued that technological developments will increase production in the future, as they have done in the past, any increase will most likely be offset by the aforementioned increase in future demand (Figure 2-3) and the expected reduction in new reserves. This was quantified by Shafiee and Topal [7] who created a model that included the projected consumption and depletion of fossil fuels into the future. The results indicated that reserve depletion times for oil, gas, and coal could be as soon as 35, 37, and 107 years respectively [7]. Therefore, although there is ambiguity surrounding the exact date of fossil fuel depletion, it is evident both within [6] and outside [7] of the petroleum industry, that reserves are depleting within decades not centuries. Consequently, due to the scale of the world's dependence on fossil fuels and the timescale required to create alternative sources of energy, changes must occur now to ensure a sustainable energy supply in the future.

As well as the inevitable decline of fossil fuel production, there are also significant issues regarding the location of reserves. In particular, oil and gas reserves are centralised in a relatively small number of countries. In fact, 90% of global oil reserves are located within 15 countries and 90% of global gas reserves are located within 20 countries [6]. In contrast, global energy demand is not focused within these areas and therefore, if the world does not reduce its dependence on oil and gas in the future then the distribution of these limited resources could become a very politically sensitive issue. Furthermore, as the historical energy prices displayed in Figure 2-4 indicate, a shortage in energy supply leads to a dramatic increase in energy costs. For example, in 1973 the United States aided the Israeli military in the Yom Kippur war with Syria and Egypt, who were supported by a coalition of oil-producing Arab states. In response, the Arab coalition reduced their oil production and hence created a global shortage. Again in 1979, the Iranian revolution occurred and reduced Iranian oil production, which created another global oil shortage. As displayed in Figure 2-4, in both 1973 and 1979 there was a dramatic increase in global fossil fuel prices when these global oil shortages occurred. Considering the historical political instability in some countries with significant fossil fuel reserves such as Iran, Iraq, Kuwait, Venezuela, Russia, Nigeria, Libya, Angola, Algeria, and Kazakhstan who between them contain over 50% of global oil and gas reserves, it is possible that a dramatic increase in fossil fuel value could also lead to conflict and disruptions in supply.

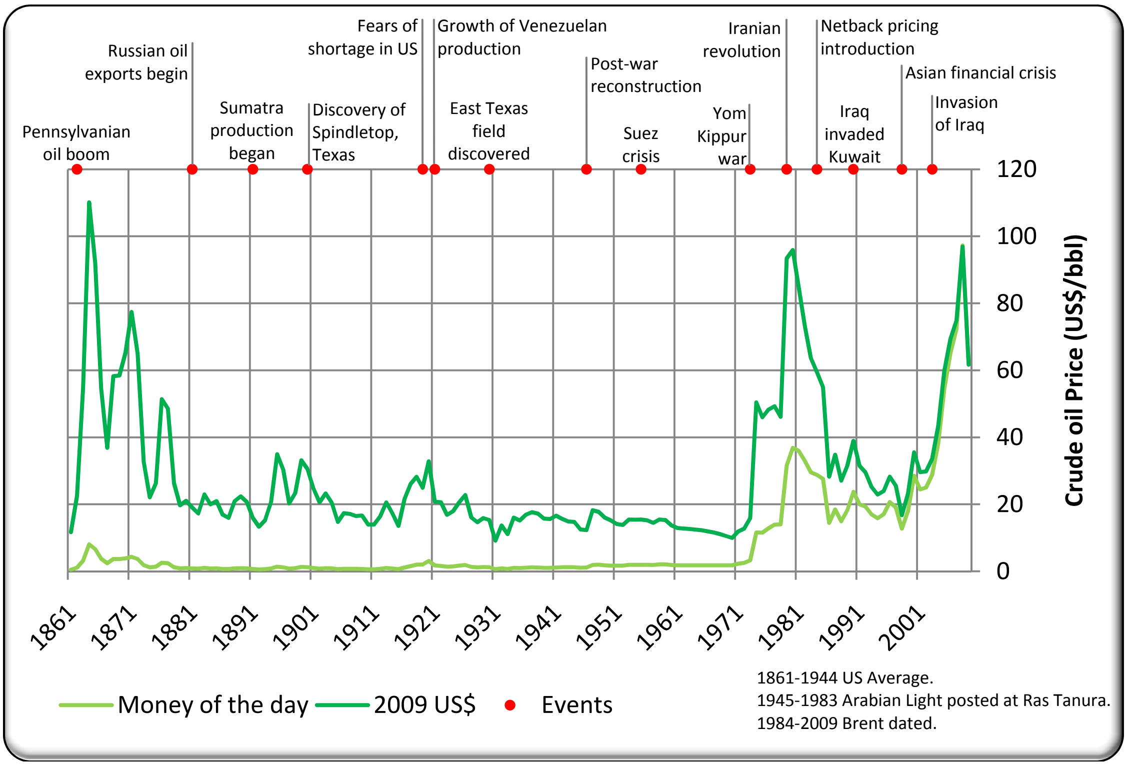


Figure 2-4: Historical price of crude oil corresponding to major global events [6].

In summary, climate change is already being witnessed around the globe through increasing surface temperatures, rising sea levels, and decreasing snow cover. However, these changes are expected to intensify as more GHG emissions are emitted into the atmosphere. It is evident that 64% of total GHG emissions are related to CO_2 from energy production alone, primarily through the burning of fossil fuels and hence the energy sector needs to be decarbonised. However, based on current and projected trends in global energy production, it is clear that the world's dependence on fossil fuels is set to increase and correspondingly GHG emissions will also increase. In addition, due to the scale of the world's fossil fuel dependence it is currently predicted that oil and gas resources will have depleted within the next century. Therefore, from an environmental, sustainability, and even security perspective, it is essential that the world eradicates its addiction to fossil fuels and moves towards a renewable based energy supply.

2.2. Renewable Energy

One solution which can produce energy without catastrophic climate issues and in a sustainable manner is renewable energy. However, renewable energy exists in many forms, with each type offering some unique advantages and drawbacks. To fully portray these issues, it is important to understand how the modern energy system was established.

Renewable energy was the most widely used energy resource in the 19th century. However, as the steam engine developed, the fossil fuel age began to mature. Coal was an energy dense and abundant fuel which enabled the development of steam engines, while steam engines were a cheap and powerful method of transportation, which brought coal to many people. Together, coal and the steam engine created the world's first source of cheap, abundant, and easily transportable fuel, which powered the industrial revolution. This new power enabled the development of new technologies such as electricity and automobiles, which caused the world's human population to sextuple in less than 200 years[2].

As more technologies evolved, energy production became more and more dependent on fossil fuels. Power plants were centralised and located near fossil fuel supply chains, automobiles were designed to burn oil, while heating systems were developed and optimised for coal, oil, and gas. Under this model, energy resources needed to be controllable, abundant, and cheap, which meant only two renewable technologies could compete with fossil fuel production during the early 20th century: biomass and hydroelectricity. Therefore, by 1974 approximately 86% of world's energy was supplied by fossil fuels, as nations immersed themselves in cheap and abundant power [8]. However, as outlined in Figure 2-4, during the 1970's the first backlash of this dependence was realised when fossil fuel prices rose dramatically. Consequently, the quest for new forms of energy began and this reinvigorated the renewable energy sector, which is evident in Figure 2-5 from the sharp increase in renewable energy RD&D budgets at the time.

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[2] The world population in 1800 was approximately 900 million people and in 2000, it was 6.08 billion.

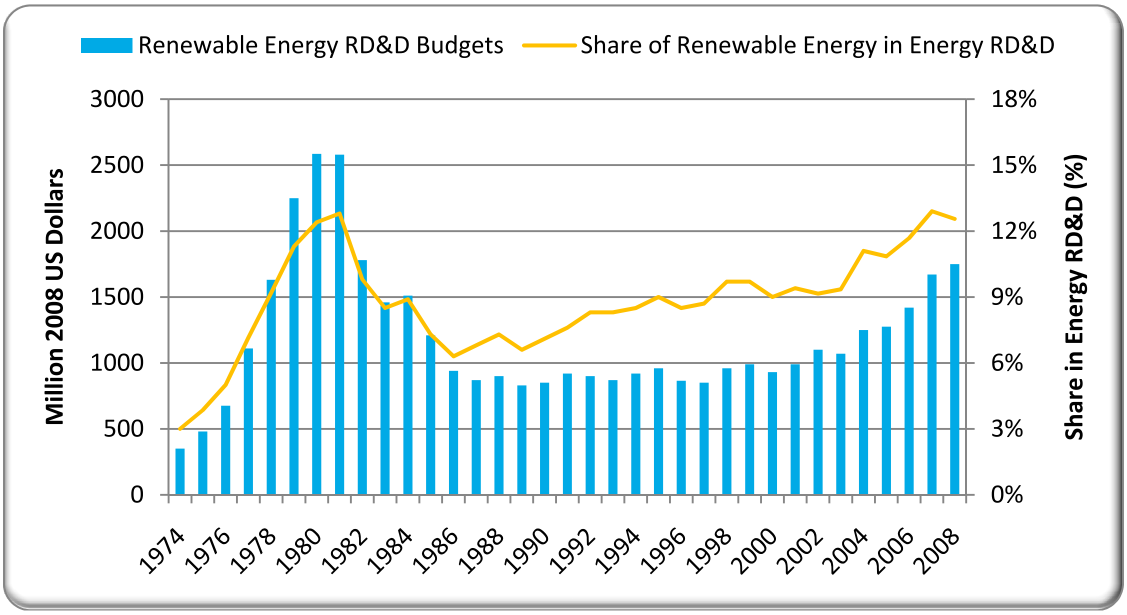

Figure 2-5: Renewable energy RD&D budgets within the IEA from 1974 to 2008 [8].

In total, there are five sources of renewable energy: biomass, wind, water, solar, and geothermal. As mentioned earlier, only biomass and water, in the form of hydroelectricity, were competitive with fossil fuels during the early 20th century. However, after 30 years of significant RD&D, a number of renewable technologies have now become economically competitive with conventional fossil fuels, which is evident from Figure 2-6. As a result, renewable energy has started to play an increasing role in energy production (Figure 2-3). Furthermore, with continued RD&D, the projections in Figure 2-6 indicate that the cost of renewable energy is expected to fall even further, while conventional fossil fuel generation is expected to rise. Consequently, from a costs perspective, renewable energy has and will continue to be a realistic alternative for large-scale energy production. However, there is one key difference between conventional fossil fuels and a number of evolving renewable energy technologies: control.

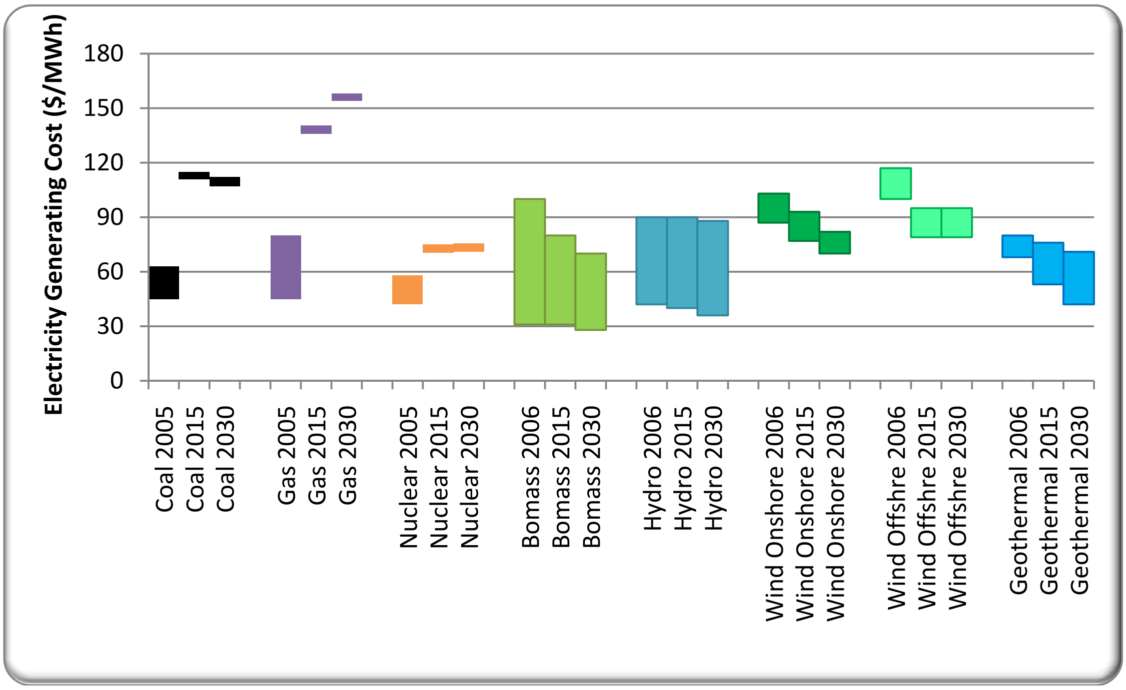

Figure 2-6: Current cost of renewable and fossil fuel based electricity generation along with projected costs for 2015 and 2030 [9-11].

These new renewable energy devices harness resources such as wind, wave, tidal, and solar, with the most suitable device usually dependent on the natural resources within the region being considered. Naturally, these resources cannot be controlled to suit the demands of humans and hence the electricity generated from these renewable devices can vary significantly, which is portrayed in Figure 2-7. Therefore, renewable energy is providing a new form of intermittent power onto a system which has been designed to operate using dispatchable and predictable fossil fuel technologies. To accommodate this, greater flexibility will be necessary within future energy systems as intermittent renewable energy becomes more prominent, especially due to the problems that occur within the electricity sector [12-19]. These issues include grid capacity constraints such as voltage regulation and network congestion, as well as the creation of harmonics, the modification of network impedances, grid stability problems, and a lack of ancillary services. Considering these, Weisser and Garcia indicated that there should be no technical issues for instantaneous penetrations of fluctuating renewable energy, in the form of wind, of up to 20% on an electric grid [14]. In the future though, Lundsager *et al.* estimates that a maximum wind penetration of 25-50% is feasible within the electricity sector [18]. However, Lundsager *et al.* also stated that the feasibility of very high wind penetrations decreases dramatically when the size of the electricity grid increases from 100 kW to 10 MW: for a 100 kW grid a wind penetration of 80% is feasible, but for a 10 MW grid a wind penetration of only 20% is feasible [18]. The authors concluded that primary reason for this dramatic reduction in feasible wind penetrations was due to the lack of energy storage on the grid [18].

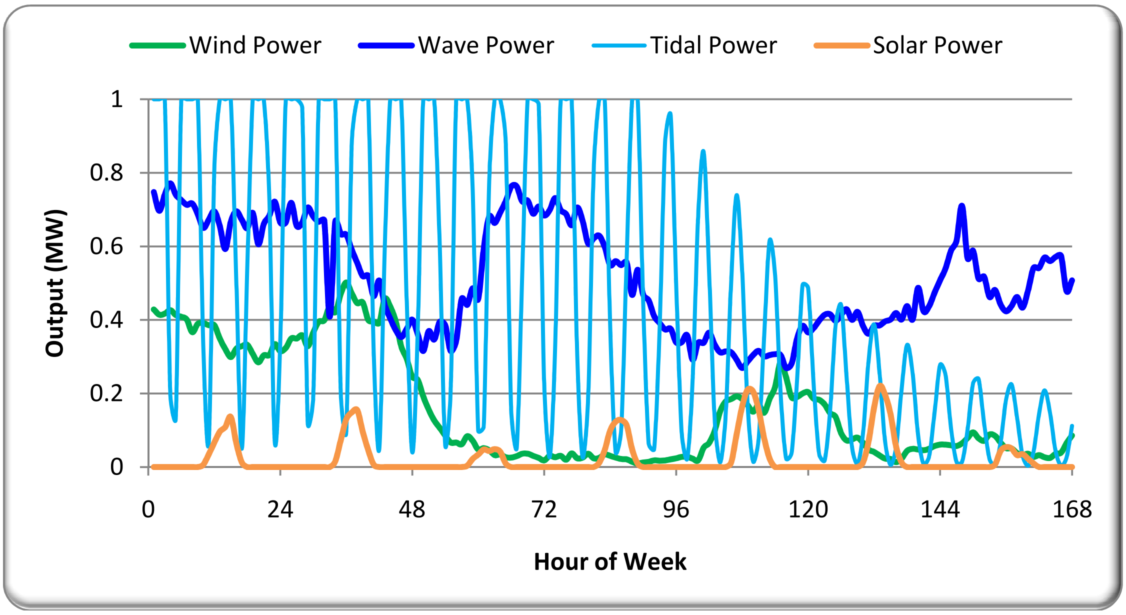

Figure 2-7: Predicted hourly output from a 1 MW wind, wave, tidal, and solar electricity generator in Ireland during week 1 of January 2007.

2.3. Role of Energy Storage

In essence, energy storage is a source of additional flexibility within an energy system. Naturally, the benefits of such flexibility will vary depending on the flexibility that already exists within that energy system and hence, energy storage is not ideal everywhere. However, for many existing energy systems the lack of sufficient flexibility is a key limiting factor for the integration of renewable energy. To illustrate the benefits of energy storage in this case, a hypothetical scenario has been created below based on real world wind data from the Irish energy system. Electricity demand and wind production data from the 17th of April 2008 in Ireland has been graphed in Figure 2-8. On this day, there was approximately 900 MW of wind power installed in Ireland [20], which produced a relatively low electrical output compared to the demand, as displayed in Figure 2-8. Therefore, in line with the findings from Weisser and Garcia [14] mentioned previously, it was possible to integrate 900 MW of wind power in Ireland. However, if this was scaled up to represent an installed wind capacity of 5400 MW, which is expected to be installed in Ireland by 2020 [21], then the wind energy generated would have exceeded the electricity demand from approximately 00:00 to 06:00 in the morning. Later in the day, demand would then have exceeded the wind energy generated and thus created a shortfall between supply and demand. If however, sufficient energy storage was available on the Irish electricity network, then the excess wind energy that was created between 00:00 and 06:00 could have been stored and subsequently discharged onto the grid later in the day when demand exceeded supply. Clearly, there are many other issues that need to be considered under this scenario, but this demonstrates the theory behind energy storage and the integration of fluctuating renewable energy. This principal can be extended over a longer period of time such as days, weeks, and in some rare cases months. Hence, the intermittent and unpredictable nature of wind can be managed by the flexibility of energy storage. This technique could also be used for any other form of fluctuating renewable energy such as wave, tidal, and solar. Therefore, energy storage could enable the large-scale integration of an intermittent resource onto an electrical system designed for predictable and dispatchable fossil fuel based generators. Such a breakthrough would connect many inflexible countries to an ample amount of renewable and sustainable energy while also combating climate change and improving global energy security. Consequently, the primary role of this research is to identify the role of energy storage for integrating fluctuating renewable energy.

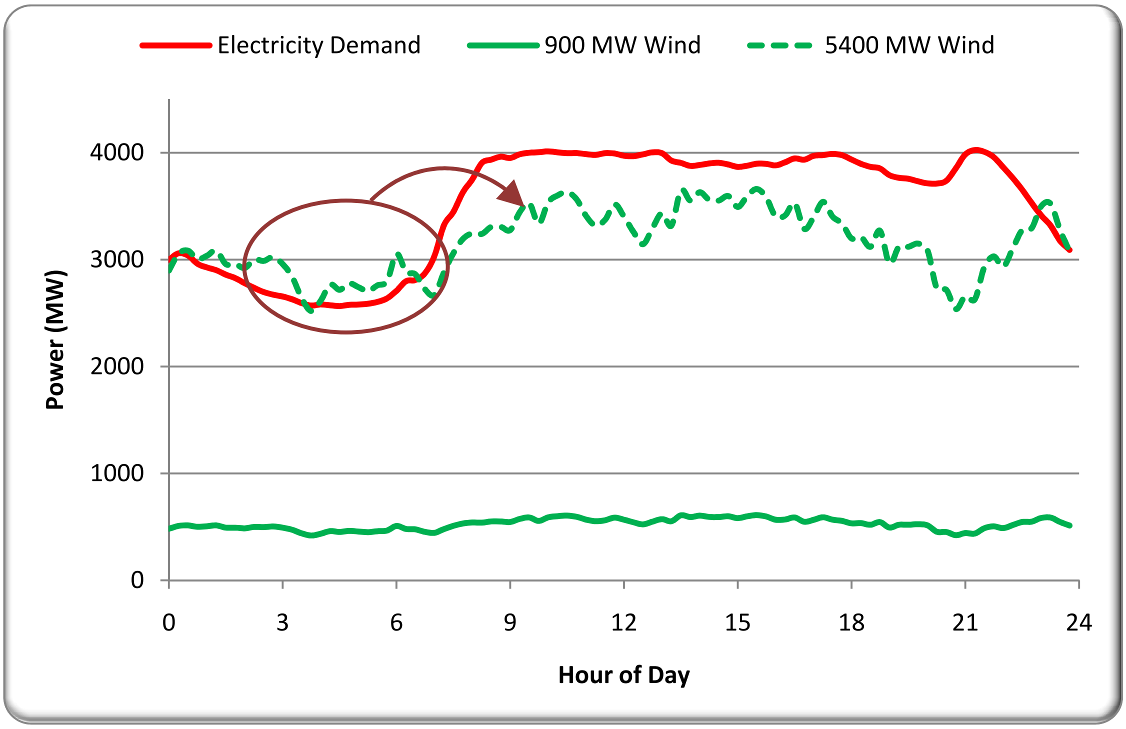

Figure 2-8: Electricity demand, actual wind energy produced (900 MW), and hypothetical scaled (5400 MW) wind energy output in Ireland on the 17th of April 2008 [22].

Chapter 3

3. Objective

Energy storage is a very unique type of plant on an energy system. Like generators energy storage can produce power for the electric grid and like consumers it can also consume power. Uniquely though, energy storage has a limit on the total amount of energy which it can generate over any period of time, and this limit is defined by the amount of energy it could consume at an earlier point in time. This specific constraint distinguishes energy storage from other plants and thus has created the uncertainty surrounding the role of energy storage, specifically when integrating fluctuating renewable energy.

Firstly, there is a lot of uncertainty surrounding the range of different energy storage technologies that currently exist. Energy storage is defined by a range of key parameters including its power capacity, storage capacity, efficiency, response time, lifespan, and costs. As each energy storage technology has its own unique value for each of these, not all technologies are suitable for the same application. Consequently, the first primary objective in this study is to identify from the literature, which energy storage technology is the most suitable for the integration of fluctuating renewable energy. Therefore, chapter 5 summarises a review of existing energy storage technologies, which is documented in detail in Appendix A. Based on the findings in this review, PHES was identified as the most suitable energy storage technology for the integration of fluctuating renewable energy and hence it is described in detail in chapter 6. However, it is also evident from the literature review in chapter 6 that PHES is generally not considered a viable alternative due to the lack of suitable sites. Hence, a software tool was then developed in this study that can locate suitable sites for the construction of PHES, which is discussed in chapter 7, Appendix B, and Appendix C.

Secondly, the actual implications of constructing energy storage are also unclear at present. Implications in this study are defined under two specific categories: technical and economical. Technically, it is unclear how much additional fluctuating renewable energy would be feasible on an electric grid with the introduction of energy storage, while economically it is unclear if this is affordable and if it is the optimum alternative. Many studies have been carried out which investigate stand alone wind-storage systems and the benefits of storage for island[3] electricity grids, which are discussed later in section 6.2.1. However, it is unclear how these

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[3] Island electricity systems refer to small-scale stand-alone energy systems where the installed generating capacity is usually between 1 and 100 MW.

results translate to a national[4] energy system assessment, especially when considering the electricity, heat, and transport sectors. Therefore, the third key objective in this work is to assess how much additional wind could be integrated onto a national energy system with more energy storage, how much would this cost, and if there are cheaper alternatives? This is discussed in chapter 8 and Appendices D, E, F, and G.

Finally, another uncertainty relating to energy storage is the policy surrounding its dispatch on existing electricity markets. Even if it is proven that energy storage is a key technology for future energy systems, under the currently policies of some electricity markets energy storage would not be able to maximise its profits. This is due to the debate on the purpose of energy storage. Many participants believe that energy storage is an additional grid asset, which enables the Transmission System Operator (TSO) to adequately maintain the electric grid. As such, the TSO should be responsible for its construction and operation. Conversely, other participants believe that energy storage should be treated as just another generator, which profits from the fluctuating prices on the electricity and regulation markets. Therefore, it should be constructed as a merchant unit by private investors who bid on these markets along with the other generators. To create some degree of clarity around this debate, the final key objective in this research was to assess if it there are any policies that could be implemented on an electricity market, which would enable energy storage to make sufficient profit to attract private investment. The results from this assessment are outlined and discussed in chapter 9 and Appendix H.

To recap, the three key objectives in this research are to identify a suitable energy storage technology for the integration of fluctuating renewable energy, to identify how much additional fluctuating renewable energy can be integrated with energy storage on a national energy system, and to investigate if it is possible to profit from an energy storage unit on electricity markets.

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[4] National energy systems refer to large-scale interconnected energy systems where the installed generating capacity is usually above 1 GW.

4. Ireland as a Case Study

For this study, Ireland was used as a case study to analyse the integration of fluctuating renewable energy using energy storage. Below is an overview of the current Irish energy system, Ireland's renewable energy consumption and potential, Ireland's energy targets, and a literature review of the work published in relation to wind energy and the Irish energy system. It is clear from this overview that Ireland's ambitious targets for wind energy in 2020, along with the lack of flexibility within its existing energy system, could make energy storage an attractive technology in the near future. Hence, Ireland is an appropriate case study for the analyses proposed in this research. In addition, as the Irish energy system is structured in similar way to many others worldwide [23], the results can be interpreted for other national energy systems also.

4.1. Ireland's Energy System

The island of Ireland is located in the North-West of Europe and is divided into two countries: Northern Ireland and Ireland. Ireland has a population of approximately 4.4 million people and an area of approximately 70,000 km^2. Economic growth in Ireland throughout the 1990s and early 2000s was very strong, with Gross Domestic Product (GDP) in 2007 reaching almost three times that of 1990. As a result, there was a corresponding increase of 74% in total primary energy supply (PES) and a 53% growth in energy-related CO_2 emissions over the same period, as outlined in Figure 4-1 and Figure 4-2 respectively.

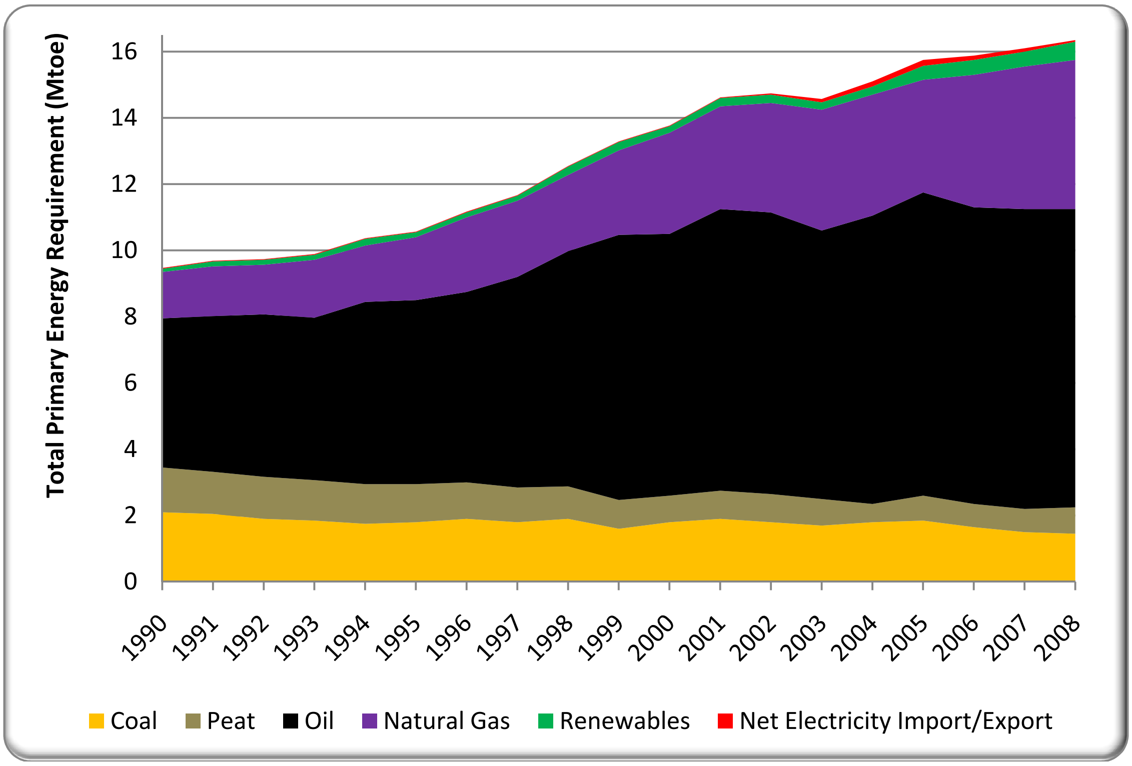


Figure 4-1: Ireland's total primary energy requirement by fuel from 1990 to 2008 [24].

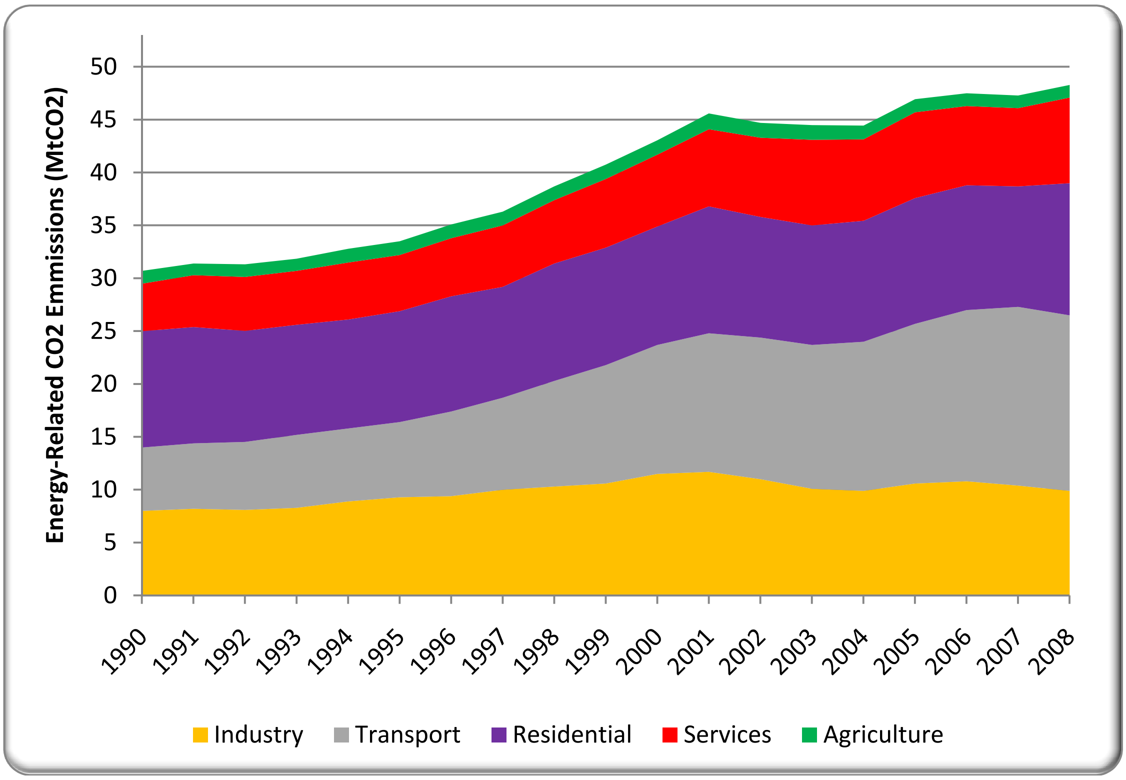


Figure 4-2: Ireland's energy-related CO_2 emissions by sector from 1990 to 2008 [24].

By 2008, transport accounted for approximately 34.5% of total energy consumed in Ireland, followed by heat at 34% and then electricity at 31.5%, as outlined in Figure 4-3. Although both the electricity and heat demands grew by approximately 67% and 30% respectively from 1990 to 2008, transport has now surpassed them both. Over this period, there was a 177% increase in the energy required for transport, which corresponded to a 103% increase in the demand for oil as displayed in Figure 4-1. As Ireland has no indigenous oil resources, Figure 4-4 reveals that Ireland's growing transport demand has dramatically increased its dependence on imported fuels. In addition, due to a declining production of Ireland's indigenous gas resources over the same period, Ireland's overall import dependency has now reached approximately 90% and as displayed in Figure 4-5, Ireland is thus spending over €6 billion each year on imported fuels (compared to an annual revenue of €3.85 billion in 2008 from all overseas visitors [25]). Therefore, Ireland is now very exposed to both the price of energy on global markets as well as the risk of failing to meet its domestic energy demand.

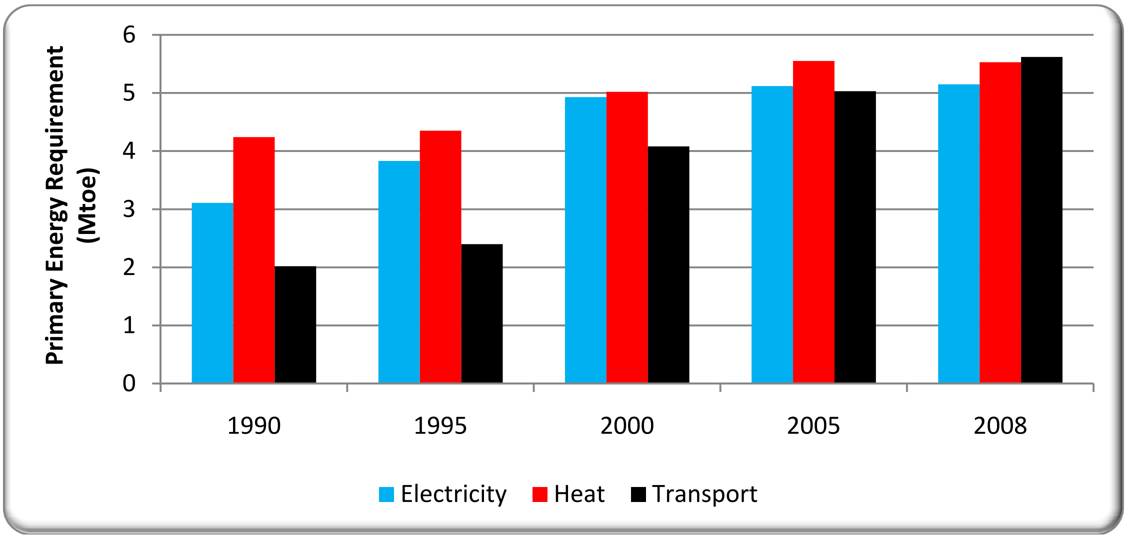


Figure 4-3: Ireland's growth in electricity, heat, and transport from 1990 to 2008 [24].

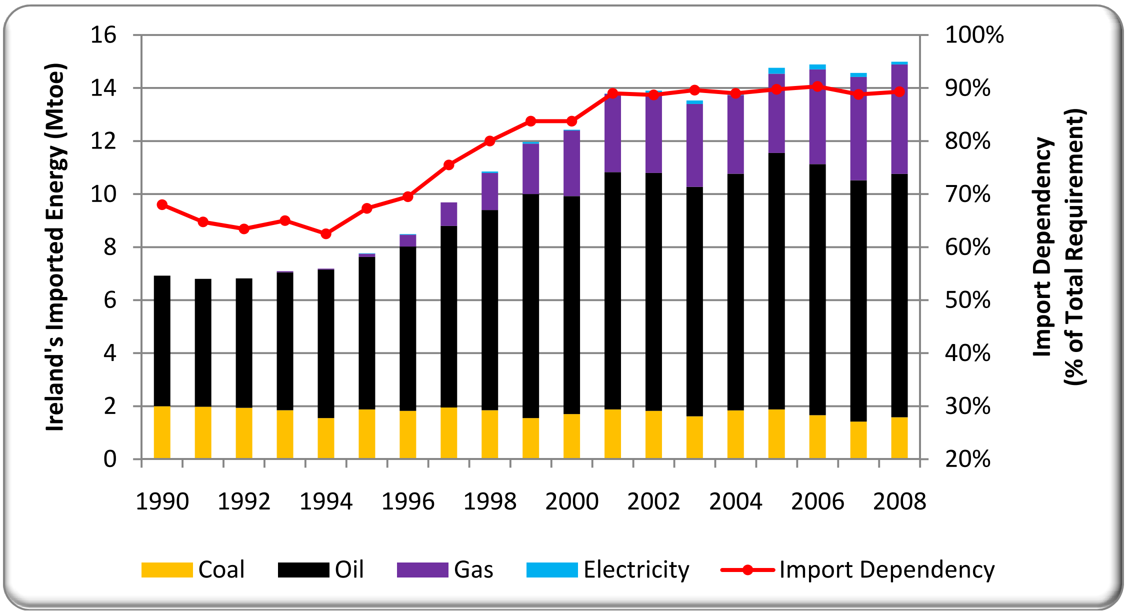


Figure 4-4: Ireland's imported energy by fuel and dependency from 1990 to 2006 [24, 26, 27].

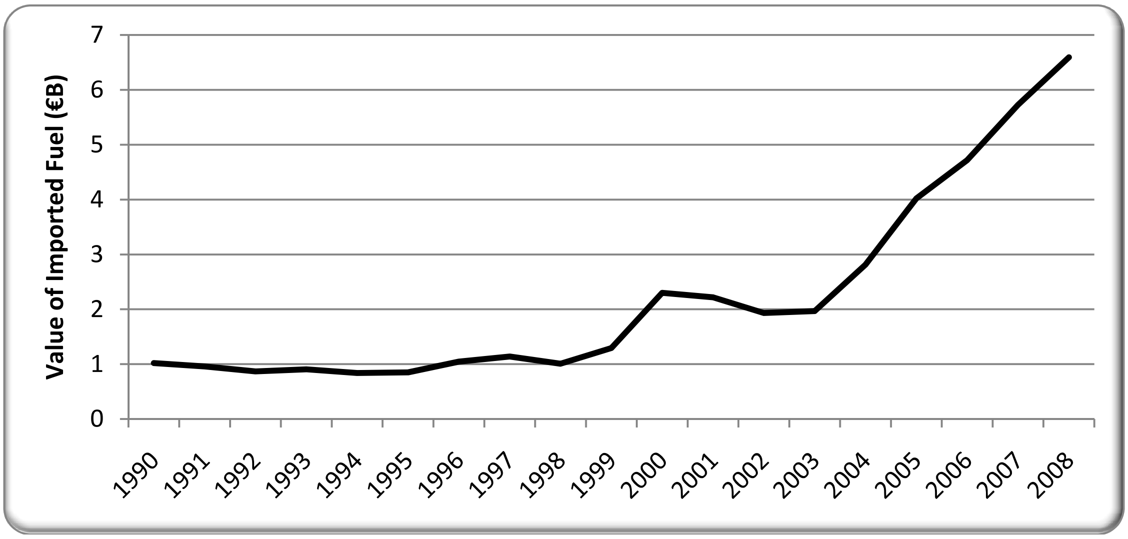


Figure 4-5: Value of imported fuel to Ireland from 1990 to 2008 [28].

On a global context Ireland's energy demands are relatively small, accounting for only 0.12% of total energy demand. In 2008 for example, Germany had a total energy demand of approximately 335 Mtoe/year in comparison to Ireland's demand of 16 Mtoe/year. This relatively small consumption is primarily due to Ireland's population, which is only 0.07% of the world's population. Hence, it is more appropriate to evaluate Ireland's energy position on a per capita basis. Figure 4-6 compares Ireland's total PES and CO_2 emissions to those for the World, individual countries, and the OECD region, while Figure 4-7 outlines Ireland's rank when compared to 137 other countries worldwide under various indices for PES, CO_2 emissions, energy production, and energy imports.

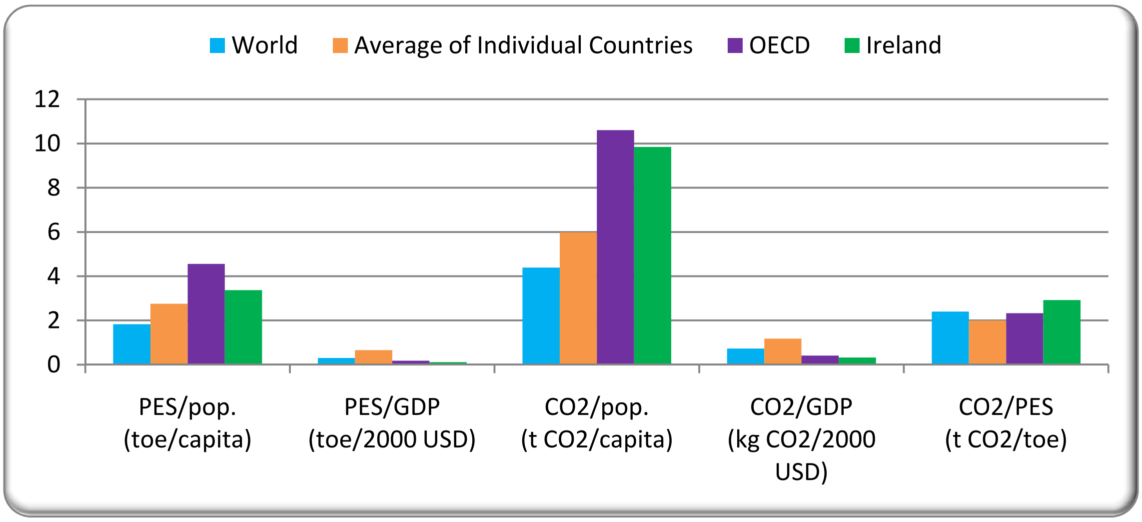


Figure 4-6: Energy indexes for the world, individual countries, the OECD region, and Ireland in 2008 [29].

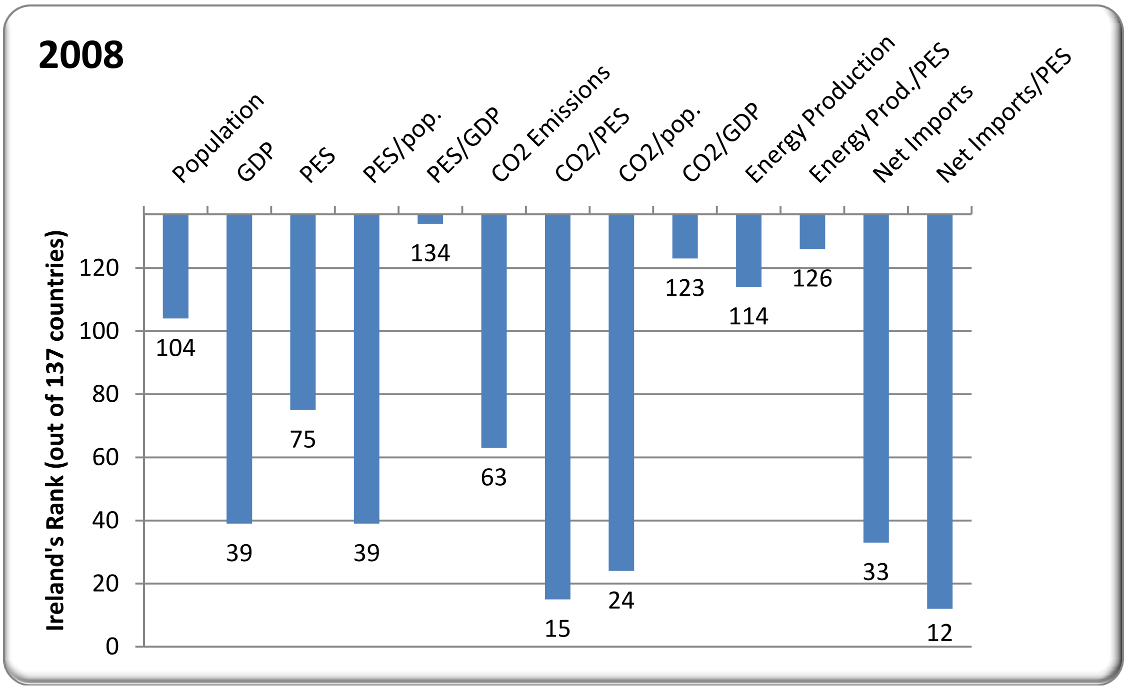


Figure 4-7: Ireland's rank out of 137 countries under various energy indexes in 2008 [29].

Figure 4-6 indicates that Ireland's PES/population is above average when compared to other countries, but it is less than the average consumption within the OECD region which suggests Ireland's consumption is low for a developed country. When assessed on a per GDP basis, Ireland's PES and CO_2 emissions are below those for the World, individual countries, and the OECD region. However, Figure 4-7 reveals that this is most likely due to Ireland's relatively high GDP in 2008, which was the 39th highest in the world. When Ireland's CO_2 emissions are assessed relative to its population, the results in Figure 4-6 indicate that they are approximately double those recorded for the World and the average of individual countries. Although Ireland's per capita CO_2 emissions are still lower than the OECD average, Figure 4-7 reveals that they are the 24th highest in the world. More significantly, Ireland's CO_2 emissions relative to its PES are above global, country, and OECD averages, at 2.92 t CO_2/toe (Figure 4-6), making Ireland the 15th largest emitter of CO_2/toe in the world (Figure 4-7).

Finally, the indices for energy security of supply in Figure 4-7 also display the vulnerability of the Ireland's energy system to global energy supply. When assessed relative to PES, Ireland is the 126th least self-sufficient country in the world and consequently, its net imports relative to its PES are the 12th highest in the world. This is specifically due to Ireland's extreme dependence on imported oil, as outlined earlier in Figure 4-4. Not only does this create risk, but the significant implications on Ireland's balance of payments have also been demonstrated in Figure 4-5 by Ireland's €6 billion/year expenditure on imported fuel each year [30]. By investing this money in domestic energy production, Ireland could improve its balance of payments, reduce risk, and increase its employment rates.

To conclude, in comparison to other developed countries, Ireland is a relatively low consumer of fuel and low emitter of CO_2. However, Ireland's CO_2 emissions relative to the energy it consumes are amongst the highest in the world and almost all of Ireland's energy is imported. Therefore, renewable energy could reduce Ireland's CO_2 emissions, while also improving its energy self-sufficiency.

4.2. Ireland's Renewable Energy Consumption and Potential

In 1990, Figure 4-8 indicates that Ireland supplied 2.3% of its total final consumption (TPC) using renewable energy, which was generated using biomass and hydro resources. During most of the 1990s, the renewable energy contribution in Ireland remained practically the same, until wind energy began to expand. From 1998 to 2008, wind energy increased its contribution to Ireland's TPC from approximately 0.3% to 2%, which correspondingly increased Ireland's total renewable energy contribution to 4.5% in 2008 (Figure 4-8).

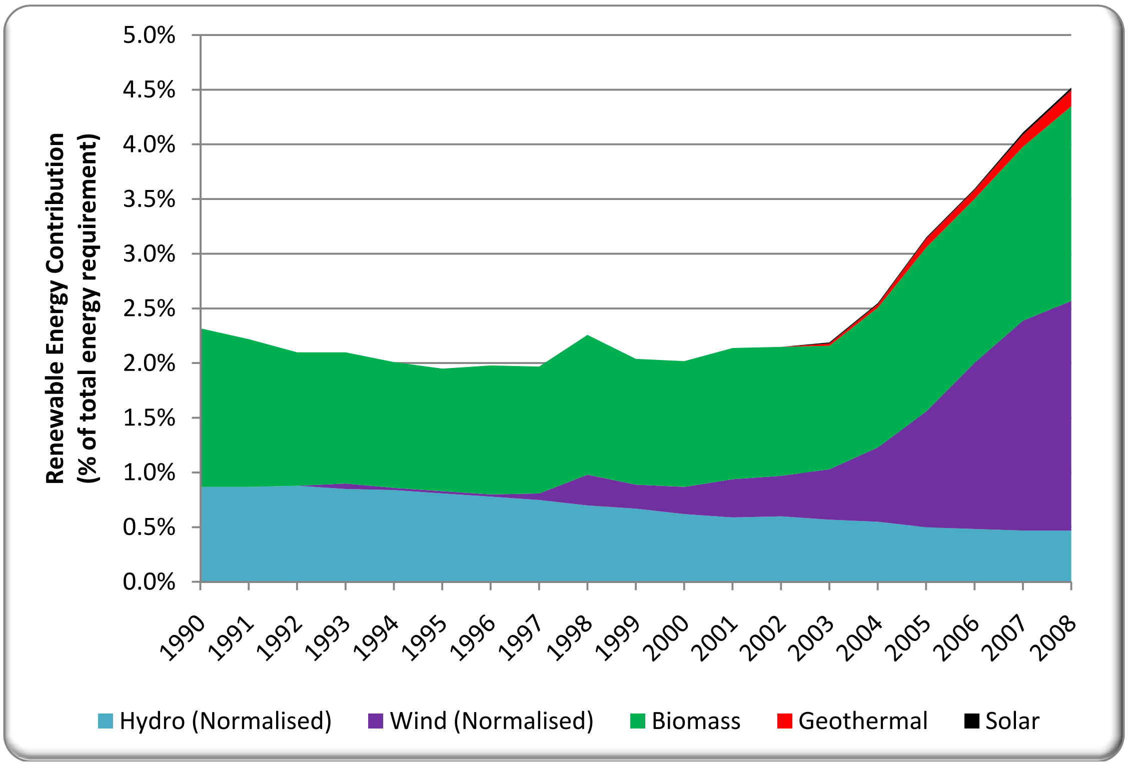
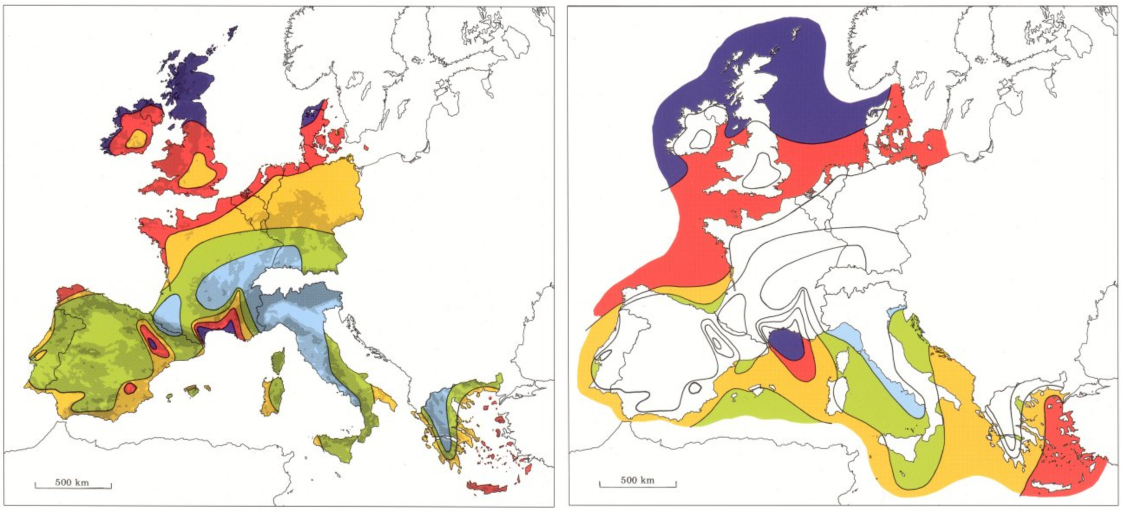


Figure 4-8: Renewable energy utilised in Ireland as a percentage of a total final consumption and divided by source [24]. Note that hydro is normalised to reflect the average hydro generation of the last 15 years and wind is normalised over the latest five years as per Directive 2009/28/EC.

Compared to other IEA member states, Ireland's utilisation of renewable energy is relatively poor. In fact, Ireland had the 5th lowest penetration of renewable energy in its energy system when compared to the 27 other IEA member states in 2008 [8]. From this comparison, it is evident that each country has introduced renewable energy into its energy mix in a different way. For example, Norway has predominately relied upon hydro power, Denmark has built a lot of wind energy, and Spain has focused on solar power. These sources have been utilised based on the resource available within each of these countries. Hence, to understand how Ireland can increase its renewable energy penetration, its renewable resources must be assessed.

To date, hydro power is currently the most utilised renewable energy within IEA member states [8]. There is 238 MW of hydro capacity currently installed in Ireland, which is approximately 3% of total generation capacity. However, this represents approximately 75% of total power available from Ireland river resources [31] and hence, hydro power will always be a relatively small source of power in Ireland.

As outlined in Figure 4-8 above, wind energy has been growing substantially in Ireland since the late 1990s. Not only is this due to global developments in wind turbine technology, but also due to the excellent wind resource available in Ireland, which is illustrated in Figure 4-9. In total, the energy available from this wind resource is estimated based on technological constraints as 613 TWh/year [32] of which, approximately 55.5 TWh/year will be economically viable in 2020 [33, 34]. Since this is approximately 170% of the electricity demand forecasted for Ireland in 2020 [35], it is clear that wind power is a key resource if Ireland is going to increase its renewable energy penetration.



Wind resources[1] at 50 metres above ground level for five different topographic conditions

	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
🟪	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
🟥	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
🟨	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
🟩	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
🟦	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Wind resources over open sea (more than 10 km offshore) for five standard heights

	10 m		25 m		50 m		100 m		200 m	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
🟪	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
🟥	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
🟨	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
🟩	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
🟦	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Figure 4-9: Onshore and offshore wind speeds in Europe [36, 37].

As Ireland has such as strong offshore wind resource, its wave energy resource is also relatively high. Not only has Europe on of the best wave energy resources in the world, but Ireland has one of the best wave energy resources in Europe, as displayed in Figure 4-10. Based on this resource and the capabilities of a Pelamis wave energy device [38], previous research estimated Ireland's theoretically available wave energy to be up to 28 TWh/year [39]. Even when this resource was refined to establish the 'accessible' wave resource in Ireland, it was predicted that wave energy could provide up to 20.76 TWh/year in Ireland [39], which is approximately 65% of the electricity demand forecasted for Ireland in 2020 [35]. Unlike wind, there is still uncertainty surrounding the capabilities of wave energy generators and therefore, although wave energy has the potential to be a significant renewable resource for Ireland, wind energy is a more attractive alternative in the immediate future.

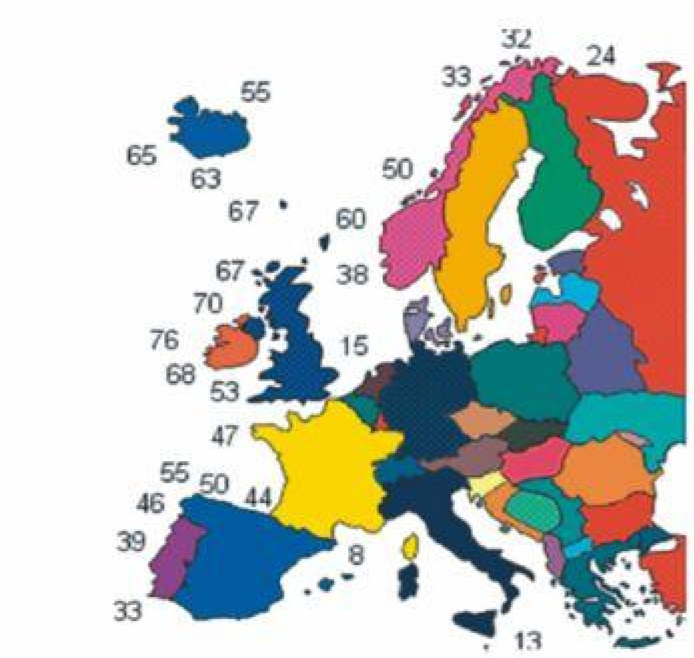


Figure 4-10: Average theoretical wave power potential (kW) in Europe [40].

In relation to tidal power, Ireland is home to one of the most advanced developers of tidal energy in the world, OpenHydro [41]. Hence, even if tidal energy is not economically competitive with other generators at present, Ireland could benefit by being one of the first to utilise this resource. Theoretically, there is an estimated tidal resource of around 230 TWh/year available around the island of Ireland. However, due to the limitations of existing technology, restricted access to certain locations, and the condition of the sea bed, only 2.63 TWh/year of this is accessible [42], which is outlined in Figure 4-11. Due to its predictability and location near populated areas around Ireland, tidal energy is a unique renewable resource in Ireland which could provide almost 10% of Ireland's 2020 electricity demand.

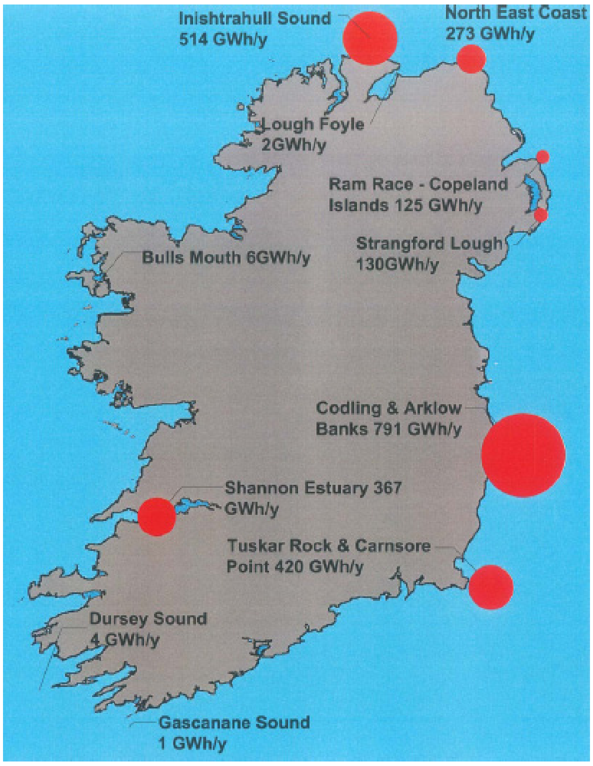


Figure 4-11: Accessible tidal energy resource around the island of Ireland [42].

Finally, agriculture is a prominent industry in Ireland and hence there are many sources of biomass that could be exploited. These include agricultural waste, energy crops, wood waste, landfill biogas, municipal waste, and sewage gas. From the literature, it was not possible to establish how much energy could be utilised from each of these resources. However, Corcoran *et al.* [43] calculated that if all suitable land was used for growing miscanthus energy crops in Ireland, then it would be possible to create 735 PJ (204 TWh) of energy each year. As displayed in Figure 4-12, this is approximately 6 TWh more than the PES forecasted for Ireland in 2020. Although this is not the accessible energy potential using biomass in Ireland, it clearly indicates that Ireland has a substantial biomass resource if it is required, especially considering the numerous other sources of biomass mentioned above that could also be utilised in addition to miscanthus energy crops.

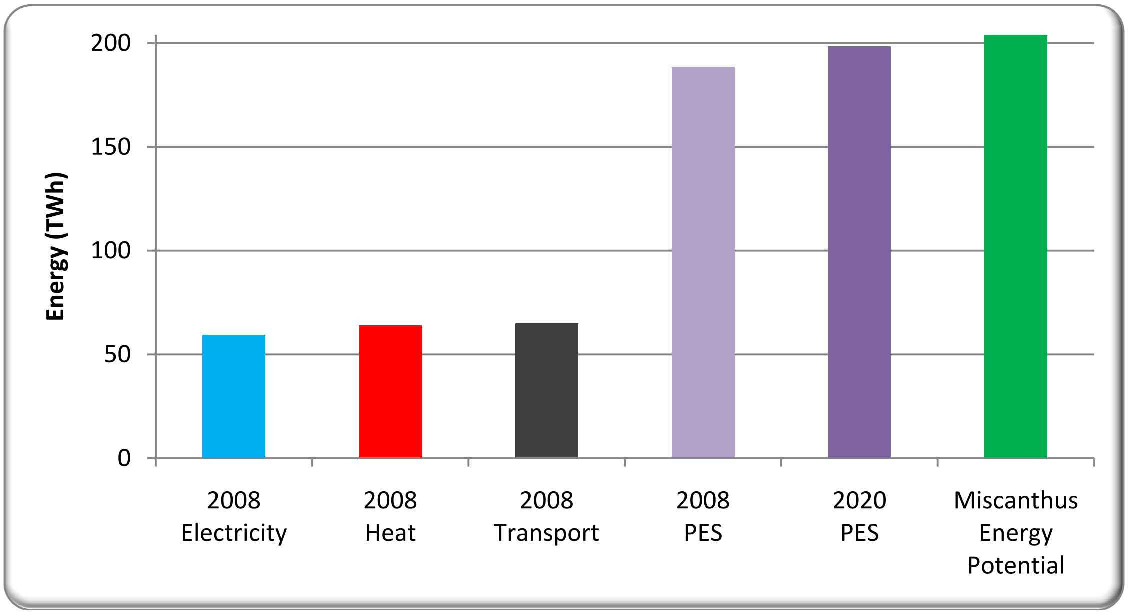


Figure 4-12: Energy feasible from miscanthus energy crops in Ireland compared to Ireland's actual 2008 and forecasted 2020 primary energy supply [24, 35, 43].

In summary, Ireland has a very significant supply of intermittent renewable energy for the production of electricity, as well as biomass which could be a direct replacement for fossil fuels. Since the use of biomass raises many other contentious issues, especially the debate relating to food production, it would be ideal if Ireland could maximise the use of its other intermittent renewable resources. Also, considering the abundance of these intermittent resources, which is summarised in Figure 4-13, utilising these resources before resorting to large-scale consumption of biomass is a pragmatic solution. Finally, from all of the renewable resources discussed, it is clear that Ireland's wind energy could be the ideal solution for increasing renewable energy utilisation. Wind turbines are a relatively mature technology and Ireland has more than enough wind to supply all of its forecasted electricity needs. Not only does this make Ireland an ideal laboratory for analysing energy storage, but this large-scale wind resource already plays a fundamental part in Ireland's current energy targets.

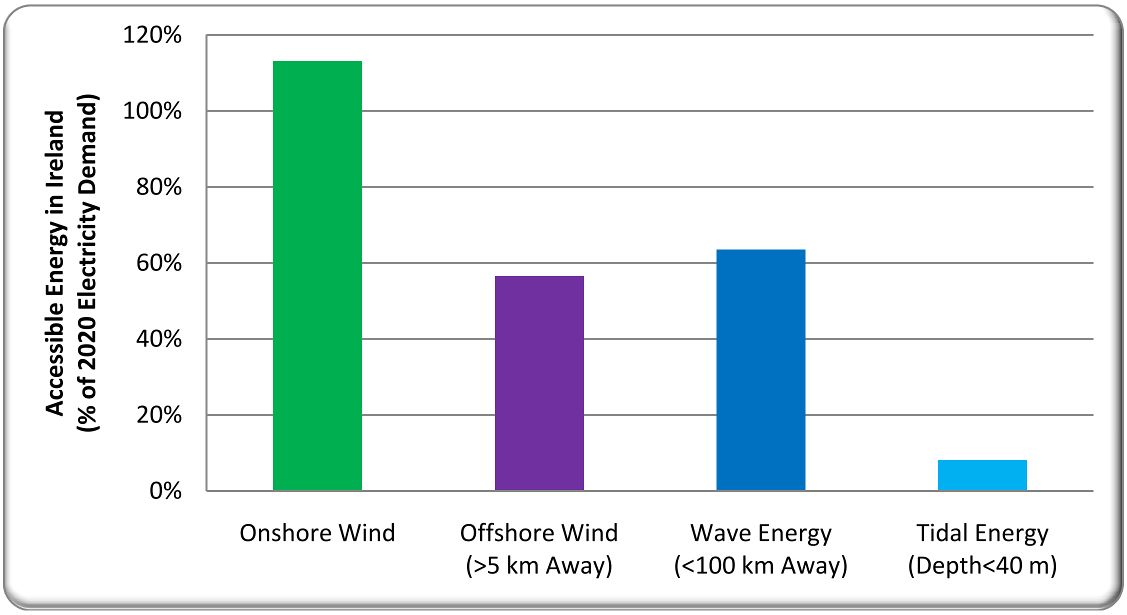


Figure 4-13: Accessible intermittent renewable energy resource in Ireland relative to forecasted 2020 electricity demand [33-35, 39, 42].

4.3. Ireland’s Energy Targets

By 2020, Ireland has an obligation under European Union (EU) initiatives to supply 16% of its total primary energy consumption from renewable sources [44]. Also, the Kyoto protocol only allows Ireland to increase its GHG emissions by 13% relative to its 1990 levels [45], but in 2008 Ireland was approximately 20% above 1990 levels [46]. As a result, the Irish government set a number targets for energy in 2007 [47] which included: 30% of fuel must be from biomass at the three state-owned peat power plants by 2015, no oil and a maximum of 50% gas in electricity generation by 2020, combined heat and power (CHP) needs to be expanded to 400 MW by 2010 and 800 MW by 2020, 500 MW of ocean energy should be in operation by 2020, 15% of electricity from renewable sources by 2010 and 40% by 2020 (see Figure 4-14), 5% of heat demand must come from renewable sources by 2010 and 12% by 2020 (see Figure 4-14), 3% of transport from renewables by 2010 and 10% by 2020 (see Figure 4-14), and finally, a 20% reduction in overall energy demands by 2020 [48].

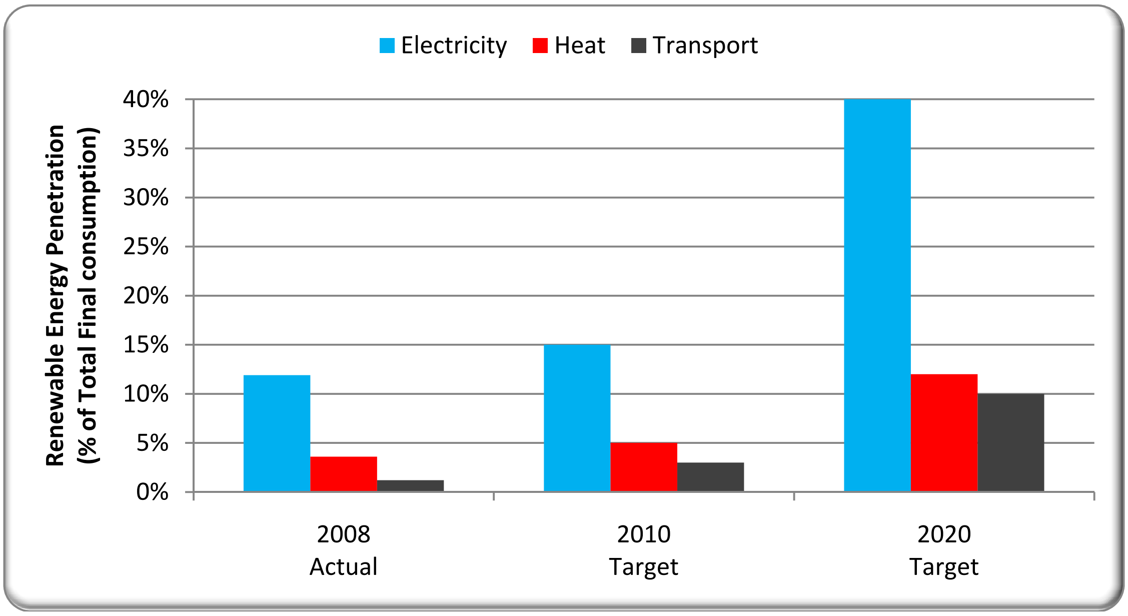


Figure 4-14: Actual and targeted renewable energy contribution in Ireland as a percentage of a total final consumption by sector [24].

Due to Ireland's significant wind energy potential which was discussed previously, this will be the primary resource utilised to achieve these targets. As outlined in Figure 4-15, Ireland is aiming for a wind penetration up to 37% by 2020, which is the highest penetration of wind energy proposed by any country within the EU. Therefore, Ireland will need to identify sources of flexibility within its energy system so this significant penetration of intermittent renewable energy can be accomplished. As there is practically no district heating in Ireland, the condensing power plants in Ireland only produce electricity. Therefore, there are a lot of hours where electricity storage would be able to directly replace power plant production (which is not the case in energy systems with a lot of CHP plants, such as Denmark [49]). As a result, electrical energy storage is an attractive option for increasing energy flexibility in Ireland based on the existing energy infrastructure. Consequently, evaluating the integration of wind energy using energy storage on the Irish energy system is not only an ideal case study for this research, but also a necessary one as Ireland's wind penetration increases.

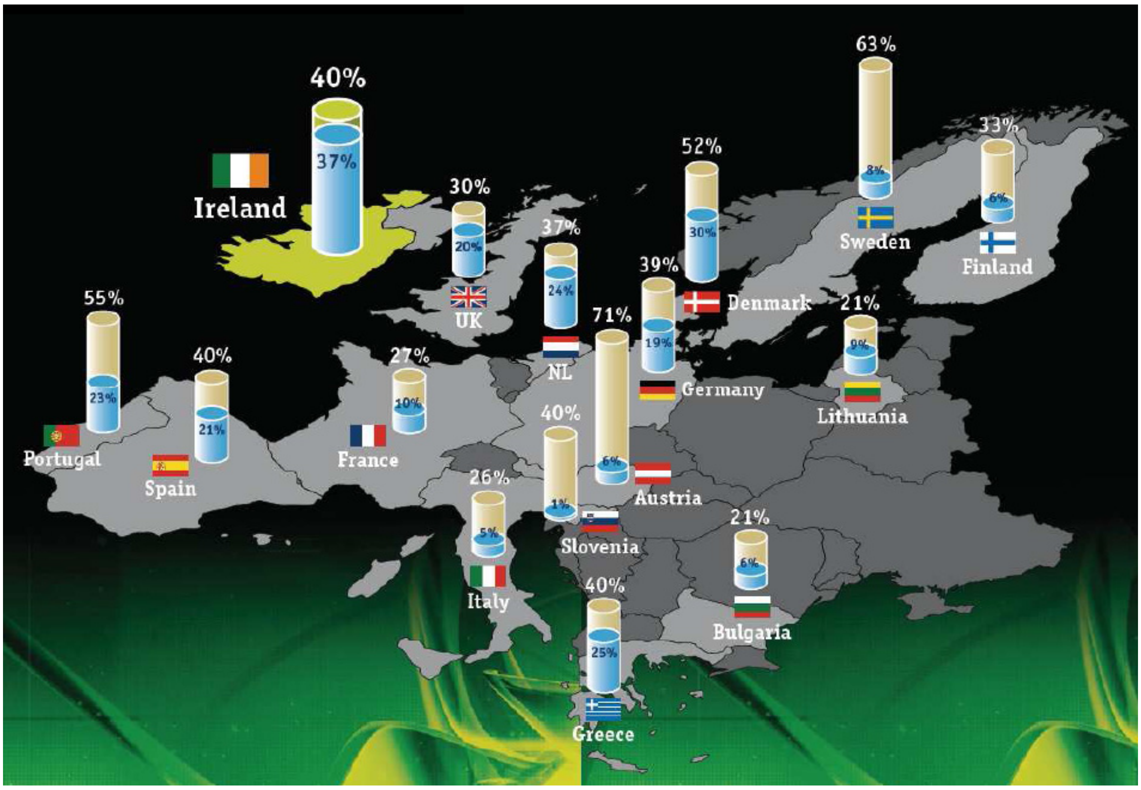


Figure 4-15: Renewable energy targets for individual EU member states for the electricity sector along with the corresponding wind penetration proposed [50].

4.4. Wind Energy Research in Ireland

A wide range of research has developed in Ireland due to its increasing penetrations of wind power in recent years. Below is a brief overview of this research which focuses on Ireland's wind resource, the implications of wind on the power system, electricity system analysis, demand side management, and energy storage.

4.4.1. Wind Resource in Ireland

Numerous studies have focused on the characteristics of the wind resource in Ireland. Bechrakis *et al.* [51] developed a method for analysing the wind energy potential at individual sites. Lang and McKeogh [52] developed a multi-scheme ensemble prediction tool for wind forecasting in Ireland and analysed its results on both a site-specific (51 wind farms) and a regional level. The authors concluded that for a 48-hour forecasting horizon, there is less than 7% error when this method is used to forecast wind generated electricity from all 51 wind farms together, but individual sites can have errors up to 21%, thus highlighting the benefits of aggregated wind forecasting. Doherty *et al.* [53] analysed the inclusion of wind forecasting in the dispatch of generators on an electricity market by using a typical 24-hour period on the All-Ireland electric grid as a case study. The implications of additional wind with and without wind forecasting were assessed by analysing the consequences for conventional generation, reserve levels, and resulting emissions. The authors concluded that the inclusion of wind forecasting during the dispatch of generators was the most promising strategy for facilitating wind on the Irish system. Leahy [54] investigated the implications of long periods of low wind speeds in Ireland during a time of high electricity demand by analysing data from December 2009 to January 2010 in Ireland. This was an extremely cold time in Ireland so electricity demand for heating was relatively high, but the data indicated that there were no notable effects on system demand or on electricity prices over this period. This was primarily due to a low total electricity demand caused by the economic recession in Ireland and also, because the cold spell corresponded with the holiday season. Hence, under normal economic conditions this could become a concern. Fusco *et al.* [55] investigated the potential correlation between wind and wave energy produced around the coast of Ireland, which was based on the predicted output from a 3.5 MW Vestas V90 wind turbine and a 750 kW Pelamis wave energy device. Results indicated a weak correlation between the two resources in the West and South-West of Ireland and hence, utilising wind and wave energy together at these locations could produce more reliable and predictable power. The authors concluded that this correlation lays the foundations for a more detailed quantification of its benefits and hence, they are not outlined here. Foley *et al.* [56] compared the wind speeds in Ireland, Scotland, England, and Wales, concluding that Britain may be able to balance its spatially variable wind resource better using the regional dispersion of wind farms within its own area rather than by interconnection with Ireland. The authors indicated that this could limit the system support available from interconnection between Ireland and Britain as wind energy increases in the future, which could be significant for the interconnector currently being constructed from Ireland to Wales. Overall, the research to date on the wind energy resource in Ireland outlines its variability, which needs to be accommodated for within the existing power system.

4.4.2. Impact of Wind Energy on the Power System

As wind penetrations increase, its unpredictability can have significant consequences on the dispatch of power plants and the stability of the electric grid. Therefore, studies have also focused these issues. Keatley and Hewitt [57] investigated the implications of increased cycling of power plants on the Irish electricity grid due to the introduction of the All-Ireland single electricity market (SEM) in 2007. The authors illustrated that some power plants have dropped down the merit order from baseload to mid-merit due to the SEM, which could dramatically reduce their lifetime due to increased creep and fatigue of components. In addition, the authors predicted that as more flexibility will be required as wind penetrations increase, it could lead to an over-reliance on gas fuelled power plants.

More specifically relating to the grid, Coughlan *et al.* [58] assessed the various wind turbine models available for power system stability studies from the perspective of the Irish TSO, EirGrid. For maximum benefit, the review indicated that generic models need to be developed between manufactures, model developers, and system operators, which should be validated using staged testing, have an agreed level of modelling error, and be incorporated into existing software. This would help the TSO achieve large-scale electricity generation using wind power. Doherty and O'Malley [59] developed a model to quantify the additional reserve required as wind energy is added to the All-Ireland electric grid, based on the probability of a generator tripping. The authors concluded that wind energy will not require any notable increase in expensive fast-acting reserve (< 1 hour), but may require additional reserve over large forecast horizons (several hours). Brownlees *et al.* [60, 61] compared the magnitude and frequency of power fluctuations from fixed-speed wind turbines and conventional generation to those experienced on the former interconnector between Northern Ireland and Ireland. Results indicated that there was a weak correlation between wind power oscillations and those on the interconnector, as they were being damped within the Northern Ireland electricity grid. Kennedy *et al.* [62] used the Northern Ireland electricity grid as a case study to compare the provision of spinning reserve to diesel generators for balancing significant short-falls of forecasted wind power. The results suggest that diesel generators are a more attractive option as they reduce system costs, can have relatively low CO_2 emissions if operated using biodiesel, and could provide network support if located in specific locations. Doherty *et al.* [63] analysed the impact of additional wind energy on the frequency of the All-Ireland electricity network, concluding that there will be significant frequency control challenges for the TSO when HVDC interconnection along with additional doubly-fed induction generators in wind turbines are introduced. Vittal *et al.* [64] assessed the impact of wind generation on the voltage stability of a power system. Using the 2013 All-Ireland electric grid with 2188 MW of wind as a case study, the results indicated that by utilising the control features found within doubly-fed induction generators, voltage stability could be improved in both transmission and distribution level buses of the electric grid, which would enable higher penetrations of wind energy without degrading the voltage stability of the system. Using a transmission expansion planning methodology, Rivera *et al.* [65] analysed the potential design of an offshore grid for Ireland which could accommodate up to 5294 MW of offshore wind power. The results indicated that an offshore grid should be meshed, there are synergies between onshore and offshore wind production specifically in congested areas, and AC grid technology is the most economically viable at present. These studies outline both the complexity and the significant implications associated with wind energy fluctuations. Consequently, to examine the economical and environmental cost of these fluctuations, as well as potential solutions for accommodating it, a wide range of research has also been carried out in electricity system analysis.

4.4.3. Electricity System Analysis in Ireland

To date, a number of electricity system analyses have already investigated the economic and environmental cost of integrating wind energy onto the Irish electric grid. In 2003, Gardner *et al.* [66] investigated the effects of additional wind energy in Ireland and identified that the most costly aspects of increasing the wind penetration are transmission reinforcement, wind curtailment, capital costs, and operating costs. In 2004, ESB National Grid [67] also analysed the costs and implications for conventional power plants associated with increasing the wind penetration in Ireland. The report concluded that increasing the wind penetration in Ireland from 0% to 11.7% would increase the total generation costs by €196M/year, while peaking and mid-merit power plants would require more frequent start-ups, need increased ramping, and have lower capacity factors. In 2006, Doherty *et al.* [68] developed a range of least cost generation portfolios for the All-Ireland electricity grid in 2020 for various discount rates, carbon taxes, and fuel price scenarios. For numerous scenarios the optimal wind capacity was the maximum assumed available, which was 3800 MW or 22% of the predicted electricity demand. Therefore, the authors concluded that even high wind penetrations could be beneficial, but to analyse these a more detailed model is required which can assess wind curtailment and energy storage. Also in 2006, Denny and O'Malley [69] developed a least-cost dispatch model to identify if additional wind energy (0-2000 MW) would reduce GHG emissions on a forecasted 2010 All-Ireland electric grid. The results indicated that wind energy could reduce CO_2 by approximately 15% when 2000 MW was installed, but an additional incentive in the form of a €20/t CO_2 carbon tax was required to reduce SO_2 and NO_X emissions also. In 2007, Denny and O'Malley [70] used the PLEXOS environment [71] to create a model which could quantify the total net benefits of additional wind energy (0-4000 MW or 0-26.7% of electricity) on the All-Ireland electricity grid for the years 2010, 2015, and 2020. The authors concluded that additional interconnection and more flexible power plants would increase the net benefits of wind, by reducing the overall system costs.

In 2007, Meibom *et al.* [72, 73] modelled the Irish electricity grid for the year 2020 using the WILMAR Planning Tool [74]. The objective of this study was to identify the effects of large wind penetrations on the island of Ireland in relation to its overall operation, costs, and emissions. Meibom *et al.* concluded that a wind penetration of approximately 34% was feasible on the island of Ireland by 2020, which will reduce overall operation costs and the CO_2 emissions compared to 2007. Building on this work, numerous other studies have since been completed using the model developed with the WILMAR Planning Tool. Gubina *et al.* [75] developed a new scheduling tool which incorporates wind forecasting in the dispatch of plants on electricity markets. The Anemos wind-forecasting tool and the WILMAR Planning Tool were integrated with one another to create the WALT methodology, which will be tested in a future pilot project by the Irish TSO, EirGrid. Tuohy *et al.* [76] used the WILMAR Planning Tool to compare stochastic and deterministic modelling of the All-Ireland electric grid in 2020 with a 34% wind penetration. The results indicated that stochastic optimisation is 0.25% to 0.9% cheaper than deterministic optimisation. In addition, it was found that more frequent updating of the dispatch schedule for an electricity market will reduce the need for reserve. Troy *et al.* [77] used the WILMAR Planning Tool to analyse the operation of baseload power plants when wind energy is added to the Irish electricity grid. Three wind scenarios (2000 MW or 11% of demand, 4000 MW or 23%, and 6000 MW or 34%) were assessed on a forecasted 2020 All-Ireland electricity grid. The results indicated that additional wind energy will affect baseload plants differently depending on their characteristics. For the combined cycle gas turbine (CCGT) and coal plants which were considered in this study, CCGT units began to start-stop cycle more often and their capacity factor dropped, while coal units increased part-load operation and ramping. Alhajali *et al.* [78] also examined the impacts of wind variability on the 2020 All-Ireland electric grid as wind penetrations increased, but investigated if additional open cycle gas turbine (OCGT) power plants would improve the operation of the system. The authors concluded that the addition of OCGT could reduce system costs by up to 5% depending on the mix of plants, but interconnection to Britain is a vital component of the 2020 All-Ireland electric grid, as it reduces fuel costs by approximately 10-15%. Denny *et al.* [79] also used the WILMAR Planning Tool to assess interconnection from Ireland to Britain for the integration of 34% wind energy on the All-Ireland electricity network. The authors concluded that increased interconnection should reduce the price of electricity in Ireland and increase the security of the electric grid. Although Ireland would have lower CO_2 emissions, these would be counter-balanced by increased emissions in Britain. However, as well as interconnection, two other solutions for creating flexibility have also been researched in Ireland: demand side management and energy storage.

4.4.4. Demand Side Management

Due to the proposed rollout of smart meters across Ireland, many studies have also looked at demand side management (DSM) to aid the integration of large-scale wind penetrations in Ireland. McKenna *et al.* [80] simulated real-time load management in MATLAB to outline how an Irish local authority (Kerry County Council) could maximise the use of electricity from a 6.8 MW wind farm to meet its electricity requirements. Finn *et al.* [81] analysed the role of time-of-use and real-time-pricing tariffs for the domestic electricity market in Ireland. After forecasting electricity prices on the 2020 Irish electricity market with a 34% wind penetration, the authors concluded that due to the expected variability in pricing in 2020, a real-time-pricing tariff is more appropriate for increasing renewables on both the supply and demand side. Subsequently, this study also illustrated how real-time pricing could be used to reschedule the load of a domestic electric water heater over a 24-hour period. In a later study, Finn *et al.* [82] also investigated the implications of using day-ahead pricing predictions to demand side manage a load with an inherent energy loss due to rescheduling. Irish electricity market prices from 2008 and an electric water heater with a thermal storage in a domestic dwelling were used to form a case study. The results indicated that price optimised DSM has the potential to promote the use of wind generated electricity on the Irish electricity system, but discrepancies between day-ahead and final electricity prices could be a significant barrier. Savage *et al.* [83] also analysed the implications of using an electric heat load to integrate wind on the Northern Ireland electric grid, but as reserve by shutting down when there was shortages of wind supplied to the grid. Results indicate that thermal storage of electric heat loads provide an ideal buffer for counteracting over-predictions of wind power and if implemented, then wind forecasting should be included in the scheduling of power plants. Akmal *et al.* [84] assessed the benefits of heat pumps as a flexible load which could enable larger penetrations of wind power, by using the WILMAR model of the All-Ireland electric grid discussed earlier and a 34% wind penetration as a case study. Two operating strategies were considered: firstly, heat pumps were operated during off-peak hours and secondly, heat pumps were operated during hours of high wind generation. Although both strategies reduced system costs, the number of plant start-ups, and wind curtailment, the off-peak strategy was consistently better. Finally, Foley discussed Ireland's target for electric vehicles (EVs), which is 10% of road cars by 2020 [85]. In a future paper, the authors will outline how demand side managing EVs will enable larger penetrations of wind energy on the Irish electric grid, by modelling it on an hourly basis using the WASP-IV energy tool.

4.4.5. Energy Storage

Before this study began in 2007, there were no studies available which simulated the integration of wind on the Irish energy system using large-scale energy storage on an hourly basis. However, numerous studies had analysed the benefits of energy storage in conjunction with a small number of wind farms. González *et al.* [86] analysed the operation of a hydrogen storage system for four wind farms (100 MW total capacity) in the South-West of Ireland utilising an electrolyser, compressor, and a hydrogen storage. The results indicated that significant cost-reductions for the hydrogen system, low average surplus wind electricity cost, and a high hydrogen market price are necessary for the economic viability of hydrogen storage. For a separate study, a demonstration project was initiated in 2007 to construct a vanadium-redox flow battery in conjunction with a 6 MW wind farm in Co. Donegal [87]. The initial economic analysis indicated that a 2 MW, 12 MWh battery would provide the greatest return and hence, these were the capacities defined for its construction, although it is unclear how the project has progressed since. In 2006, Allen *et al.* [88] developed a model using MATLAB-Simulink to investigate the operation of a single wind farm in conjunction with a PHES facility. The study analysed the operation of a 20 MW wind farm using a 30 minute time-step over a 1-year period in conjunction with two different PHES facilities, a 4 MW and a 6 MW. For each PHES considered, the model was run with various PHES storage capacities, up to a maximum of 500 MWh. Allen et al. discovered that the power variations from the wind-PHES system reduced as the power capacity and storage capacity of the PHES increased, until eventually a saturation point is reached.

Since this study began, there have been some significant developments in relation to PHES in Ireland. Firstly, in 2009 a new campaign was launched call “Spirit of Ireland” [89], which promoted the large-scale (>100 GWh) deployment of wind farms and PHES in Ireland. The PHES facilities in the proposal utilised U-shaped valleys along the Irish coastline as their upper reservoirs and the sea as their lower reservoirs. However, no detailed analysis of the size and economics of the proposal have been provided to date. Also, as mentioned earlier the All-Island Grid Study analysed the implications of a 34% wind penetration in Ireland by 2020. In this study, Meibom *et al.* [72, 73] found that the operation of energy storage on the Irish electricity grid didn’t change when wind power was increased to a penetration of 34% and hence, concluded that it was not necessary until the wind penetration surpassed this. Using the WILMAR Planning Tool, Tuohy and O'Malley [90] simulated the All-Ireland electricity grid with and without a 500 MW 5 GWh PHES facility for wind capacities between 3 GW and 15 GW, which is 17% to 80% of total electricity. The results indicated that the PHES plant did not have any impact on the operation of the system until the wind penetration exceeded 40%. Also, even though it reduced the operating costs of the system, the additional capital costs were too high to justify its construction. However, the authors did emphasise that future work should analyse the implications of different capacities and operating strategies for the PHES facility. In 2010 Nyamdash *et al.* [91] did this by analysing the implications of energy storage on the 2006 All-Ireland electricity grid with wind capacities of 1300 MW, 1950 MW, and 2550 MW. In this study, energy storage and wind power were simulated using three different operation strategies: one where the wind-hydro system provided a 24 hour baseload output and replaced baseload plant, a second where it charged for 12 hours at night and discharged for 12 hours during the day by replacing mid-merit plant, and thirdly, where it generated for 6 peak hours of the day and replaced peaking plant. Each operating strategy was analysed for a PHES power capacity ranging from 0 MW to 1800 MW. The results indicated that the baseload and peaking strategies increased the variability of wind, but the mid-merit strategy decreased it. Also, a subsequent economic assessment was carried out which indicated that the revenue made by the energy storage under all three strategies was not sufficient to make it an attractive investment, even when it was analysed as four different technologies: PHES, compressed air, battery, and flow battery. Therefore, the authors concluded that without any economic subsidy, energy storage would not be an attractive investment. Similarly, this research will also assess the role of PHES, but using a new methodology and different operating strategies to those proposed in existing studies.

4.5. Conclusions

This chapter has indicated that Ireland has an energy system which uses a lot fossil fuel, is currently emitting more CO_2 than permissible under the Kyoto protocol, and is very dependent on energy imports. All of these concerns could be reduced if Ireland began to utilise its indigenous renewable energy resource which is currently only providing around 4.5% of PES, even though there is enough to supply all of Ireland's energy needs. In line with this, ambitious energy targets have been set by the Irish government, which include 40% of electricity, 12% of heat, and 10% of transport to be supplied using renewable energy by 2020. The primary resource which will be utilised to reach these targets is intermittent wind energy, which needs to provide approximately 34-37% of electricity in Ireland by 2020.

In line with this, a significant variety of research has been carried out in relation to the implementation and facilitation of Ireland’s wind energy target, which includes areas such as resource assessment, implications for the power system, energy modelling, demand side management, and energy storage. Most relevant to this research, is the work completed on electricity system analysis and energy storage in sections 4.4.3 and 4.4.5 respectively. This study will complement existing research by identifying PHES as a suitable energy storage technology for integrating Ireland’s wind, quantifying the freshwater PHES resource available in Ireland, simulating larger capacities and new operating strategies for PHES, analysing the implications of PHES for the entire Irish energy system, defining new alternatives to PHES, and proposing a new operating strategy so that PHES can maximise its profits on existing electricity markets. In line with this, the first task of this work investigates the various energy storage technologies currently available, to identify the most suitable technology for Ireland.

Chapter 5

5. Review of Energy Storage Technologies

There are a wide variety of energy storage technologies currently available, each with its own specific capabilities, maturity, costs, and applications. Hence, the primary objectives of this literature review were to identify the various types of energy storage technologies that exist and subsequently, to assess their suitability as an aid for the integration of fluctuating renewable energy, especially in relation to the Irish energy system. This chapter summarises the results of this review, which is fully described in Appendix A.

In total, 11 different types of energy storage were assessed during the review. These were pumped hydroelectric energy storage (PHES), underground pumped hydroelectric energy storage (UPHES), compressed air energy storage (CAES), battery energy storage (BES), flow battery energy storage (FBES), flywheel energy storage (FES), supercapacitor energy storage (SCES), superconducting magnetic energy storage (SMES), a hydrogen energy storage system (HESS), thermal energy storage (TES), and electric vehicles (EVs). Each technology was analysed under the following key headings: how it works; advantages; applications; cost; disadvantages and future potential, so its suitability for the integration of fluctuating renewable energy could be assessed.

A detailed description and theoretical analysis of each storage facility can be found in Appendix A and hence, only a brief summary of their operation is provided here. PHES utilises two reservoirs of water at different vertical heights that are connected via a penstock. Typically these are freshwater facilities located on mountainous terrain, although recent proposals have been made based on seawater facilities [89, 92]. UPHES is based on the same concept as PHES, but the upper reservoir is located at ground level and the lower reservoir is located underground [93]. CAES operates in the same was as a conventional gas turbine. However, unlike a conventional gas turbine which uses 66% of its gas to compress air at the time of generation, CAES utilises off peak electricity to compress air and store it in an underground cavern until it is required. This reduces the gas required by approximately one third.

BES operates in the same way as conventional batteries, which exploit the chemical reactions that occur when two electrodes are immersed in an electrolyte. In the review, three different types were assessed: lead-acid, nickel-cadmium, and sodium-sulphur. Although FBES is also based on electrochemistry, its structure is very different to BES. Two electrolytes are stored in separate tanks, which react with one another when they are pumped to a cell stack. The power capacity is dependent on the size of the cell stack, while the storage capacity is dependent on the size of the electrolyte tanks. Once again, three different types were investigated: vanadium-redox, polysulphide-bromide, and zinc-bromine.

FES utilises the momentum within a mass which is spinning anywhere between 10,000 (low-speed) and 80,000 (high-speed) rpm. SCES functions in the same way as standard electronic capacitors, but on a much larger scale. SMES stores energy in the magnetic field created by the flow of direct current in a coil of wire. Typically, when current is passed through a wire it is dissipated as heat. However, if the wire used is kept in a superconducting state (i.e. cooled <150 K), zero resistance occurs and hence energy can be stored with practically no losses.

The HESS consists of three stages: creating, storing, and using hydrogen. Hydrogen can be created by extracting it from fossil fuels, reacting steam with methane, or by electrolysis using electricity. Subsequently, it can be stored as a gas by compressing it into containers or underground reservoirs, as a liquid by pressurising and cooling the gas, or in metal hydrides which absorb molecular hydrogen. Finally, the hydrogen can be used in an internal combustion engine or in a fuel cell.

Two distinct types of TES were assessed: air-conditioning thermal energy storage (ACTES) and a thermal energy storage system (TESS). ACTES uses off-peak electricity to power chillers which create blocks of ice. These ice blocks can then be used during the day as a cooling load for air conditioners. A TESS takes advantage of large hot water storage tanks and CHP plants which are typically used in district heating systems. Although multiple technologies must operate coherently with one another to ensure this system operates successfully, a simple example is described here using wind power, CHP, and thermal storage, to outline the fundamental operation of a TESS. When wind power production is low the CHP electrical and heat output is high and hence, too much heat is typically produced. Therefore, this excess heat is stored in hot water storage tanks. When wind power production is high the CHP output is low, too little heat is typically being produced. Therefore, heat is obtained from the hot water storage to account for the deficit.

Finally, a single EV has a power connection to the grid of approximately 5 kW and a storage capacity of approximately 50 kWh. Due to the number of cars in developed countries, EVs could act as an energy storage system for the grid, if there was a large-scale rollout and their capacities were aggregated. EVs can be classified under three primary categories: battery electric vehicles (BEV) which act as an additional load to the electricity network, smart electric vehicles (SEV) which charge when it is suitable for the electricity network, and vehicle to grid (V2G) which not only receive power from the grid, but also give power back.

Once the fundamental operation of each energy storage technology was identified, it was evident that there was a broad range of capacities feasible. As a result, they were grouped together based on the size of power and storage capacity that they can achieve. Four categories were created: devices with large power (>50 MW) and storage (>100 MWh) capacities; devices with medium power (1-50 MW) and storage capacities (5-100 MWh); devices with small power (<10 MW) and storage capacities (<10 MWh); and finally, a section on energy storage systems. These are energy storage technologies that were placed within the various categories defined:

1.	PHES	Large Power and Storage Capacities
2.	UPHES	
3.	CAES	
4.	BES	Medium Power and Storage Capacities
5.	FBES	
6.	FES	Small Power and Storage Capacities
7.	SCES	
8.	SMES	
9.	HESS	Energy Storage Systems
10.	TESS	
11.	EVs	

The characteristics of these storage technologies are outlined in Table 5-1 and their corresponding costs are displayed in Table 5-2. In addition, typical applications for the storage technologies are outlined in Table 5-3. The HESS, TESS, and EVs have unique characteristics as they are constructed from a range of different technologies and not just one single plant. As energy storage is only part of the system they are composed of, it is difficult to compare HESS, TESS, and EVs to the other energy storage technologies directly. Hence, documenting the costs and characteristics of these technologies is an area which will require further research in the future.

Table 5-1: Characteristics of various energy storage technologies [93-97].

Technology	Power rating	Discharge duration	Response time	Efficiency (%)	Parasitic losses	Lifetime	Maturity
Pumped hydro	100 – 4000 MW	4 – 12 h	sec - min	70 – 85	Evaporation	30 - 50 y	Commercial
Underground pumped hydro	100 – 4000 MW	4 – 12 h	sec - min	70 - 85	Evaporation	30 – 50 y	Concept
CAES (in reservoirs)	100 – 300 MW	6 – 20 h	sec - min	64	-	30 y	Commercial
CAES (in vessels)	50 – 100 MW	1 – 4 h	sec - min	57	-	30 y	Concept
Lead-acid battery	< 50 MW	1 min – 8 h	< ¼ cycle	85	Small	5 – 10 y	Commercial
Nickel-cadmium	< 50 MW	1 min – 8 h	n/a	60 - 70	~2 - 5%	3500 cycles	Commercial
Sodium sulphur battery	< 10 MW	< 8 h	n/a	75 – 86	5 kW/kWh	5 y	In development
Vanadium redox flow battery	< 3 MW	< 10 h	n/a	70 – 85	n/a	10 y	In test
Polysulphide bromide flow battery	< 15 MW	< 20 h	n/a	60 – 75	n/a	2000 cycles	In test
Zinc bromine flow battery	< 1 MW	< 4 h	< ¼ cycle	75*	Small	2000 cycles	In test / commercial units
Flywheels (low speed)	< 1650 kW	3 – 120 s	< 1 cycle	90	~1%	20 y	Commercial products
Flywheels (high speed)	< 750 kW	< 1 h	< 1 cycle	93	~3%	20 y	Prototypes in testing
Supercapacitor	< 100 kW	< 60 s	< ¼ cycle	95	-	10,000 cycles	Some commercial products
SMES (Micro)	10 kW – 10 MW	1 – 60 s	< ¼ cycle	95	~4%	30 y	Commercial
SMES	10 – 100 MW	1 – 30 min	< ¼ cycle	95	~1%	30 y	Design concept
Hydrogen (fuel cell)	< 250 kW**	As needed	< ¼ cycle	34 – 40*	n/a	10 – 20 y	In test
Hydrogen (engine)	< 2 MW**	As needed	Seconds	29 – 33*	n/a	10 – 20 y	Available for demonstration

*** AC-AC efficiency.**

****Discharge device. An independent charging device (electrolyser) is required.**

Table 5-2: Costs of various energy storage technologies [93-97].

	Capital cost			O&M cost				
Technology	Power related cost ($/kW)	Energy related cost ($/kWh)	BOP ($/kWh)	Fixed ($/kW-y)	Variable (c$/kWh)	Cost certainty	Environmental issues	Safety issues
Pumped hydro	600 – 2000	0 – 20	Included	3.8	0.38	Price list	Reservoir	Exclusion area
Underground pumped hydro	n/a	n/a	n/a	3.8	0.38	Estimate	Reservoir	Exclusions area
CAES (in reservoirs)	425 – 480	3 – 10	50	1.42	0.01	Price quotes	Gas emissions	None
CAES (in vessels)	517	50	40	3.77	0.27	Estimate	Gas emissions	Pressure vessels
Lead-acid battery	200 – 580	175 – 250	~50	1.55	1	Price list	Lead disposal	Lead disposal, H_2
Nickel-cadmium	600 – 1500	500 – 1500	n/a	n/a	n/a	Estimate	Toxic cadmium	Toxic cadmium
Sodium sulphur battery	259 – 810	245	~40	n/a	n/a	Project specific	Chemical handling	Thermal reaction
Vanadium redox flow battery	1250 – 1800	175 – 1000	n/a	n/a	n/a	Project specific	Chemical handling	Chemical handling
Polysulphide bromide flow battery	1000 – 1200	175 – 190	n/a	n/a	n/a	Project specific	Chemical handling	Chemical handling
Zinc bromine flow battery	640 – 1500	200 – 400	Included	n/a	n/a	Project specific	Chemical handling	Chemical handling
Flywheels (low speed)	300	200 – 300	~80	n/a	n/a	Price list	-	Containment
Flywheels (high speed)	350	500 – 25,000	~1000	7.5	0.4	Project specific	-	Containment
Supercapacitor	300	82,000	10,000	5.55	0.5	Project specific	-	-
SMES (Micro)	300	72,000	~10,000	26	2	Price quotes	-	Magnetic field
SMES	300	2000	~1500	8	0.5	Estimate	-	Magnetic field
Hydrogen (fuel cell)	1100 – 2600	2 – 15	n/a	10	1	Price quotes	-	-
Hydrogen (engine)	950 – 1850	2 – 15	n/a	0.7	0.77	Price list	Emissions	-

Table 5-3: Technical suitability of energy storage technologies to different applications [95].

	Storage Technology	Pumped hydro	Underground pumped hydro	Compressed air	Lead-acid batteries	Advanced batteries	Flow batteries	Flywheels	Supercapacitors	Superconducting magnetic	Hydrogen fuel cell	Hydrogen engine
Storage Application	■											
Transit and end-use ride-through					X		X	X	X	X	X	
Uninterruptible power supply					X	X	X	X			X	X
Emergency back-up				X	X	X	X				X	X
T&D stabilisation and regulation					X		X			X	X	
Load levelling		X	X	X	X	X	X				X	X
Load following					X	X	X				X	X
Peak generation		X	X	X	X	X	X	X			X	X
Fast response spinning reserve					X	X	X	X			X	X
Conventional spinning reserve		X	X	X	X	X	X	X			X	X
Renewable integration		X	X	X	X	X	X	X			X	
Renewables back-up		X	X	X	X	X	X				X	

To chose a suitable energy storage technology based on the characteristics outlined in Table 5-1, Table 5-2, and Table 5-3, existing research on the integration of wind was also reviewed. By looking at the energy storage technologies used during island investigations, it was apparent that very large storage capacities are necessary to obtain high wind penetrations. Bakos [98] and Kaldellis [99] concluded that a storage capacity in the region of 1 to 3 days of the energy system's power requirement is necessary to obtain a wind penetrations above 90%. Although larger energy systems will probably require less energy storage than island systems, primarily due to the possibilities of creating flexible loads such as electric vehicles or demand side management, these island case studies indicate that large-scale energy storage will most likely be necessary for large wind penetrations. Therefore, the scale of energy storage necessary for Ireland to integrate large penetrations of wind energy reduced the energy storage technologies feasible to PHES, UPHES, and CAES.

Studies indicate that PHES is the most utilised and mature large-scale energy storage technology currently available, but its major drawback is the lack of suitable sites [100-102]. In theory UPHES could benefit from the maturity of PHES as it uses a number of similar components, but it is still only at the conceptual stage of development and hence, the definition of a suitable site is still even vague. Finally, not only does the feasibility of CAES rely on the availability of suitable locations, but it will also depend on the price and availability of gas within future energy systems. In addition, although CAES is classified as a mature technology, there are currently only two facilities constructed worldwide.

In conclusion, it is evident that large-scale energy storage facilities all share one key issue: the availability of suitable locations. However, UPHES and CAES utilising vessels are still only concepts and thus unproven, while CAES using underground reservoirs is often considered a mature technology, but there are currently two facilities operating worldwide. In comparison, there is over 90 GW of PHES at over 240 facilities currently in operation, as well as 7 GW of additional plants planned in Europe alone over the next eight years [103]. Therefore, based on the scale, maturity, and future outlook, it was concluded that PHES is most likely large-scale energy storage technology feasible for the integration of wind energy on Irish energy system. Consequently, the literature was reviewed again to identify the potential for suitable PHES sites and the benefits of additional PHES on an energy system, as discussed in chapter 6.

6. Pumped Hydroelectric Energy Storage

This chapter gives a more detailed over of the PHES technology including its operation, applications, costs, disadvantages, current development, and future prospects. Subsequently, a summary of the existing literature in relation to the location of suitable PHES sites and the integration of wind energy using PHES is provided.

6.1. Overview of Technology

PHES consists of two large reservoirs located at different elevations and a number of pump/turbine units, as displayed in Figure 6-1. Typically during off-peak electrical demand, water is pumped from the lower reservoir to the higher reservoir where it is stored until it is needed. Once required, usually during peak electrical production, the water in the upper reservoir is released through the turbines which are connected to generators that thus produce electricity. Therefore, during production a PHES facility operates similarly to a conventional hydroelectric system.

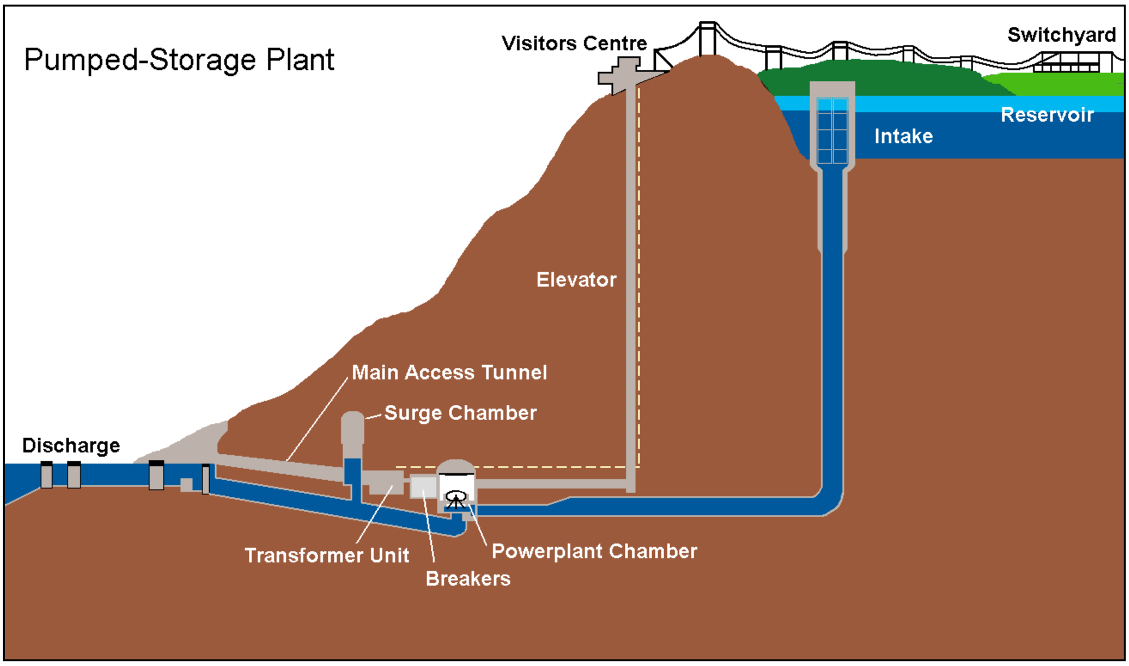


Figure 6-1: Layout of a pumped hydroelectric energy storage facility [104].

The round-trip efficiency of modern pumped storage facilities is in the region of 70% - 85%. The efficiency is typically limited by the efficiency of the pump/turbine unit used in the facilities [95], which is currently being improved through the use of variable speed machines. Until recently, PHES units have always used fresh water as the storage medium. However, in 1999 the 30 MW PHES facility displayed in Figure 6-2 was constructed using seawater as the storage medium [92]: corrosion was prevented by using paint and cathodic protection. A typical PHES facility has 300 m of hydraulic head (the vertical distance between the upper and lower reservoir). The power capacity (kW) is a function of the flow rate and the hydraulic head, whilst the energy stored (kWh) is a function of the reservoir volume and hydraulic head. To calculate the mass power output of a PHES facility, the following relationship can be used [93]:

$$P_{Capacity} = \rho g Q H \eta \tag{1}$$

Where $P_{Capacity}$ is the power capacity in watts, ρ is the mass density of water in kg/m^3, g is acceleration due to gravity in m/s^2, Q is discharge through the turbines in m^3/s, H is the effective head in m, and η is the pumping or turbine efficiency. To evaluate the storage capacity of the PHES the following must be used [105]:

$$C_{Storage} = \frac{\rho g H V \eta_{Turbine}}{3.6x10^3} \tag{2}$$

Where $C_{Storage}$ is storage capacity in watt-hours, V is volume of water that can be drained from the reservoir in m^3, and $\eta_{Turbine}$ is the efficiency of the turbine. It is evident that the power and storage capacities are respectively dependent on the head and the volume of the PHES. It is typically cheaper to construct a facility with a large hydraulic head and small reservoirs, than to construct a facility of equal capacity with a small hydraulic head and large reservoirs, because less material needs to be removed to create the reservoirs required, smaller piping is necessary, and the pump/turbine is physically smaller. Hence, facilities are usually designed with the greatest hydraulic head possible rather than the largest upper reservoir possible. Currently, there is over 90 GW in more than 240 PHES facilities around the world, which is roughly 3% of the world's global generating capacity. Each individual facility can store from 30 MW to 4000 MW and up to 15 GWh of electrical energy [95].

Figure 6-2: Photograph of a pumped hydroelectric storage facility using seawater [92].

As well as large storage capacities, PHES also has a fast reaction time which makes it ideal for the integration of fluctuating renewable energy. Facilities can have a reaction time as short as 10 minutes or less from complete shutdown (or from full reversal of operation) to full power [94]. In addition, if kept on standby, full power can even be reached within 10 to 30 seconds. Also, with the recent introduction of variable speed machines, PHES systems can now be used for frequency regulation in both pumping and generation modes (this has always been available in generating mode). This allows PHES units to absorb power in a more cost-effective manner that not only makes the facility more useful, but also improves the efficiency by approximately 3% [94]. PHES can also be used for peak generation and black starts due to its large power capacity and sufficient discharge time.

The cost of PHES ranges from $600/kW [95] to upwards of $2000/kW [94], depending on a number of factors such as size, location and connection to the power grid. In order to make a PHES facility economical viable, it is usually constructed on a large scale. Although the cost per kWh of storage is relatively economical in comparison to other techniques, this necessity for large-scale projects results in a very high initial construction cost, thus detracting investment in PHES e.g. Bath County storage facility in the United States which has a power capacity of 2,100 MW cost $1.7 billion in 1985. Due to the design requirements of a PHES facility, the ultimate drawback is its dependence on specific geological formations that is; two large reservoirs with a sufficient amount of hydraulic head between them must be located within close proximity to build a PHES system. However, as well as being rare these geological formations normally exist in remote locations such as mountains, where construction is difficult and the power grid is not present. Hence, there is a 300+% variation in costs associated with PHES facilities. In recent times, development has focused on the upgrading of old PHES facilities with new equipment such as variable speed devices, which can increase capacity by 15% to 20% and efficiency by approximately 3% without the high initial construction costs. However, over the next few years a resurgence of new PHES facilities is expected, with over 7 GW planned in Europe alone [103]. Consequently, before embarking on the research carried out in this study, a review of existing literature was carried out to identify how suitable sites were being located for PHES and if its ability to integrate fluctuating renewable energy had been documented.

6.2. Review of Existing Research

As mentioned earlier, PHES is a very mature and well-established technology which was introduced in the early 20th century [106]. As a result, there is very little research being published surrounding the development of the technology itself, with any studies focusing on technical improvements usually relating to site-specific problems such as those that have recently been reported for Chinese [107], Korean [108], and American [109] facilities. Furthermore, although a lack of suitable sites is usually perceived as the most significant barrier to the development of PHES [100-102], there is very little research carried out on this issue. Studies have been carried out to locate small run-of-the-river hydro projects [110-112] and large hydropower facilities [113-116], but these studies do not specify which sites would be suitable for PHES. The two studies which have investigated suitable sites for PHES were completed manually using maps, by Levine [117, 118] who analysed the state of Colorado in the USA and by Black [119], who searched for seawater PHES around the coast of Britain and Northern Ireland [119]. As a lack of suitable sites was such as key issue within PHES, it was concluded from the literature review that a tool should be developed which could identify suitable locations for the construction of PHES. Therefore, this was the first aim of this study, which is examined in chapter 7.

With very little research on the technical development and suitability of sites for PHES, current research is primarily focused on the dispatch of PHES, especially in relation to the utilisation of wind energy and its role on electricity markets. Hence, these are discussed in detail in the following sections.

6.2.1. PHES and Wind Energy

Numerous studies have been carried out in recent times analysing the potential wind penetration feasible by introducing a PHES facility, especially on island[5] electric-grids. In 2003 Bakos [98] analysed the benefits of introducing a PHES on Ikaria island in Greece using the computer simulation outlined in Figure 6-3.

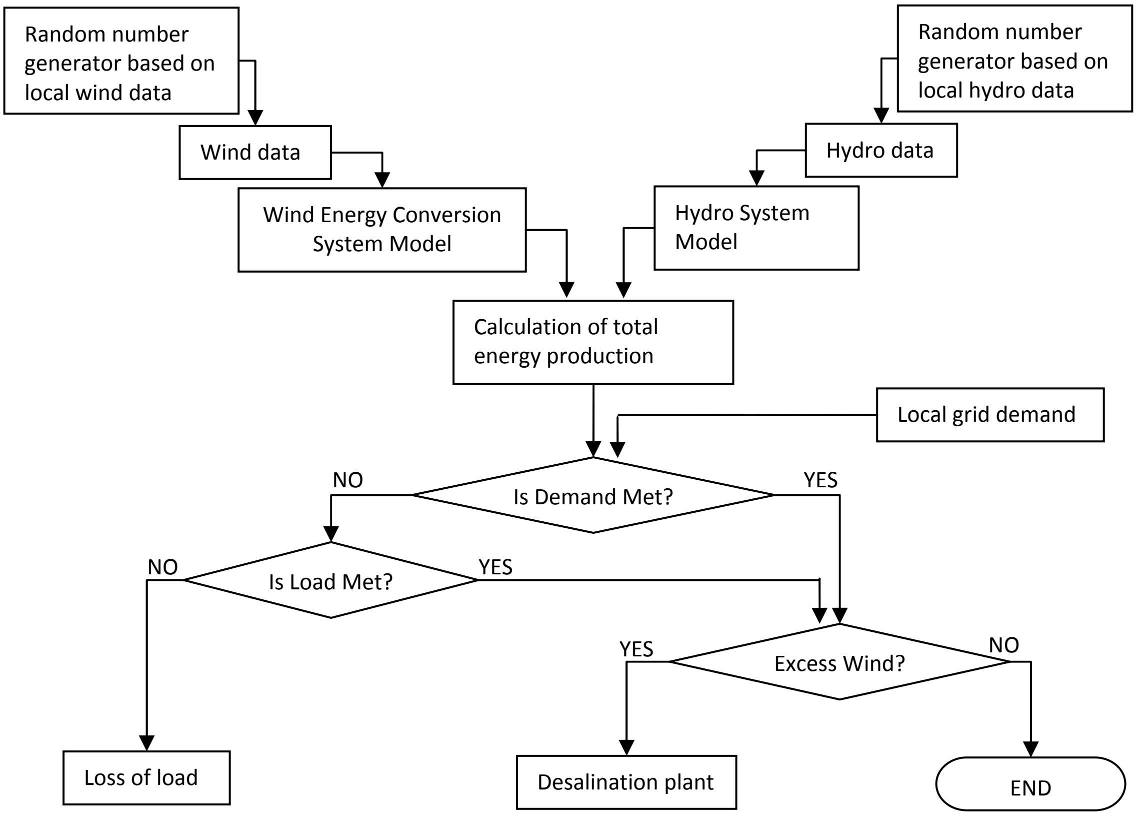


Figure 6-3: Flow chart of the computer simulation used by Bakos to analyse the potential of a PHES facility on Ikaria island in Greece [98].

This was followed by a variety of island studies that created simulations of wind-PHES hybrids [99, 120-137]. In general, the objectives of these simulations were quiet similar: to analyse a system without PHES, subsequently analyse a system with PHES and finally, identify if the benefits of the PHES were worthy of the costs associated with it. A number of intriguing conclusions were made during these studies. Bakos [98] concluded that electricity on Ikaria island could be generated cheaper using a wind-PHES system than using conventional generation. Theodoropoulos *et al.* [120] stated that the amortization period for a PHES facility on Ikaria island (Greece) is only four to five years. Castronuovo and Peças-Lopes [121] concluded that a small wind-PHES hybrid system in North Portugal would produce more

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[5] Island electricity systems refer to small-scale stand-alone energy systems where the installed generating capacity is usually between 1 and 100 MW.

revenue each year than the same system without the PHES facility, and they also investigated various tariffs to improve the profits from a wind-PHES system [122]. Anagnostopoulos and Papantonis [123, 124] defined the capacities for a PHES facility at which it became economically viable, and also identified a new pumping configuration for a PHES facility in a wind-PHES hybrid system. Bueno and Carta developed a very detailed wind-PHES model [125] which was used to study a wind-PHES system on the Spanish island of El Hierro [126]. This study simulated the wind-PHES under various operating strategies and concluded that the most economic one was, to define a maximum percentage of electricity allowed from wind energy and to supply the rest using PHES where possible. If the PHES could not be used, then supply was met using conventional generation. Bueno and Carta's wind-PHES model was later used to identify the most economical capacities for a PHES facility in the Gran Canaria [127]. Caralis and Zervos [128] identified the PHES capacities required to make wind-PHES facilities feasible on the Greek islands of Crete, Lesvos, and Serifos, stating that up to 72%, 79% and 83% of the energy for these islands respectively could come from the wind-PHES facilities proposed. Katsaprakakis *et al.* [129] analysed the effects of a PHES plant on all the various types of thermal generation within the energy system of two Greek islands: Crete and Rhodes. The authors concluded that for an island electrical system with an energy cost of approximately €0.15/kWh, a PHES will always be attractive, between €0.05/kWh and €0.15/kWh a PHES may be an attractive investment, and below €0.05/kWh a PHES system is not expected to improve the power system. Papathanassiou *et al.* [130] also developed a model of a wind-PHES system which was used to identify the optimum capacities [130], operation strategies [131], and economic viability [132] of various wind-PHES units, concluding that they are not an economical option unless specific tariffs are in place to support their operation. Segurado *et al.* [133] identified how PHES could be used in conjunction with water desalination to achieve a 30% wind penetration on the island of S. Vicente Island in Cape Verde. Kaldellis has been involved in a variety of island studies which analysed the feasibility of different wind-storage systems for various Aegean Archipelago Islands [99, 134-136]. The results indicated that sodium-sulphur batteries were the most economical storage device for islands with an annual electricity demand less than 90 MWh and peak demand less than 300 kW. However, for larger islands up to an annual demand of 200 GWh and peak of 50 MW, PHES was not only the most economical storage technology for integrating wind power, but it was a cheaper alternative to conventional fossil fuel based generation. In addition, Kaldellis *et al.* [137] also demonstrated how the size of the PHES used to integrate wind energy onto island energy systems can affect the amount of wind energy utilised and the operation of the system. In summary, this variety of island studies completed outlines the range of key issues which can be altered within a wind-PHES system such as size, operation, cost, and the mix on other technologies. Hence, it is unclear how the conclusions drawn during these island studies can be translated onto national[6] electricity systems.

Although PHES and wind energy has been assessed extensively on island electric grids, there has been much less research carried in relation to national electric grids. Benitez *et al.* [138] analysed the impacts of additional wind capacity on the Alberta electricity network in Canada, concluding that when PHES is added in conjunction with wind power, it can provide most of the peak load requirements of the system and thus, peak-load gas generators are no longer required. Dursun and Alboyaci [139] carried out a detailed review of previous wind-PHES studies and outlined how this solution could be incorporated in the Turkish energy system, by utilising the mountainous areas around the Black Sea and the electrical infrastructure to other hydro facilities. Black and Strbac [140, 141] examined the benefits of PHES on the British energy system with a wind penetration of 20%, which equates to an installed wind capacity of 26 GW. After paying particular attention to reserve requirements and systems costs, the authors concluded that the value of PHES is very dependent on the flexibility of the conventional generation also on the system. The results also indicated that energy storage could reduce system costs, wind curtailment, and the amount of energy required for conventional generation. Krajačić *et al.* [142] analysed how Portugal could achieve a 100% renewable electricity system where wind and PHES played a key role. On a system with a maximum peak demand of 8777 MW, the authors indicated that approximately 6000 MW and 4500 GWh of storage is required, hence outlining the scale of storage necessary for integrating large-scale wind penetrations. As outlined in section 4.4.5, two previous studies [90, 91] also assessed the implications of PHES for increased wind penetrations on the All-Ireland electricity grid, with both concluding that the additional investment required for PHES exceeded the corresponding reduction in operating costs of the system.

In summary, the majority of island studies conclude that PHES reduces operating costs and increases the wind penetrations feasible. However, studies completed on national electric grids are more ambiguous and hence, it is difficult to assess if the results from the island studies are relevant to national energy systems. Therefore, this research will contribute to this debate by quantifying the maximum wind penetrations feasible on the Irish electric grid for

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[6] National electricity systems refer to large-scale interconnected energy systems where the installed generating capacity is usually above 1 GW.

various capacities of PHES, investigating the economic savings associated with this additional wind energy, and comparing PHES to alternative technologies, while not only considering the electricity sector, but the heat and transport sectors also. The details and results from these analyses are outlined in chapter 8.

6.2.2. PHES and Electricity Markets

The dispatch of energy storage on deregulated electricity markets is another significant area of research in recent years. As a merchant unit, an energy storage facility will earn most of its revenue from the sale of electricity to the market [91, 143]. However, there is many ways that an energy storage facility can make a profit on these markets and hence, it is still unclear how they should be operated especially with increasing amounts of wind energy. Furusawa *et al.* analysed energy storage as a demand side management tool utilising electricity prices for domestic scale consumers [144]. Sioshansi *et al.* investigated the arbitrage value of small-scale energy storage for the PJM market in the USA [145], while Walawalkar and Mancini analysed the potential of sodium-sulphur batteries and flywheel energy storage systems in New York state's electricity market [146]. Kazempour *et al.* [147] completed an economic comparison between emerging (sodium-sulphur battery) and traditional (PHES) electric energy storage technologies assuming perfect pricing foresight one week in advance. Kazempour *et al.* created a scheduling tool for a group of hydro plants supplemented by a PHES facility [148], while Figueiredo and Flynn [105] optimised the size of two specific PHES plants in Alberta, Canada based on electricity arbitrage profits. Kanakasabapathy *et al.* [149, 150] created a bidding strategy for PHES based on day-ahead market prices, but assumed that pumping always takes place before generation, which may not be suitable for all electricity markets. Bathurst and Strbac [151] simulated the dispatch of an energy storage facility on day-ahead markets in conjunction with a wind farm, concluding that there is an optimal capacity of energy storage for maximising profits from a wind farm on energy markets. For the 10 MW wind farm considered by the authors, a 6 MW 36 MWh storage captured almost all of the additional revenue feasible from the addition an energy storage facility. Zhao and Davison [152] examined the dispatch of PHES facilities with water inflows on electricity markets, concluding that the dispatch of facilities with small inflows is very dependent on the daily variation in electricity prices, but for facilities with large inflows the dispatch is more dependent on water management and maximising the power generated by the facility.

In summary, there have been numerous studies that analysed the dispatch of PHES under very specific circumstances which do not reflect the procedures followed by PHES on some deregulated markets, including the Irish market. This includes a group of plants together [148], pumping always ahead of generation [149, 150], dispatch in conjunction with a single wind farm [151], and PHES plants with inflows [152]. Consequently, the final part of this research analyses a range of realistic operation strategies for a PHES on a deregulated electricity market like Ireland's, which is documented in chapter 9.

6.3. Conclusions

PHES is clearly a well-established, mature, and effective energy storage technology. As a result, there is very little research currently being published which focuses on the technology itself, but instead recent studies are typically related to the utilisation of wind energy in conjunction with PHES and the dispatch of PHES on deregulated electricity markets. The findings from this literature review are in agreement with those outlined by Wilson *et al.* [153], who identified a number of key issues that needed to be addressed for the development of electricity energy storage including the size, location, and market structure required for them. Hence, this study will add to the existing PHES literature by:

1. Developing a tool which will locate suitable locations for the construction new freshwater PHES facilities and applying it to Ireland (chapter 7).
2. Identifying the additional wind energy feasible on the Irish energy system due to the addition of different PHES capacities (section 8.3).
3. Assessing the economic implications of additional wind and PHES on the Irish energy system (section 8.4).
4. Comparing PHES to alternative technologies which could also reduce the costs of operating the Irish energy system (section 8.4.4).
5. Creating new dispatch strategies for PHES on the Irish deregulated electricity market, which will maximise its profits when utilising electricity arbitrage (chapter 9).

The results from these investigations will not only illustrate the feasibility, implications, and potential operation of PHES on existing energy systems, but they will also establish how PHES compares to completely different alternatives, which is often overlooked in existing research.

Chapter 7

7. The Potential for Additional PHES in Ireland

As outlined in section 6.2, it is widely believed that suitable locations to construct PHES facilities are limited and hence it is one of the most crucial factors when evaluating its feasibility. Consequently, to quantify the potential PHES resource in Ireland, the number of suitable locations remaining had to be identified. Therefore, this chapter doesn't focus on the benefits of PHES, but instead the focus is on whether or not PHES is still technically a feasible option. Existing research carried out to identify suitable locations has usually been done manually with aid of maps and therefore, it has been limited to specific areas [117, 118] or seawater facilities [89, 119, 154]. Although seawater PHES was successfully demonstrated when the first facility was built in 1999 [92], its capacity was only 30 MW compared to the 480 MW [154] and 100+ GWh [89] seawater sites that are currently being proposed for Ireland. As a result, there are still concerns surrounding the effects of these seawater facilities in relation to the technology itself and the surrounding landscape. In comparison, freshwater PHES has been in use for over 100 years and is thus a proven and well-established technology. Therefore, this study tried to establish the freshwater PHES resource in Ireland and to do so, a program was created that can scan a user-specified terrain and identify if there are technically suitable locations for the construction of freshwater facilities. The discussion below is an overview of the work reported in Appendix B and Appendix C.

7.1. Methodology

After assessing a range of geographic information system (GIS) tools for the development of the program, Atlas Computers' Survey Control Centre (SCC) was chosen [155]. The SCC is a unique land survey and modelling package which has been in development for 18 years. The inclusion of very advanced tools, such as dynamic cut to fill balancing, meant it was ideally suited for manipulating terrain and identifying if a suitable PHES sites existed. Therefore, in this study an add-on module was developed which utilised the functionality of the SCC, but searched for PHES facilities specifically.

To begin, suitable terrain data was required. After an initial search, 'Digital Terrain Model' (DTM) data files were sourced from Ordinance Survey Ireland (OSI) [156], that provide a regular grid of x, y, and z points, at 10 m intervals for any area in Ireland. This data can be imported into the SCC software and processed to form a Delaunay Triangulated Irregular Network model (TIN). A TIN model displays the x, y, and z data as a 3D terrain that can then be analysed using different constraints (TIN modelling and its applications are discussed further in

Hjelle [157]). The add-on PHES module for the SCC utilised the TIN model to find adjacent polygonal areas of acceptable flatness, A_U and A_L, with a minimum acceptable vertical separation, H, and a maximum acceptable horizontal separation, d, as portrayed in Figure 7-1. The program created could only identify regular shaped polygons as the areas for the reservoirs, and hence a circle was chosen.

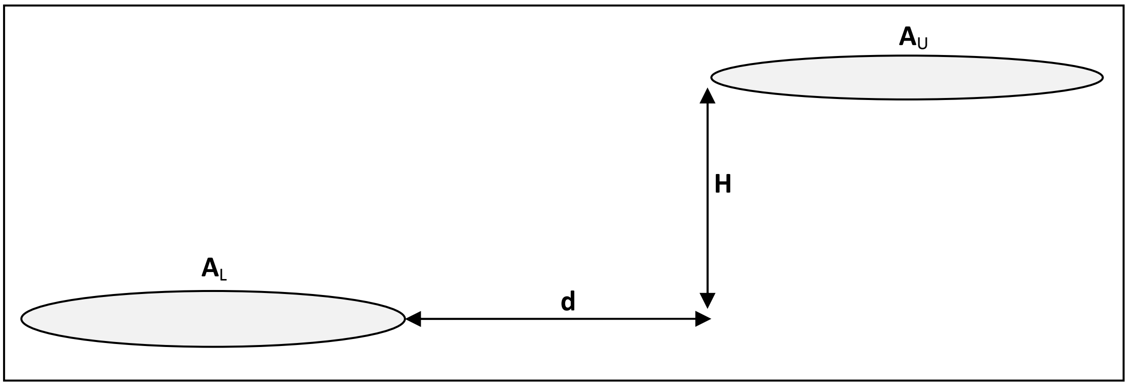


Figure 7-1: Area and parameters utilised by the SCC computer program to search for PHES.

The upper and lower reservoir areas identified by the program had to be flat. Flatness in this case is specified in terms of the maximum allowable 'cut' and 'fill' excavation volumes, E_U and E_L, which are required to construct a polygon at an arbitrary datum, where the software selects an optimal value for that datum. In other words, the level of flatness required was specified by quantifying the maximum amount of earth that could be moved in order to make the site flat, E, as displayed in Figure 7-2. The earth that needs to be moved to make the area flat must be obtained within the investigated site i.e. the circular area. There was an E value for the upper reservoir, E_U, and an E value for the lower reservoir, E_L.

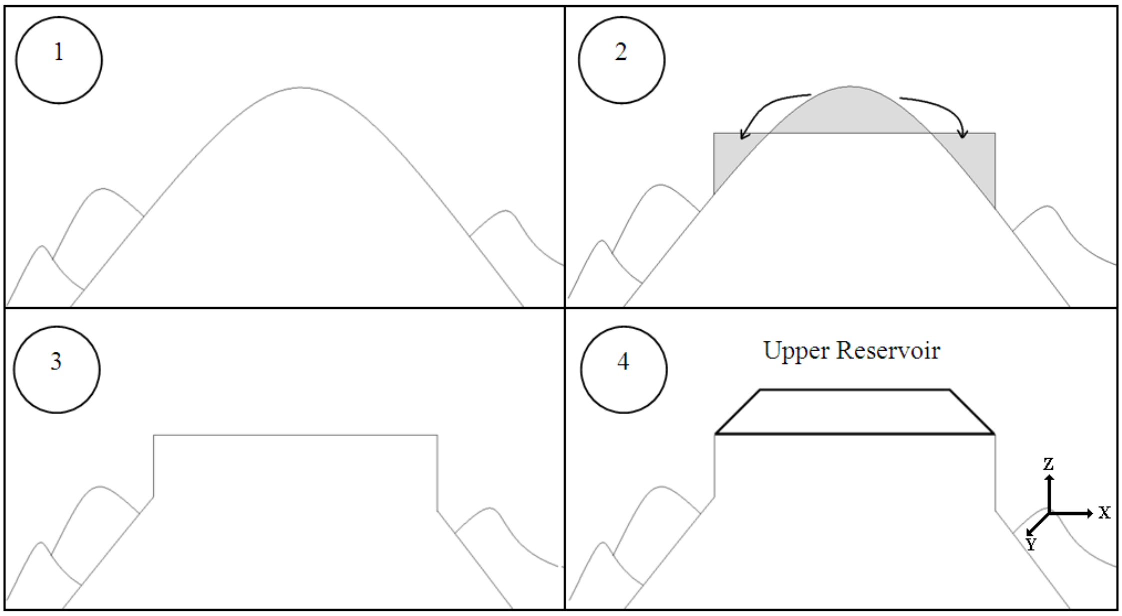


Figure 7-2: Earth moving procedure within the program to make the investigated area flat for PHES.

Initially, the search was iterated at a specified plan interval, *FR*, in the x and y axes over the entire area being analysed for potential lower reservoir sites. On finding such a site, the border of that site was searched radially for upper reservoir sites over a specified interval, *SR*. Determining 'flatness' required modelling the polygon representing the reservoir area, and vertically searching over a specified interval, *SV*, for an optimal datum where the volumes of cut and fill material to be excavated to construct the reservoir were the same. Thus the parameters required for each search are displayed in Table 7-1 below.

Table 7-1: Parameters used by the SCC software to identify potential PHES facilities.

Name	Symbol	Unit
Polygon area for upper reservoir	A_U	m^2
Polygon area for lower reservoir	A_L	m^2
Minimum acceptable vertical separation	H	m
Maximum acceptable horizontal separation	d	m
Flatness / maximum excavation volume for upper reservoir	E_U	m^3
Flatness / maximum excavation volume for lower reservoir	E_L	m^3
Grid search interval for lower reservoir	FR	m
Radial search interval for upper reservoir	SR	m
Vertical search tolerance for 'flatness'	SV	m

To verify the PHES algorithm above worked as designed, a series of test cases were created that comprised of artificially generated terrain data similar to that displayed in Figure 7-3. Boundary value analysis [158] was employed to produce a suitable set of test cases. These test terrains were generated containing locations where all search criteria were met, to ensure the search worked as anticipated. Subsequently, additional test cases where all but one of the search criteria were met, were also created in order to ensure that the algorithm did not produce any false positives. Multiple versions of each test case were generated at either side of the boundaries of each parameter under test, to verify the search tolerances were working correctly.

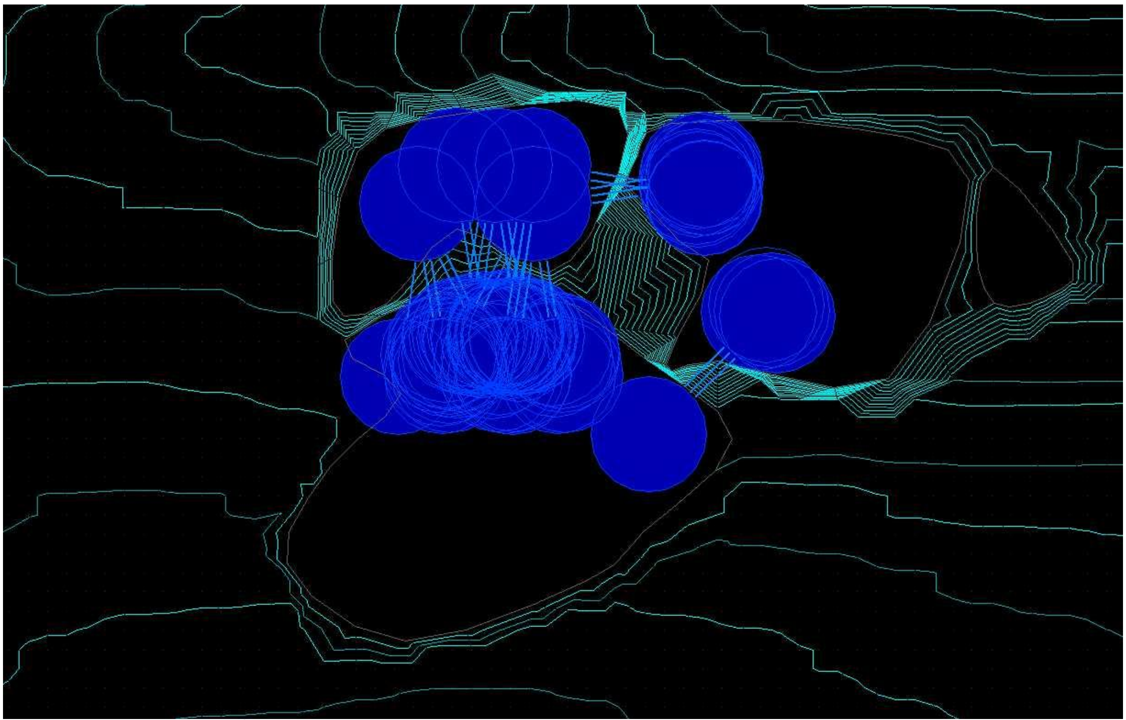
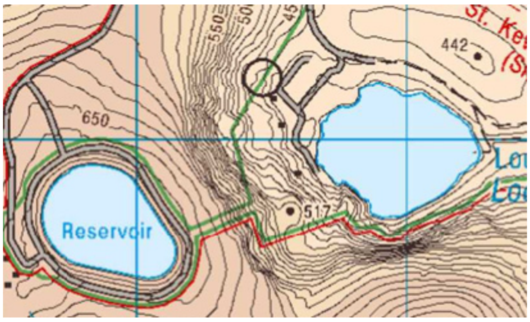
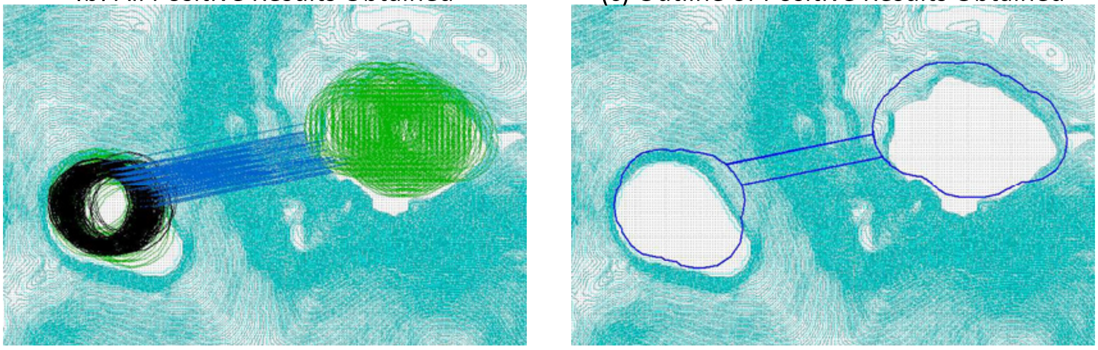


Figure 7-3: A 1 km^2 artificially created terrain for testing the PHES module in the SCC software.

Once testing was completed using artificial data, the software was then tested on an existing PHES site, Turlough Hill, which is the only freshwater PHES in Ireland (see Figure 7-4a). As displayed in Figure 7-4b, the program identified numerous positive results at this site indicating that the program was functioning correctly. In addition, the results could be combined with one another, which is displayed in Figure 7-4c, to create an accurate representation of the maximum potential reservoir that could be constructed at that site. Based on the results obtained during this testing phase, it was concluded that the program was operating correctly.


(a) Existing PHES Site (Turlough Hill, Ireland)


(b) All Positive Results Obtained

(c) Outline of Positive Results Obtained

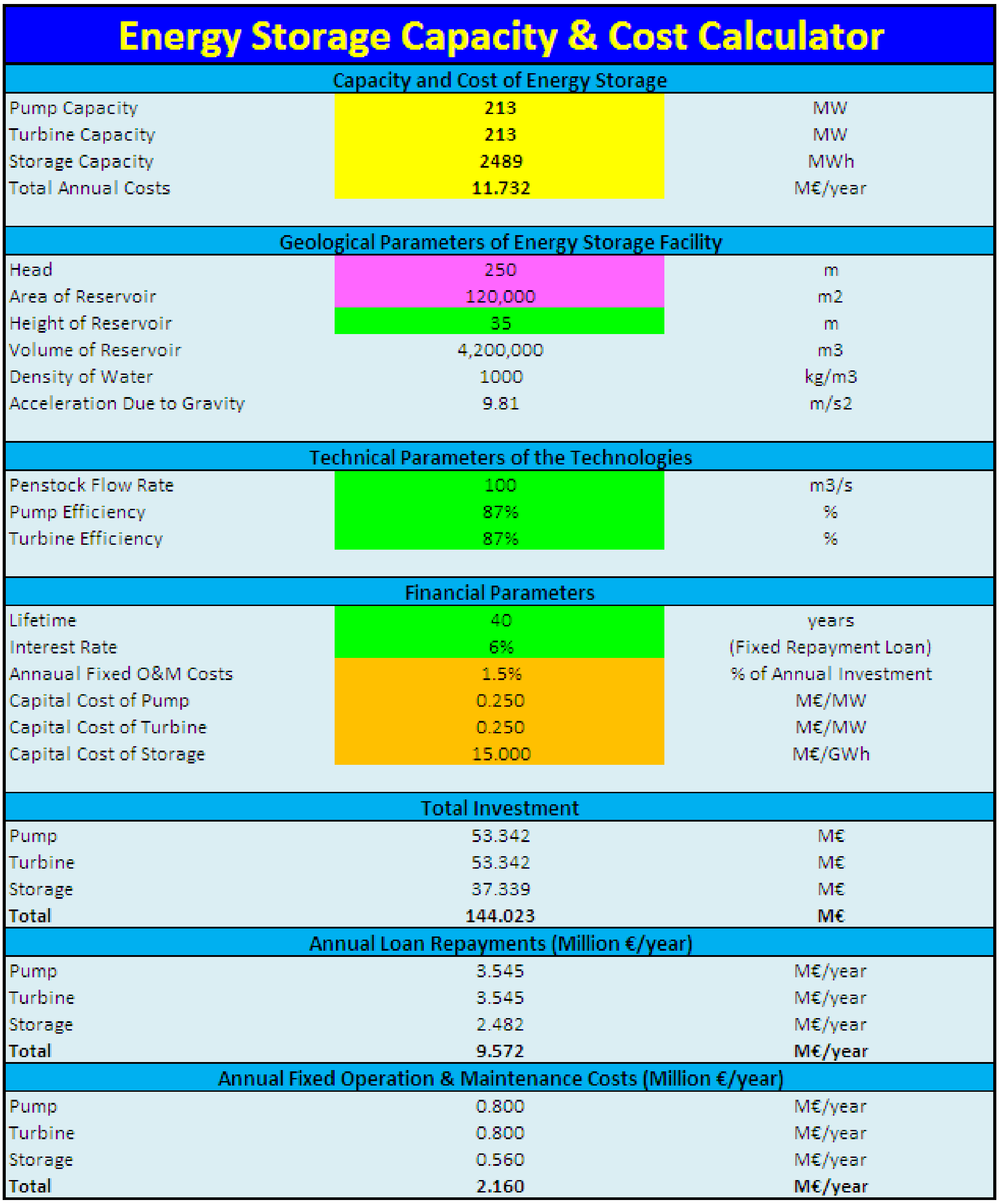
Figure 7-4: Results obtained (b, c) when the new program was tested on an existing PHES facility: Turlough Hill in Ireland (a).

7.2. Capacity and Cost Calculator

The SCC software is specifically designed to identify locations which have a user-specified terrain and hence, a separate program was designed to convert these results into PHES capacities and costs, which is displayed in Figure 7-5. The underlying equations used in the calculator for the power and storage capacities are Equations 1 and 2, which have been discussed in section 6.1. Six different variables are required to calculate the power and storage capacities using these equations. However, the program assumes that reservoirs can be constructed at a site because it can be made flat. To do so, a reservoir wall must be constructed similar to that displayed in Figure 7-6. Therefore, the reservoir volume, V, must be calculated using the reservoir area, A_L or A_U, and the assumed reservoir wall height, R_H from:

$$V = AR_H \tag{3}$$

Consequently, there are now seven variables necessary to convert the results from the SCC software into PHES capacities, which are displayed in Table 7-2. Two of these, A and H, are outputs from the SCC software, while two others, g and ρ, are constants. Therefore, assumptions had to be developed for the volumetric flow rate, Q, the height of the reservoir wall, R_H, and the round-trip efficiency of the PHES, η_{PHES}.



Energy Storage Capacity & Cost Calculator

Capacity and Cost of Energy Storage

Pump Capacity	213	MW
Turbine Capacity	213	MW
Storage Capacity	2489	MWh
Total Annual Costs	11.732	M€/year

Geological Parameters of Energy Storage Facility

Head	250	m
Area of Reservoir	120,000	m2
Height of Reservoir	35	m
Volume of Reservoir	4,200,000	m3
Density of Water	1000	kg/m3
Acceleration Due to Gravity	9.81	m/s2

Technical Parameters of the Technologies

Penstock Flow Rate	100	m3/s
Pump Efficiency	87%	%
Turbine Efficiency	87%	%

Financial Parameters

Lifetime	40	years
Interest Rate	6%	(Fixed Repayment Loan)
Annaual Fixed O&M Costs	1.5%	% of Annual Investment
Capital Cost of Pump	0.250	M€/MW
Capital Cost of Turbine	0.250	M€/MW
Capital Cost of Storage	15.000	M€/GWh

Total Investment

Pump	53.342	M€
Turbine	53.342	M€
Storage	37.339	M€
Total	**144.023**	**M€**

Annual Loan Repayments (Million €/year)

Pump	3.545	M€/year
Turbine	3.545	M€/year
Storage	2.482	M€/year
Total	**9.572**	**M€/year**

Annual Fixed Operation & Maintenance Costs (Million €/year)

Pump	0.800	M€/year
Turbine	0.800	M€/year
Storage	0.560	M€/year
Total	**2.160**	**M€/year**

Figure 7-5: User-interface of the Energy Capacity and Cost Calculator.

Figure 7-6: PHES upper reservoir (of Taum Sauk PHES in the USA) with a man-made reservoir wall [159].

Table 7-2: Variables used for converting the program parameters into energy capacities.

Variable	Symbol	Value	Unit
Reservoir area	A	-	m^2
Head	H	-	m
Volumetric flow rate through pump/turbine unit	Q	-	m^3/s
Reservoir-wall height	R_H	-	m
Volume of water that can be utilised	V	-	m^3
Acceleration due to gravity	g	9.81	m/s^2
Density of water	ρ	1000	kg/m^3
Round-trip efficiency of PHES	η_{PHES}	-	-

To establish realistic assumptions, the parameters at existing PHES facilities were investigated [160]. The flow rate is dependent on the size of the turbine and penstock with typical values ranging from 50 m^3/s to 150 m^3/s. In relation to reservoir height, existing man-made reservoirs have been constructed in excess of 20 m. For example, Coo-Trois-Ponts PHES in Belgium has a reservoir wall that is 47 m high, Revin PHES in France has a reservoir that is 20 m high, and Turlough Hill PHES in Ireland has a reservoir that reaches heights up to 30 m. Also, pump and turbine efficiencies are not only dependent on the technology used, but also on the way the PHES facility is operated i.e. as a grid asset or as a merchant unit [91]. Due to the broad range of parameters that could be correctly assumed when calculating potential capacities at suitable locations, a range of parameters were included in the calculator, which are outlined in Table 7-3. These are pre-defined values which can be selected from the green cells displayed in

Figure 7-5. This enables the user to evaluate the sensitivity of a site based on typical parameters found at existing PHES facilities. Note that the parameters are not related to one another in any way. A minimum value for the penstock flow rate could be combined with a maximum height for the reservoir. Therefore, the user can specify the value for each parameter individually. Once a user has inputted the results from the PHES search and selected values from the pre-defined parameters, the power and storage capacity of that site are displayed in the yellow boxes of the calculator, which are again illustrated in Figure 7-5.

Table 7-3: Predefined parameters included in the PHES calculator (see green cells in Figure 7-5).

Parameter	Minimum	Medium	Maximum
Height of Reservoir (m)	20	35	50
Penstock Flow Rate (m^3/s)	50	100	150
Pump Efficiency (%)	82	87	92
Turbine Efficiency (%)	82	87	92
Lifetime (years)	30	40	50
Real Interest Rate (%)	3	6	9

The orange inputs in Figure 7-5 are used for evaluating the costs of a PHES facility. These are fully editable as costs can vary substantially with each site and also over time. However, as outlined in Table 7-3 predefined values have been included for the lifetime, n, and the interest rate, i, within the calculator. The annual repayment costs, I_{Annual}, are calculated based on the unit investment cost (I) and capacity (C) for the pump (P), turbine (T), and storage (S), as well as the fixed operation and maintenance costs, $O\&M_{Fixed}$, according to Equation 4 below.

$$I_{Annual} = \left(I_{Pump}C_{Pump} + I_{Turbine}C_{Turbine} + I_{Storage}C_{Storage}\right)\left\{\left[\frac{i}{1-(1+i)^{-n}}\right] + O\&M_{Fixed}\right\} \quad (4)$$

Finally, none of the blue inputs in the calculator can be edited to ensure the validity of the results produced by the software. However, it is important that a user understands the accuracy of their inputs when using the calculator. A disclaimer and a full list of instructions is provided in the calculator software, which can be downloaded from [161].

7.3. Results and Discussion

Firstly, an initial analysis (which is discussed in detail in Appendix B) was carried out on a 20 km x 40 km area in Ireland which is illustrated in Figure 7-7. The region analysed was limited due to the costs associated with purchasing the required data files and the cost of computer processing time for completing the analysis. Three different searches were completed over this area using the parameters illustrated in Table 7-4.

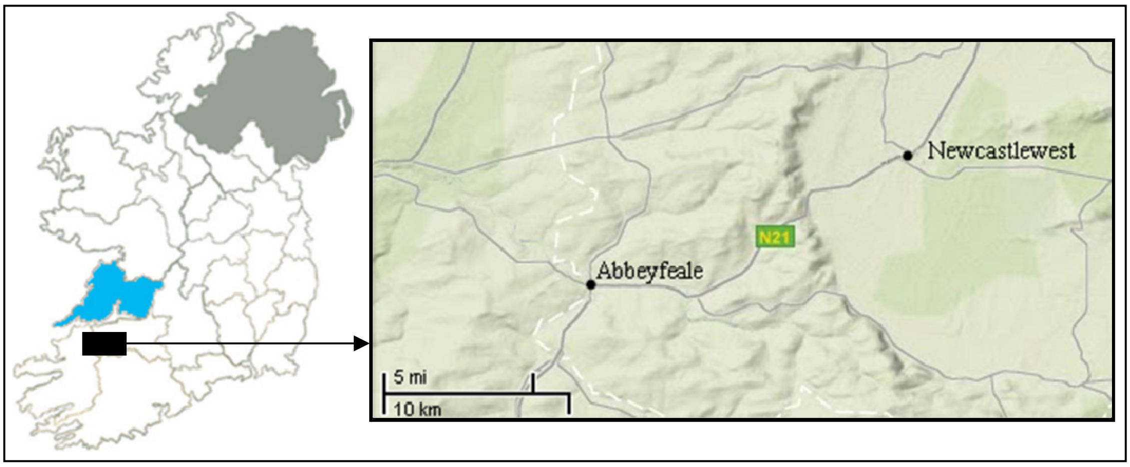


Figure 7-7: Black area was searched for the initial analysis completed with the software and County Clare is highlighted in blue, which was also searched afterwards.

Table 7-4: Parameters used for the three different searches carried out during the initial analysis.

Parameter	First Search	Second Search	Third Search	Unit
A_U	120,000	180,000	70,000	m^2
A_L	120,000	120,000	70,000	m^2
H	200	150	200	m
d	1000	1000	1000	m
E_U	300,000	400,000	200,000	m^3
E_L	300,000	300,000	200,000	m^3
FR	50	50	40	m
SR	10	10	10	m
SV	0.5	0.5	0.5	m

Using these parameters, five potential PHES sites were identified, which are illustrated in Figure 7-8. For the purposes of this initial investigation, the capacity of all sites were calculated using the same efficiency, flow rate, and reservoir wall height that exists at Ireland's only PHES facility, Turlough Hill. The average annual round-trip efficiency of Turlough Hill in 2007 was 63.9% [162], so a pump efficiency of 80% and a turbine efficiency of 80% were assumed. The flow rate at Turlough Hill is 113 m^3/s and the upper reservoir was constructed at a maximum height of 30 m [163]. Based on these assumptions, it was calculated that the five sites identified in this initial search had a combined capacity of approximately 700 MW and 9 GWh. One specific site, which is highlighted in green in Figure 7-8, had a capacity of approximately 180 MW and 1.5 GWh. Considering the capacity of Turlough Hill is 292 MW and 1.7 GWh, the scale of the sites identified are significant for the Irish electric grid. In addition, it is worth noting that the area analysed here was only 800 km^2, which is approximately 1% of the total island of Ireland [164, 165].

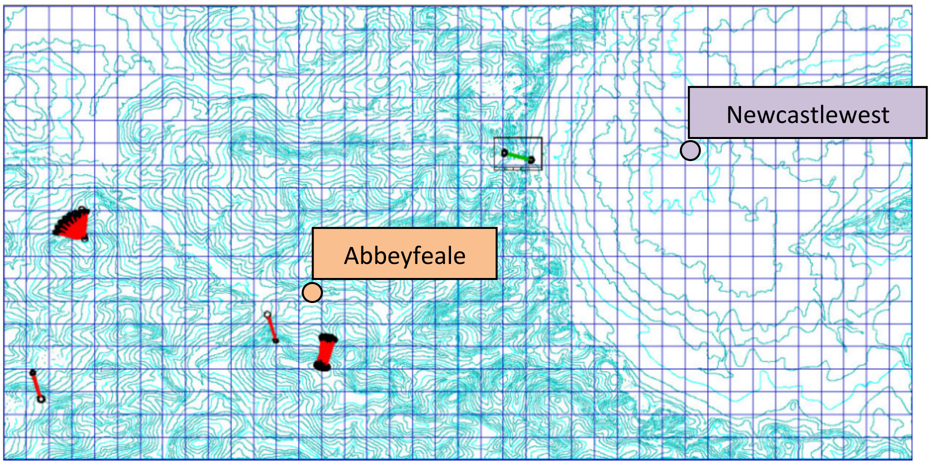


Figure 7-8: Potential PHES sites identified after the initial analysis using the parameters displayed in Table 7-4. The green site was found in the first search and the red sites in the second search.

In summary, the primary goal of this initial analysis was to identify the frequency and scale of freshwater PHES sites in Ireland. After locating five potential sites of such significant scale within only 1% of the island of Ireland, the initial analysis indicated that large-scale freshwater PHES is technically feasible in Ireland.

Based on the positive results in the initial analysis, funding was secured to carry out a more elaborate search of County Clare in Ireland, which is discussed in detail in Appendix C. County Clare has a total area of approximately 3150 km^2 and is highlighted in Figure 7-7. The search was carried out in line with the "Strategic Wind Farm Development Areas" contained in the Clare Wind Energy Strategy [166], so the county was divided into the following sections and given this preference (see Figure 7-9):

1. Strategic Areas (Blue).
2. Acceptable in Principle (Green).
3. Open to Consideration (White).

Although areas defined as "Not Normally Permissible (Red)" were included in the search, results within this area were deemed unacceptable.

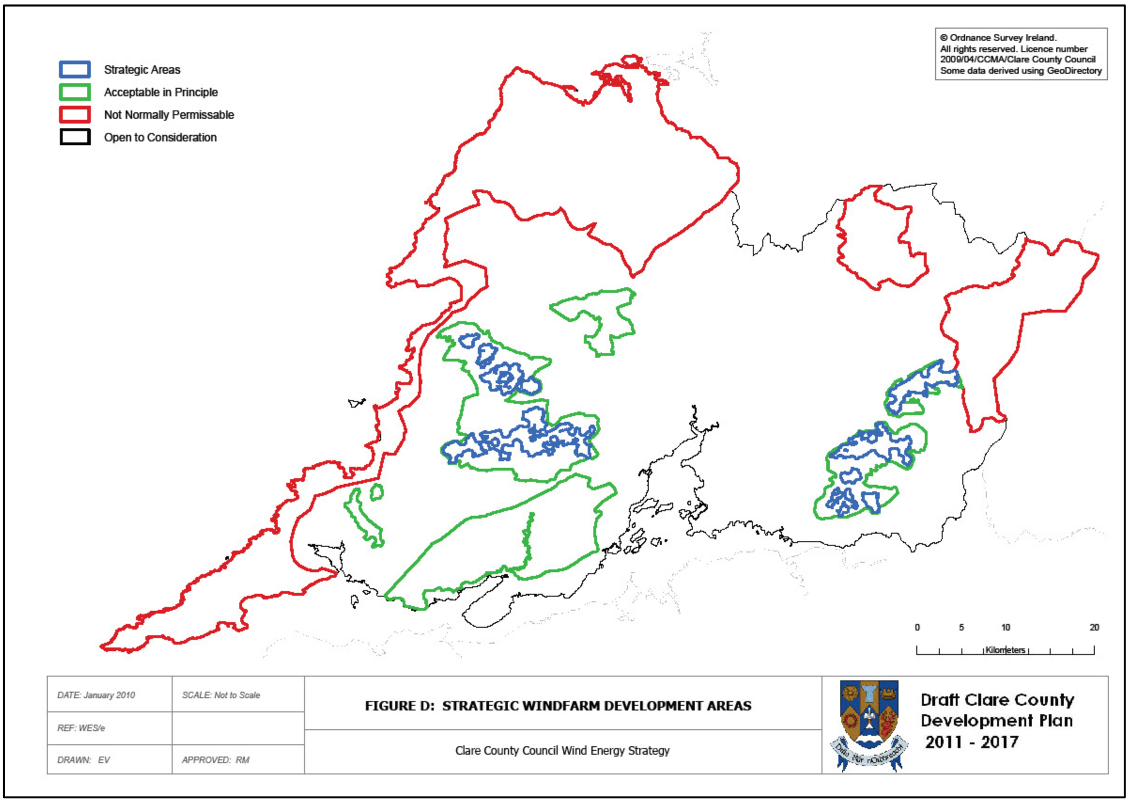


Figure 7-9: Division of County Clare for the PHES search.

A detailed list of the search criteria used by the software to search County Clare for PHES sites is provided in Table 7-5. To locate potential reservoir sites that were shaped liked irregular polygons, initial searching was carried out using circles of 100 m in radius, and where multiple adjacent sites were found these were combined. After being combined, if the multiple adjacent sites did not meet the area criteria specified in Table 7-5, then they were discarded.

Table 7-5: Search criteria specified to identify potential locations for PHES in County Clare.

Parameter	Symbol	Value	Unit
Area (minimum) of upper reservoir	A_U	120,000	m^2
Area (minimum) of lower reservoir	A_L	120,000	m^2
Height (minimum) between reservoirs	H	200	m
Distance (horizontal) between reservoirs	d	3000	m
Flatness at upper reservoir (maximum earth to be moved to make a flat base)	E_U	500,000	m^3
Flatness at lower reservoir (maximum earth to be moved to make a flat base)	E_L	500,000	m^3
Vertical search tolerance for "flatness"	SV	0.5	m
Radial search interval for upper reservoir	SR	3	m
Grid search interval for lower reservoir	FR	50	m

Based on the technical criteria defined, 14 separate locations were identified that had suitable parameters for the construction of PHES in County Clare. However, due to the area restrictions, only 8 of these locations were classified as acceptable, which are outlined in Figure 7-10. It should be noted that a range of different upper and lower reservoir combinations could be chosen at each location identified. Therefore, although 8 locations have been identified in this search, there are a much greater number of individual PHES facilities that could be constructed.

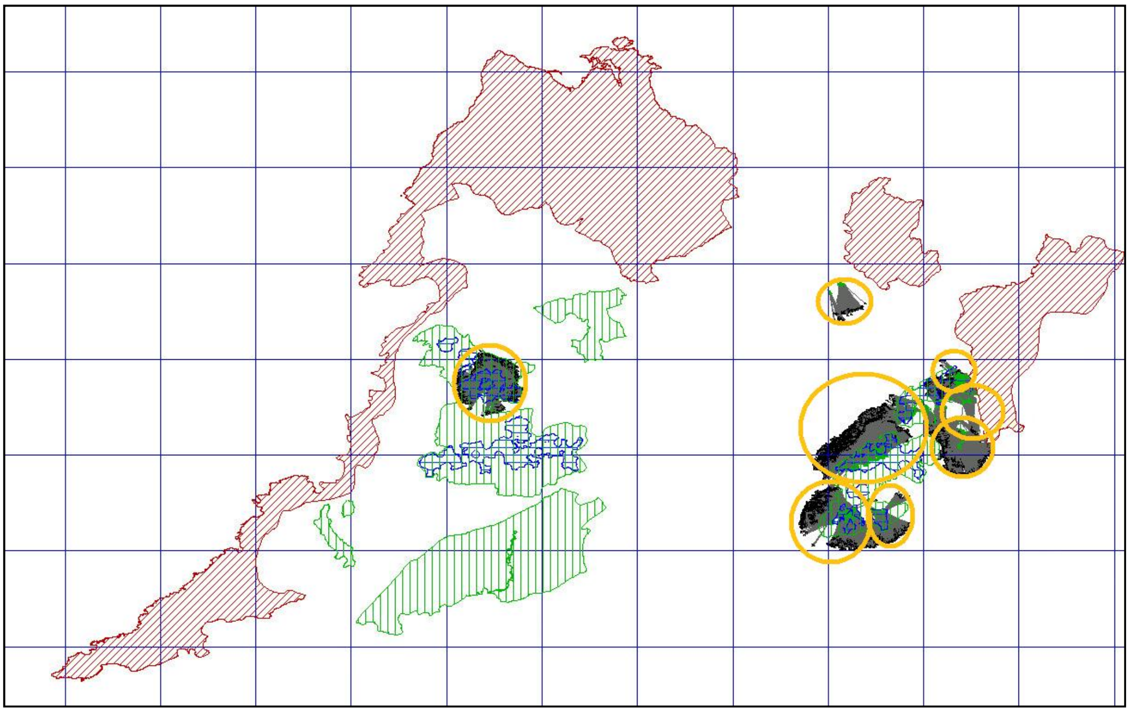


Figure 7-10: Potential freshwater PHES sites found within acceptable areas of County Clare.

To examine the type of sites which are available in County Clare, the initial sites were limited to those with a head greater than 250 m. As outlined in Figure 7-11, this reduced the number of potential locations to 5. Then, three unique sites were chosen from the remaining five locations for further analysis. One site was chosen from Area 1 of Figure 7-11 as it was the only site which was entirely located in the area of strategic interest for wind farm development and hence it was called “TotalArea”. The site chosen in Area 2 had the largest reservoir area found and was called “BigReservoir”. Finally, the site in Area 3 had the largest vertical head identified and was named “BigHead”. Due to these unique characteristics, these three sites will illustrate the range of PHES capacities feasible in County Clare.

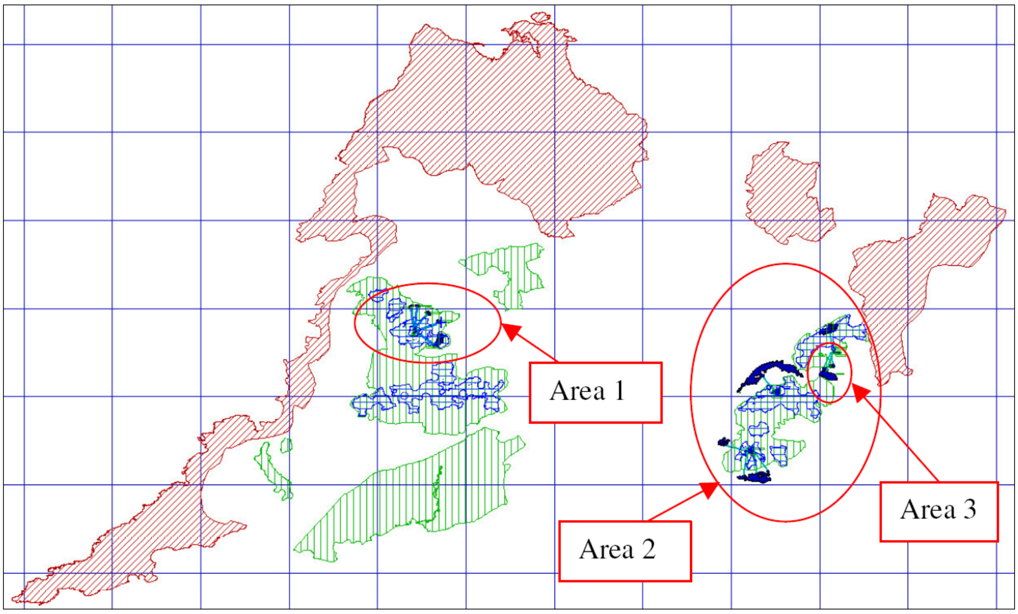


Figure 7-11: Potential PHES sites found within acceptable areas of County Clare with a head greater than 250 m.

The size and cost of these PHES facilities were assessed using the calculator in Figure 7-5. In addition, a detailed discussion and a sensitivity analysis are available in Appendix C for each of the three sites. In summary, the maximum capacity that could be constructed at each of these three sites is displayed in Table 7-6. Once again, compared to Ireland's current PHES capacity of 292 MW and 1.7 GWh, the PHES facilities feasible in County Clare are very big, especially in relation to their potential storage capacities. The largest power capacity feasible at a single site in County Clare was estimated at 570 MW, which is almost double the existing PHES capacity in Ireland, while the total power capacity at the three sites could be approximately 1300 MW.

Table 7-6: Capacities for a selection of PHES facilities found in County Clare based on the max technical parameters defined in Table 7-3*.

Capacity Results	TotalArea	BigReservoir	BigHead
Pump Capacity (MW)	405	340	570
Turbine Capacity (MW)	405	340	570
Storage Capacity (GWh)	15.4	22.5	12.7

***These are indicative values only based on existing PHES facilities. Hence, new facilities could vary.**

Similarly, the maximum storage capacity at one site was estimated at 22.5 GWh, which is over 13 times the existing storage capacity in Ireland. However, it is unlikely that a storage capacity this large would ever be profitable, so for the economic analysis a smaller storage capacity corresponding to a 12 hour discharge was assumed. As displayed in Table 7-7, the total annual investment costs for the three PHES facilities would be approximately €20-30M/year for a power capacity of approximately 300-600 MW and a storage capacity of 4-7 GWh respectively. This corresponds to a total investment over the lifetime of the facilities of approximately €230-

390 million. It is worth stressing once again that these cost calculations are based on typical construction costs and borrowing costs which have previously been reported [95, 167]. Therefore, they are indicative only and the actual costs could vary substantially depending on the site-specific construction costs and the financial parameters agreed for the construction of this facility.

Table 7-7: Cost of the selected PHES facilities found in County Clare based on a 6 hour discharge and the medium economic parameters defined in Table 7-3*.

Capacity Results	TotalArea	BigReservoir	BigHead
Pump Capacity (MW)	405	340	570
Turbine Capacity (MW)	405	340	570
Storage Capacity (GWh)	4.9	4.1	6.8
Cost Results	TotalArea	BigReservoir	BigHead
Total Annual Costs (€M/year)	23	19	32
Total Investment (€M)	276	230	387

***These are indicative values only based on existing PHES facilities. Hence, new facilities could vary.**

7.4. Conclusions

In total, five potential sites were located when an 800 km^2 area of Ireland of Ireland was searched during the first analysis with the program. Due to their cumulative estimated power capacity of approximately 700 MW and 8.6 GWh, it is evident that the program is capable of identifying potential freshwater PHES sites. In addition, the program is capable of identifying sites that may otherwise go unnoticed, as it can identify sites after the earth has been modified. To supplement the PHES search program, a spreadsheet calculator has also been created which can convert the PHES search results into estimated capacities and costs, based on predefined assumptions for a number of key variables.

Using both the PHES search program and the calculator, a detailed search and analysis of potential freshwater PHES sites in County Clare was carried out. Overall 14 locations were identified in County Clare where freshwater PHES facilities could be constructed, but only 8 of these were in acceptable areas of the county. After analysing three potential PHES facilities which could be constructed at these locations, it was estimated that one site alone in County Clare could have a power capacity up to 570 MW and a storage capacity up 22.5 GWh, at a total investment cost of approximately €230-390M. However, the specific capacities and costs determined are not the most significant results from this chapter. Instead it is the scale and frequency of technically feasible PHES sites which can be constructed in Ireland. In total, 19 separate locations have already been established after searching approximately 5% of the island of Ireland. Therefore, the most significant conclusion from this chapter is that Ireland has a significant freshwater PHES resource and the availability of technical suitable sites is no longer a limiting factor. This outcome is in agreement with a very recently published article, which assessed the feasibility of PHES in the United States [168]. Here, Yang and Jackson concluded that “the main limiting factors for PHES appear to be environmental concerns and financial uncertainties rather than the availability of technically feasible sites” [168]. As a result, the next stage in this research will try to examine the implications of additional PHES (chapter 8) and how PHES can be accommodated on deregulated electricity markets (chapter 9).

Chapter 8

8. The Implications of Additional PHES in Ireland

So far, this research concluded in chapter 5 that PHES is the most likely large-scale energy storage technology to be deployed for the integration of fluctuating renewable energy, while it is evident from chapter 7 that PHES is still technically a feasible option for Ireland. Therefore, the next objective in this research is to investigate the implications of adding PHES to the Irish energy system. Implications in this research refer to two key issues: technical and economical. From a technical perspective, the objective is to identify how much additional wind power can be added to the Irish energy system with the introduction of large-scale energy storage. From an economic perspective, the objective is to calculate if the fuel savings realised from the additional wind power feasible as a result of energy storage, will pay for the initial investment costs required to construct them. This chapter is a summary of the work completed in Appendices D, E, F, and G.

8.1. Methodology

A broad range of issues need to be considered when evaluating the implications of PHES on an energy system including the size, operation, output, and costs of the energy system and all of its components. Due to the complexity of the problem proposed, the range of technologies that need to be considered, and the methodologies proposed in other similar studies [88, 98, 99, 120-135, 137], it was evident that a computer tool[7] would be necessary to answer the questions proposed in this chapter. Therefore, the first task was to carry out a review of existing computer tools, to identify if there were any which could be used to model the implications of PHES on the Irish energy system.

Appendix D gives a detailed account of the review which was completed to identify a suitable computer tool. It outlines the methodology undertaken to assess each energy tool, the corresponding results, provides an individual description about each of the energy tools reviewed, and gives a sample of the existing studies completed using each of the tools. Therefore, these will not be discussed in detail here, but instead the results and primary conclusions are discussed.

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[7] Energy tools are used to create energy models: Therefore, a computer program discussed here is referred to as a ‘tool’, which can be used to create various types of models.

8.1.1. Review of Energy Tools

To obtain a detailed understanding of the energy tools analysed, a survey was completed (using SurveyXact [169]) and distributed to a number of tool developers: a short summary of the survey can be seen in Appendix D. In summary, the survey consisted of five sections:

A. Background information: an insight into the background of the respondent.
B. Users: who and how many people were using the tool, and how the tool could be obtained?
C. Tool properties: basic characteristics about the type of tool in question.
D. Applications: what applications *can* the tool be used for and what applications is it *typically* used for?
E. Case studies: how was the tool previously used with a specific focus on renewable energy?
F. Further information: the respondents provided a description of the tool in their own words, listed the tools they had previously known before this review, and answered general queries about the process of this study.

After the surveys were answered and returned by the tool developers, the results were used to generate a range of tables which compared the tools along with a detailed description of each one. The tables act as a directory by providing a concise overview of each tool, while the paragraphs (which are available in Appendix D) provide a more in depth discussion where further information is required.

Initially, 68 energy tools were considered for the review, but as displayed in Table 8-1 only 37 of these were included in the final analysis. Table 8-1 also provides the most appropriate web-link available, along with a brief description of a typical application for each energy tool reviewed. The organisations responsible for each of the 37 tools reviewed, along with their availability, and number of downloads/sales are displayed in Table 8-2. From discussions with the tool developers, it became apparent that there is no common language shared amongst them which classifies the different types of energy tools. Consequently, to ensure that the tools were described correctly, a common language was created and distributed to the developers. Seven different tool types were defined, which can be used exclusively or collectively to describe an energy tool. The energy tool types are:

1. A simulation tool simulates the operation of a given energy system to supply a given set of energy demands. Typically a simulation tool is operated in hourly time-steps over a one-year time period.
2. A scenario tool usually combines a series of years into a long-term scenario. Typically scenario tools function in time-steps of one year and combine such annual results into a scenario of typically 20 to 50 years.

3. An equilibrium tool seeks to explain the behaviour of supply, demand, and prices in a whole economy or part of an economy (general or partial) with several or many markets. It is often assumed that agents are price takers and that equilibrium can be identified.
4. A top-down tool is a macroeconomic tool using general macroeconomic data to determine growth in energy prices and demands. Typically top-down tools are also equilibrium tools (see 3).
5. A bottom-up tool identifies and analyses the specific energy technologies and thereby identifies investment options and alternatives.
6. Operation optimisation tools optimise the operation of a given energy system. Typically operation optimisation tools are also simulation tools (see 1) optimising the operation of a given system.
7. Investment optimisation tools optimise the investments in an energy system. Typically optimisation tools are also scenario tools (see 2) optimising investments in new energy stations and technologies.

These definitions were then used to define each tool reviewed, which is illustrated in Table 8-3. The different types of analyses that can be completed with each of the tools are displayed in Table 8-4. Also, the energy sectors considered by each tool along with the renewable energy penetrations already simulated are shown in Table 8-5. By combining the details in the tables below with the detailed descriptions in Appendix D, a suitable tool can be identified for different investigations. These investigations vary from small renewable penetrations where they do not influence the energy system significantly, to penetrations where renewables begin to compete with conventional production and even to penetrations where renewable technologies replace conventional technologies.

Table 8-1: Tools considered in the review and the status of their inclusion in the final analysis.

Considered and Included [website]: Description of a typical application		Considered but Not Included	
AEOLIUS [170]: Power plant dispatch simulation tool	BALMOREL [171]: Open source electricity and district heating tool	BESOM	CEEM
BCHP Screening Tool [172]: Assesses CHP in buildings	COMPOSE [173]: Techno-economic single project assessments	CEPEL	CHP Capacity Optimizer
E_4cast [174]: Tool for energy projection, production, and trade	EMCAS [175]: Creates techno-economic models of the electricity sector	CHPSizer	CO2BD
EMINENT [176]: Early stage technologies assessment	EMPS [177]: Electricity systems with thermal/hydro generators	DER-CAM	DIMES
EnergyPLAN [178]: User friendly analysis of national energy systems	energyPRO [179]: Techno-economic single project assessments	DREAM	E3database
ENPEP-BALANCE [180]: Market-based energy system tool	GTMax [181]: Simulates electricity generation and flows	EFOM	Elfin
H_2RES [182]: Energy balancing models for Island energy systems	HOMER [183]: Techno-economic optimisation for stand-alone systems	Endur	GmbH
HYDROGEMS [184]: Renewable and H_2 stand-alone systems	IKARUS [185]: Bottom-up cost-optimisation tool for national systems	GREET	H2A Analysis
INFORSE [186]: Energy balancing models for national energy systems	In*vert* [187]: Simulates promotion schemes for renewable energy	HUD CHP Screening Tool	HyDIVE
LEAP [188]: User friendly analysis for national energy systems	MARKAL/TIMES [189]: Energy-economic tools for national energy systems	HYPRO	HyTrans
MESAP PlaNet [190] Linear network models of national energy systems	MESSAGE [191]: National or global energy systems in medium/long term	MENSA	MOREHyS
MiniCAM [192, 193]: Simulates long-term, large-scale global changes	NEMS [194]: Simulates the US energy market	NESSIE	PSAT
ORCED [195]: Simulates regional electricity-dispatch	PERSEUS [170]: Family of energy and material flow tools	PSR	Ready Reckoner
PRIMES [196]: A market equilibrium tool for energy supply and demand	ProdRisk [197]: Optimises operation of hydro power	Samplan	SEDS
RAMSES [198]: Simulates the electricity and district heating sector	RETScreen [199]: Renewable analysis for electricity/heat in any size system	SGM	TESOM
SimREN [200]: Bottom-up supply and demand for national energy systems	SIVAEL [201]: Electricity and district heating sector tool	UREM	
STREAM [202]: Overview of national energy systems to create scenarios	TRNSYS16 [203]: Modular structured models for community energy systems		
UniSyD3.0 [204]: National energy systems scenario tool	WASP [205]: Identifies the least-cost expansion of power plants		
WILMAR Planning Tool [74]: Increasing wind in national energy systems			

Table 8-2: Tool information and the number of users in terms of downloads/sales.

Tool	Organisation (Link)	Availability	Downloads / Sales
Very High Number of Users			
RETScreen	RETScreen International (http://www.retscreen.net/)	Free to Download	>200000
HOMER	National Renewable Energy Laboratory and HOMER Energy LLC (www.homerenergy.com)	Free to Download	>28000
LEAP	Stockholm Environment Institute (http://www.energycommunity.org/)	Commercial / Free for developing countries and students	>5000
BCHP Screening Tool	Oak Ridge National Laboratory (http://www.ornl.gov/)	Free to Download	>2000
energyPRO	Energi-Og Mijødata (EMD) International A/S (http://www.emd.dk/)	Commercial	>1000
High Number of Users			
EnergyPLAN	Aalborg University (http://www.energyplan.eu/)	Free to Download	100-1000
In*vert*	Energy Economics Group, Vienna University of Technology (http://www.invert.at/)	Free to Download	100-1000
MARKAL/TIMES	Energy Technology Systems Analysis Program, International Energy Agency (http://www.etsap.org/)	Commercial	100-1000
MESSAGE	International Institute for Applied Systems Analysis (http://www.iiasa.ac.at/)	Free / Simulators must be purchased	100-1000
ORCED	Oak Ridge National Laboratory (http://www.ornl.gov/)	Free to Download	100-1000
TRNSYS16	The University of Wisconsin Madison (http://sel.me.wisc.edu/trnsys/)	Commercial	100-1000
WASP	International Atomic Energy Agency (http://www.iaea.org/OurWork/ST/NE/Pess/PESSenergymodels.shtml)	Commercial / Free to IAEA member states	100-1000
Medium Number of Users			
EMCAS	Argonne National Laboratory (http://www.dis.anl.gov/projects/emcas.html)	Commercial	20-50
EMPS	Stiftelsen for Industriell og Teknisk Forskning (SINTEF) (http://www.sintef.no/)	Commercial	20-50
ENPEP-BALANCE	Argonne National Laboratory (http://www.dis.anl.gov/projects/Enpepwin.html)	Free to Download	20-50
GTMax	Argonne National Laboratory (http://www.dis.anl.gov/projects/Gtmax.html)	Commercial	20-50
Low Number of Users			
AEOLIUS	Institute for Industrial Production, Universität Karlsruhe (http://www-iip.wiwi.uni-karlsruhe.de/)	Commercial	1-20
COMPOSE	Aalborg University (http://www.socialtext.net/energyinteractivenet/index.cgi?compose)	Free to Download	1-20
IKARUS	Research Centre Jülich, Institute of Energy Research (http://www.fz-juelich.de/ief/ief-ste/index.php?index=3)	Commercial / Earlier versions are free	1-20
INFORSE	The International Network for Sustainable Energy (http://www.inforse.org/europe/Vision2050.htm)	Distributed to non-governmental organisations	1-20
Mesap PlaNet	seven2one (http://www.seven2one.de/de/technologie/mesap.html)	Commercial	1-20
NEMS	Office of Integrated Analysis and Forecasting, Energy Information Administration (http://www.eia.doe.gov/)	Free / Simulators must be purchased	1-20
PERSEUS	Institute for Industrial Production, Universität Karlsruhe (http://www-iip.wiwi.uni-karlsruhe.de/)	Commercial: only sold to large European utilities	1-20
ProdRisk	Stiftelsen for Industriell og Teknisk Forskning (SINTEF) (http://www.sintef.no/Home/)	Commercial	1-20
RAMSES	Danish Energy Agency (http://www.ens.dk/)	Projects completed for a fee	1-20
SIVAEL	Energinet.dk (http://www.energinet.dk/en/menu/Planning/Analysis+models/Sivael/SIVAEL.htm)	Free to Download	1-20
EMINENT	Instituto Superior Técnico, Technical University of Lisbon (http://carnot.ist.utl.pt/~eminent2/)	To be decided	0
PRIMES	National Technical University of Athens (http://www.e3mlab.ntua.gr/)	Projects completed for a fee	0
Number of Users is Not Specified as it is Not Monitored			
BALMOREL	Project Driven with a users network and forum around it (http://www.balmorel.com/)	Free to Download (Open Source)	Not Specified
E4cast	Australian Bureau of Agricultural and Resource Economics (http://www.abare.gov.au/)	Commercial	Not Specified
H2RES	Instituto Superior Técnico and the University of Zagreb (http://powerlab.fsb.hr/h2res/)	Internal Use Only	Not Specified
HYDROGEMS	Institutt for energiteknikk (http://www.hydrogems.no/)	Commercial / Free for TRNSYS Users	Not Specified
MiniCAM	Pacific Northwest National Laboratory (http://www.globalchange.umd.edu/)	Free to Download Once Contacted	Not Specified
SimREN	Institute of Sustainable Solutions and Innovations (http://www.isusi.de/theerjreport.html)	Projects completed for a fee	Not Specified
STREAM	Ea Energy Analyses (http://www.ea-energianalyse.dk/)	Free to Download Once Contacted	Not Specified
UniSyD3.0	Unitec New Zealand (http://www.unitec.ac.nz/)	Contact Prof. Jonathan Leaver: jleaver@unitec.ac.nz	Not Specified
WILMAR Planning Tool	Risø DTU National Laboratory for Sustainable Energy (http://www.wilmar.risoe.dk/)	Commercial	Not Specified

Table 8-3: Type of each tool reviewed.

Tool	Type						
	Simulation	Scenario	Equilibrium	Top-Down	Bottom-Up	Operation Optimisation	Investment Optimisation
AEOLIUS	Yes	-	-	-	Yes	-	-
BALMOREL	Yes	Yes	Partial	-	Yes	Yes	Yes
BCHP Screening Tool	Yes	-	-	-	Yes	Yes	-
COMPOSE	-	-	-	-	Yes	Yes	Yes
E4cast	-	Yes	Yes	-	Yes	-	Yes
EMCAS	Yes	Yes	-	-	Yes	-	Yes
EMINENT	-	Yes	-	-	Yes	-	-
EMPS	-	-	-	-	-	Yes	-
EnergyPLAN	Yes	Yes	-	-	Yes	Yes	Yes
energyPRO	Yes	Yes	-	-	-	Yes	Yes
ENPEP-BALANCE	-	Yes	Yes	Yes	-	-	-
GTMax	Yes	-	-	-	-	Yes	-
H2RES	Yes	Yes	-	-	Yes	Yes	-
HOMER	Yes	-	-	-	Yes	Yes	Yes
HYDROGEMS	-	Yes	-	-	-	-	-
IKARUS	-	Yes	-	-	Yes	-	Yes
INFORSE	-	Yes	-	-	-	-	-
In*vert*	Yes	Yes	-	-	Yes	-	Yes
LEAP	Yes	Yes	-	Yes	Yes	-	-
MARKAL/TIMES	-	Yes	Yes	Partly	Yes	-	Yes
Mesap PlaNet	-	Yes	-	-	Yes	-	-
MESSAGE	-	Yes	Partial	-	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	-	-
NEMS	-	Yes	Yes	-	-	-	-
ORCED	Yes	Yes	Yes	-	Yes	Yes	Yes
PERSEUS	-	Yes	Yes	-	Yes	-	Yes
PRIMES	-	-	Yes	-	-	-	-
ProdRisk	Yes	-	-	-	-	Yes	Yes
RAMSES	Yes	-	-	-	Yes	Yes	-
RETScreen	-	Yes	-	-	Yes	-	Yes
SimREN	-	-	-	-	-	-	-
SIVAEL	-	-	-	-	-	-	-
STREAM	Yes	-	-	-	-	-	-
TRNSYS16	Yes	Yes	-	-	Yes	Yes	Yes
UniSyD3.0	-	Yes	Yes	-	Yes	-	-
WASP	Yes	-	-	-	-	-	Yes
WILMAR Planning Tool	Yes	-	-	-	-	Yes	-

Table 8-4: Type of analysis conducted by each tool reviewed.

Tool	Geographical Area	Scenario Timeframe	Time-Step	Specific Focus
1. National Energy System Tools				
1.1. Time-Step Simulation Tools				
Mesap PlaNet	National/State/Regional	No Limit	Any	-
TRNSYS16	Local/Community	Multiple Years	Seconds	-
HOMER	Local/Community	1 Year*	Minutes	-
SimREN	National/State/Regional	No Limit	Minutes	-
EnergyPLAN	National/State/Regional	1 Year*	Hourly	-
SIVAEL	National/State/Regional	1 Year*	Hourly	-
STREAM	National/State/Regional	1 Year*	Hourly	-
WILMAR Planning Tool	International	1 Year*	Hourly	-
RAMSES	International	30 Years	Hourly	-
BALMOREL	International	Max 50 Years	Hourly	-
GTMax	National/State/Regional	No Limit	Hourly	-
H2RES	Island	No Limit	Hourly	-
MARKAL/TIMES	National/State/Regional	Max 50 Years	Hourly, Daily, Monthly using user-defined time slices	-
1.2. Sample periods within a year				
PERSEUS	International	Max 50 Years	Based on Typical Days with 36 to 72 slots for one year	-
UniSyD3.0	National/State/Regional	Max 50 Years	Bi-weekly	-
RETScreen	User Defined	Max 50 Years	Monthly	-
1.3. Scenario Tools				
E4cast	National/State/Regional	Max 50 Years	Yearly	-
EMINENT	National/State/Regional	1 Year*	None / Yearly	-
IKARUS	National/State/Regional	Max 50 Years	Yearly	-
PRIMES	National/State/Regional	Max 50 Years	Years	-
INFORSE	National/State/Regional	50+ Years	Yearly	-
ENPEP-BALANCE	National/State/Regional	75 Years	Yearly	-
LEAP	National/State/Regional	No Limit	Yearly	-
MESSAGE	Global	50+ Years	5 Years	-
MiniCAM	Global and Regional	50+ Years	15 Years	-
2. Tools with a Specific Focus				
2.1. Time-Step Simulation Tools				
AEOLIUS	National/State/Regional	1 Year*	Minutes	Effects of fluctuating renewable energy on conventional generation
HYDROGEMS	Single-Project Investigation	1 Year*	Minutes	Renewable energy and hydrogen stand-alone systems
energyPRO	Single-Project Investigation	Max 40 Years	Minutes	Single power plant analysis
BCHP Screening Tool	Single-Project Investigation	1 Year*	Hourly	Combined heat and power
ORCED	National/State/Regional	1 Year*	Hourly	Dispatch of electricity
EMCAS	National/State/Regional	No Limit	Hourly	Electricity markets
ProdRisk	National/State/Regional	Multiple Years	Hourly	Hydro power
COMPOSE	Single-Project Investigation	No Limit	Hourly	CHP with electric boilers or heat pumps
2.2. Sample periods within a year				
EMPS	International	25 Years	Weekly (With a load duration curve representing fluctuations within the week)	Hydro power
WASP	National/State/Regional	Max 50 Years	12 Load Duration Curves for a year	Power plant expansion on the electric grid
2.3. Scenario Tools				
In*vert*	National/State/Regional	Max 50 Years	Yearly	Heat sector
NEMS	National/State/Regional	Max 50 Years	Yearly	US Energy Markets

***Tools can only simulate one year at a time, but these can be combined to create a scenario of multiple years.**

Table 8-5: Energy sectors considered and renewable energy penetrations simulated by each tool reviewed.

	Energy Sectors Considered			Renewable-Energy Penetrations Simulated	
Tool	**Electricity Sector**	**Heat Sector**	**Transport Sector**	**100% Electricity Simulated**	**100% Renewable Energy System**
Reports available detailing these renewable-energy penetrations					
EnergyPLAN	Yes	Yes	Yes	Yes	Yes
INFORSE	Yes	Yes	Yes	Yes	Yes
Mesap PlaNet	Yes	Yes	Yes	Yes	Yes
H2RES	Yes	Yes	Partly	Yes	Yes
SimREN	Yes	Yes	Partly	Yes	Yes
energyPRO	Yes	Partly	-	Yes	Partly*
HOMER	Yes	Yes	-	Yes	Partly*
TRNSYS16	Yes	Yes	-	Yes	Partly*
PERSEUS	Yes	Yes	Partly	Yes	-
MESSAGE	Yes	Yes	Yes	-	-
NEMS	Yes	Yes	Yes	-	-
Reports <u>NOT</u> available detailing these renewable-energy penetrations					
LEAP	Yes	Yes	Yes	Yes	Yes
In*vert*	Yes	Yes	Partly	Yes	Yes
EMPS	Yes	-	-	Yes	Partly*
ProdRisk	Yes	-	-	Yes	Partly*
RETScreen	Yes	Yes	-	Yes	Partly*
MiniCAM	Yes	Partly	Yes	Yes	-
SIVAEL	Yes	Partly	-	Yes	-
COMPOSE	Yes	Yes	Yes	-	-
ENPEP-BALANCE	Yes	Yes	Yes	-	-
IKARUS	Yes	Yes	Yes	-	-
MARKAL/TIMES	Yes	Yes	Yes	-	-
PRIMES	Yes	Yes	Yes	-	-
E4cast	Yes	Yes	Partly	-	-
STREAM	Yes	Yes	Partly	-	-
EMINENT	Yes	Yes	-	-	-
UniSyD3.0	Yes	Partly	Yes	-	-
WILMAR Planning Tool	Yes	Partly	Partly	-	-
BALMOREL	Yes	Partly	-	-	-
GTMax	Yes	Partly	-	-	-
RAMSES	Yes	Partly	-	-	-
HYDROGEMS	Yes	-	-	-	-
ORCED	Yes	-	Partly	-	-
EMCAS	Yes	-	Partly	-	-
WASP	Yes	-	-	-	-
AEOLIUS	Yes	-	-	-	-
BCHP Screening Tool	-	-	-	-	-

*Have simulated a 100% renewable energy penetration in all the sectors they consider.

From this review it is evident that there is a wide range of different energy tools available which are diverse in terms of the regions they analyse, the technologies they consider, and the objectives they fulfil. Out of the 37 energy tools which were reviewed in detail, EnergyPLAN was chosen for this study for a number of key reasons. Firstly, it is a very user-friendly tool and hence the initial training period required to begin using the model is usually less than one month. In addition, online training is available and EnergyPLAN is free to download from its website [178]. Also, in the programming of EnergyPLAN, any procedures which would increase the calculation time have been avoided. For example, it uses deterministic modelling as opposed to stochastic, so with the same input it will always come to the same result. Also, EnergyPLAN is based on analytical programming as opposed to iterations, dynamic programming, or advanced mathematical tools. This makes the calculations direct and the tool very fast when performing calculations. As a result, the computation of one year requires only a few seconds on a normal computer, even in the case of complicated national energy systems. Therefore, it is ideal for analysing a wide range of alternatives against one another. Furthermore, the results created in EnergyPLAN are published within academic journals and many of these were closely related to the objectives of this study, such as analysing the integration of wind power [206] and the feasibility of large-scale energy storage [49, 207, 208]. Finally, one of the most distinguishing features within EnergyPLAN was the fact that it considered the three primary sectors of any national energy system: electricity, heat, and transport. As fluctuating renewable energy such as wind power becomes more prominent within energy systems, flexibility will become a vital consideration, which is the primary attraction of PHES. However, one of the most accessible methods of creating flexibility within an energy system is the integration of the electricity, heat, and transport sectors using technologies such as CHP, heat pumps, electric vehicles, and hydrogen. Therefore, although PHES is only used in the electricity sector, the construction of a PHES facility also impacts technologies which operate within the heat and transport sectors. In addition, alternative sources of flexibility to PHES depend on the consideration of the heat and transport sectors. Therefore, as the objective of this study is to evaluate the implications of PHES and compare it to alternatives on the Irish energy system, it is vital that all three sectors are considered and hence, EnergyPLAN was ideal for this analysis.

8.1.2. EnergyPLAN

EnergyPLAN has been developed and expanded on a continuous basis since 1999 at Aalborg University in Denmark. Approximately ten versions of EnergyPLAN have been created and it has been downloaded by more than 1200 people. The current version can be downloaded for free along with a range of training material from the EnergyPLAN website [178]. The training period required can take a few days up to a month, depending on the level of complexity required.

EnergyPLAN is a user-friendly tool designed in a series of tab sheets and programmed in Delphi Pascal. Input is defined by the user in terms of technologies and cost specifications. The main purpose of the tool is to assist the design of national or regional energy planning strategies on the basis of technical and economic analyses of the consequences of implementing different energy systems and investments. It encompasses the whole national or regional energy system including heat and electricity supplies as well as the transport and industrial sectors. All thermal, renewable, storage, conversion, and transport technologies can be modelled by EnergyPLAN. The tool is a deterministic input/output tool and, as outlined in Figure 8-1, general inputs are demands, renewable energy sources, energy station capacities, costs, and a number of optional regulation strategies for import/export and excess electricity production. Outputs are energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity. EnergyPLAN uses an hourly time step in its simulation so it is able to analyse the influence of fluctuating renewable energy sources on the system, as well as weekly and seasonal differences in electricity and heat demands and water inputs to large hydro power systems. EnergyPLAN simulates a one year time-period in total, although several analyses each covering one year may be combined to create longer scenarios. In the interest of speed, EnergyPLAN is aggregated in its system description instead of modelling each individual station and component, e.g. in EnergyPLAN district-heating systems are aggregated and defined as three principle groups. Also, EnergyPLAN provides a choice between different regulation strategies for a given system instead of incorporating a specific institutional framework. Therefore, the system can not only be optimised based on costs, but also based on its operation so that investments can be compared based on their socio-economic gains.

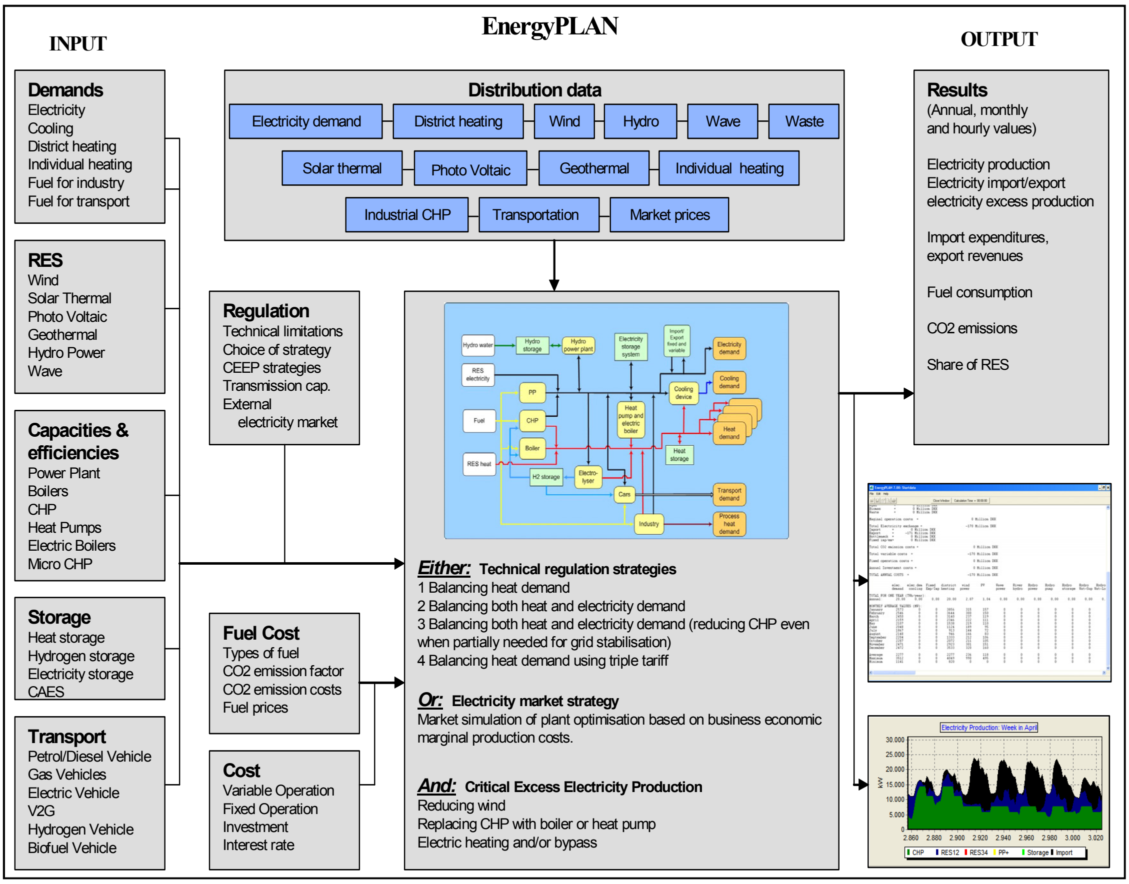

Figure 8-1: The structure of the EnergyPLAN tool.

Previously, EnergyPLAN has been used to analyse the large-scale integration of wind [206] as well as optimal combinations of renewable energy sources [209], management of surplus electricity [210], the integration of wind power using V2G electric vehicles [211], the implementation of small-scale CHP [212], integrated systems and local energy markets [213], renewable energy strategies for sustainable development [214], the use of waste for energy purposes [215], the potential of fuel cells and electrolysers in future energy systems [216, 217], the potential of thermoelectric generation in thermal energy systems [218], and the effect of energy storage [219], with specific work on compressed air energy storage [49, 207, 208] and the thermal energy storage system [220, 221]. In addition, EnergyPLAN was used to analyse the potential of CHP and renewable energy in Estonia, Germany, Poland, Spain, and the Britain [222]. Other publications can be seen on the EnergyPLAN website [178], while an overview of the work completed using EnergyPLAN is discussed by Lund [223]. Finally, EnergyPLAN has been used to simulate a 100% renewable energy system for the island of Mljet in Croatia [224] and the entire county of Denmark [225-229].

8.2. Modelling the Irish Energy System

After concluding that EnergyPLAN was the most suitable energy tool, the next step was to create a reference model of the Irish energy system based on an historical year. This was to ensure that EnergyPLAN is capable of accurately modelling the Irish energy system. As this work began in 2008, the most recent complete year of data available was for 2007 and hence, this was chosen as the reference year.

In summary EnergyPLAN requires two specific types of data: an annual production/demand and a corresponding hourly distribution of that annual value. The foundation for the annual data is the national energy balance which is usually available in every country. In Ireland, this is developed by the Sustainable Energy Authority of Ireland (SEAI), so a detailed breakdown of the 2007 Irish energy balance is available from their website [162] and in Appendix E. The relevant data for this study from the 2007 energy balance is displayed in Table 8-6, which displays the total annual energy requirement and consumption for each fuel within each sector of the energy system. Although some of these needed to be manipulated to satisfy the EnergyPLAN inputs, many could be taken directly.

For the distribution data, hourly values must be obtained based on historical records or theoretical assumptions. This data is then indexed by the EnergyPLAN software so it can be manipulated for an alternative scenario. For example, in Table 8-7 the historical output of a 100 MW wind farm is used to simulate the predicted output from a 400 MW wind farm and in Figure 8-2, the Irish electricity demand for January 2007 is manipulated to represent hypothetical demands of 1.5 TWh, 1 TWh, and 0.5 TWh.

To construct a new model in EnergyPLAN, over 100 separate pieces of data relating to the Irish energy system were required. As the construction of the model is not critical here, the details of the technical data used and economical assumptions made are described in detail in Appendix E and F. Instead, the most important outcome for this study is the accuracy of the model after it was constructed.

Table 8-6: Energy balance for the Irish energy system in 2007 (last updated by SEAI on the 21st October 2009): for all data, see reference [162] or Appendix E.

2007 Energy Balance **Units = ktoe**	**Coal**	**Peat**	**Oil**	**Jet Kerosene**	**Gasoline / Petrol**	**Gasoil / Diesel /DERV**	**Natural Gas**	**Renewables**	**Hydro**	**Wind**	**Wave**	**Biomass**	**Solar**	**Geothermal**	**Electricity**	**TOTAL**
Primary Energy Requirement	*1508*	*701*	*9047*	*1043*	*1920*	*3885*	*4293*	*467*	*57*	*168*	*0*	*239*	*1*	*1*	*-114**	*16130*
Power Plant Consumption	1124	431	368				2737	33				33				4660#
Power Plant Production	460€	181€	116€				1307€	237	57	168	0	12				2064#
Transmission & Distribution Losses															229	229
Total Final Energy Consumption	*374*	*272*	*8604*	*1043*	*1920*	*3885*	*1584*	*213*				*211*	*1*	*1*	*2224*	*13271*
Industry	140		1015			178	655	152				152			729	2691
Transport			5659	1043	1920	2695	0	21				21			4	5685
Residential	208	272	1127			230	593	24				30	1	1	693	2917
Commercial/Public Services	26		551			530	336	8							749	1670
Agricultural			252			252	0	7				7			48	308

***Negative sign indicates an electricity net import.**

#Figure represents fossil fuel power plants only.

€This was not available in the energy balance and hence it was obtained from [20].

Table 8-7: How a distribution is indexed and subsequently used in EnergyPLAN.

Time (h)	Output from a 100 MW Wind Farm (MW)	Index Data		Using Indexed Data to Simulate a 400 MW Wind Farm	
		Fraction	Decimal		
1	20	20/100	0.2	0.2*400	80
2	30	30/100	0.3	0.3*400	120
3	60	60/100	0.6	0.6*400	240
4	100	100/100	1.0	1.0*400	400
5	80	80/100	0.8	0.8*400	320
6	40	40/100	0.4	0.4*400	160

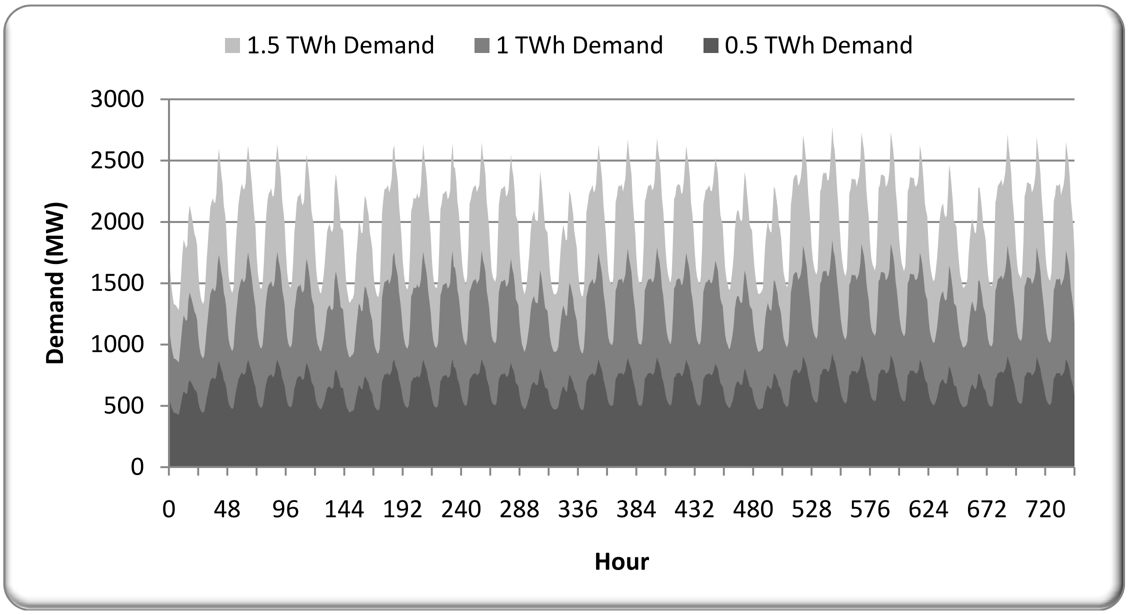

Figure 8-2: One sample distribution being modified by the total electricity demand required over the 30 day period (based on the Irish electricity demand in January 2007 [22]). This illustrates how data is manipulated in EnergyPLAN.

To validate the model, a comparison was made between the results from the EnergyPLAN model and the actual figures from 2007. The first parameter that was compared was the electricity demand. The total electricity generated for 2007 (28.5 TWh), including a 1.31 TWh net import were being simulated correctly in the model. Also, the distribution of the electricity generated over the year was also being simulated correctly, as indicated by the average monthly electricity demands displayed in Table 8-8.

Table 8-8: Comparison of average monthly electricity demands obtained from the EnergyPLAN model and actual values for Irish energy system in 2007.

Month	Average Monthly Electricity Demand (MW)		Difference (MW)	Difference (%)
	Actual 2007	EnergyPLAN 2007		
January	3564	3559	-5	-0.14
February	3576	3573	-3	-0.09
March	3414	3386	-28	-0.82
April	3079	3084	5	0.18
May	3029	3025	-4	-0.14
June	2991	2970	-21	-0.71
July	2937	2947	10	0.34
August	2964	2960	-4	-0.15
September	3094	3105	11	0.36
October	3279	3281	2	0.07
November	3515	3508	-7	-0.20
December	3531	3519	-12	-0.35

Once it was verified that the electricity demand was being simulated correctly, the electricity produced from various units was compared. As seen in Table 8-9, the total electricity generated from the various production units is very similar in both the actual 2007 figures [162] and the results from the reference model. The only significant difference occurred for wind power production, which is most likely attributed to the 8.5% variation in installed wind capacity at the beginning and end of 2007[8]. As power plants contributed such a large proportion of the electricity supply, a further comparison was made for them.

Table 8-9: Comparison between electricity produced for Ireland in 2007 and in the EnergyPLAN simulation.

Production Unit	2007 Production [162] (TWh)	EnergyPLAN Production 2007 (TWh)	Difference	
			TWh	%
Power Plants	23.56	23.54	0.02	0.08
Onshore Wind	1.88*	1.86	0.06	3.20
Offshore Wind		0.08		
Industrial CHP	0.93	0.93	0.00	0.00
Hydro Power	0.66	0.65	-0.01	-1.52

***Onshore and offshore data could not be obtained separately.**

Power plant production could not be compared individually because EnergyPLAN aggregates the power plants within an energy system and consequently, the production from each power plant is not available from the results. Therefore, electricity production was not compared for each power plant, but instead the annual fuel consumed by each fuel type of power plant was compared. From Table 8-10 it is clear that the model provides an accurate representation of

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[8] There was an 8.5% increase in wind capacity in Ireland in 2007 from 723.8 MW to 785.2 MW.

the power plants on the Irish energy system in 2007, as the largest difference that occurred was 0.47%.

Table 8-10: Comparison between the fuel consumed in power plants for Ireland in 2007 and in the EnergyPLAN simulation.

Power Plant	2007 Production [162] (TWh)	EnergyPLAN Production 2007 (TWh)	Difference	
			TWh	%
Natural Gas	29.10	29.23	0.13	0.45
Coal	18.08	18.16	0.08	0.44
Oil	4.28	4.30	0.02	0.47
Biomass	0.28	0.28	0.00	0.00

After the electricity sector was analysed, the heat and transport sectors were compared with the reference model. However, all heat in Ireland is produced by individual boilers and all transport is powered by conventional vehicles. Therefore, due to the lack of integration between the sectors in the Irish energy system, no hourly simulations are necessary in the heat or transport sectors. The only input required is the annual fuel requirements which are used as inputs in EnergyPLAN. Therefore, comparing the EnergyPLAN results with the actual data from 2007 would result in no difference, as it would be the same data. Therefore, for the heat and transport sectors, the accuracy of the model needs to be based on the assumptions made while constructing the input data, not on the figures produced by the model, which are outlined in detail in Appendix E.

Next the total fuel consumption within the Irish energy system is compared with those calculated in EnergyPLAN. As seen in Table 8-11, the total fuel consumptions from actual 2007 figures and from the reference model are very similar for all fuels: the largest relative difference occurred for biomass at 2.17%.

Table 8-11: Comparison between the total fuel consumed in Ireland in 2007 and in the EnergyPLAN simulation.

Fuel	2007 Fuel Consumption (TWh)	EnergyPLAN Fuel Consumption (TWh)	Difference	
			TWh	%
Oil	105.22	104.44	-0.78	-0.74
Natural Gas	49.92	50.41	0.49	0.98
Coal/Peat	25.70	25.76	0.06	0.23
Biomass	2.77	2.83	0.06	2.17
Renewables	2.54	2.59	0.05	1.97

Finally, the actual CO_2 emissions for Ireland in 2007 were compared with those from the EnergyPLAN simulation. The total energy-related CO_2 emissions for Ireland in 2007 were calculated as 46.8 Mt using fuel consumptions from [162] and emission factors from [20], as seen in Table 8-12. In comparison, EnergyPLAN calculated the CO_2 emissions for Ireland in

2007 as 47.21 Mt. This is 0.88% (0.41 Mt) higher than those calculated from the statistics, and thus indicates that the reference model provided an accurate representation of the Irish energy system.

Table 8-12: CO_2 emissions for Ireland in 2007 and CO_2 emissions from the EnergyPLAN simulation.

Fuel	Consumption [162] (TWh)	CO_2 Emission Factor [20] (kg/GJ)	CO_2 Emitted (Mt)
Gasoil	45.188*	73.30	11.92
Electricity	25.867	150.83	14.05
Gasoline	22.325	70.00	5.63
Natural Gas	18.424*	57.10	3.79
Jet Kerosene	12.134	71.40	3.12
Kerosene	10.620	71.40	2.73
Coal	4.354*	94.60	1.48
Fuel Oil (Residual Oil)	4.295*	76.00	1.18
Coke	3.637	100.80	1.32
Sod Peat	2.167	104.00	0.81
LPG	1.853*	63.70	0.42
Peat Briquettes	0.992	98.90	0.35
Naphtha	0.012	73.30	0.003
Total			46.80

***Excludes fuel required for electricity generation.**

After completing the comparison between the reference model and the actual 2007 figures, it was concluded that the model was capable of accurately modelling the Irish energy system as the largest difference recorded was 2.17%. Therefore, the EnergyPLAN tool could be used to assess the implications of large-scale energy storage in Ireland. However, to do so a future model of the Irish energy system was required instead of the 2007 historical reference.

In line with this, a new model of the Irish energy system was developed based on the year 2020. For the most part, the technical and economical assumptions from the 2007 reference model, which are outlined in Appendices E and F, were applied to the 2020 model also. However, the annual consumption and demand data were taken from the 2020 reference projected by the Irish energy authority, SEAI [35]. More specifically, the 2020 model was based on SEAI's "White Paper Plus" scenario for 2020, which is outlined in Table 8-13. The total electricity demand assumed was approximately 34 TWh with an average demand of approximately 3400 MW, a peak of approximately 5500 MW, and a minimum demand of approximately 1900 MW. In addition, the installed capacity assumed for each technology is outlined in Table 8-14. Using this new 2020 model of the Irish energy system, the technical and economical consequences of PHES could be assessed in relation to the integration of wind power.

Table 8-13: Projected energy balance for the Irish energy system in 2020 (White Paper Plus Scenario) [35].

2020 White Paper Plus Energy Balance **Units = ktoe**	**Coal**	**Peat**	**Oil**	**Jet Kerosene**	**Gasoline / Petrol**	**Gasoil / Diesel /DERV**	**Natural Gas**	**Renewables**	**Hydro**	**Wind**	**Wave**	**Biomass**	**Solar**	**Geothermal**	**Electricity**	**TOTAL**
Primary Energy Requirement	*606*	*483*	*8721*	*800*	*1873*		*3916*	*2481*	*91*	*718*	*118*	*1450*	*20*	*84*	*-127**	*16080*
Power Plant Consumption	373	338	345				2397	500				500				3453#
Power Plant Production	137	120	118				1356	1109	91	718	118	183				1732#
Transmission & Distribution Losses															242	242
Total Final Energy Consumption	*233*	*146*	*8376*	*800*	*1873*		*1519*	*1055*				*950*	*20*	*84*	*2447*	*13776*
Industry	98		877				778	345				345			630	2728
Transport			5933	800	1873	3259	0	464				464			95	6492
Residential	112	146	1210				516	103				141	20	84	648	2734
Commercial/Public Services	23		60				225	143							998	1448
Agricultural			296												76	373

***Negative sign indicates an electricity net import.**
#Figure represents fossil fuel power plants only.

Table 8-14: Predicted capacities on the Irish electric grid in 2020 [35].

Technology	Installed Capacity (MW)
Coal Power Plants	845
Peat Power Plants	346
Open Cycle Gas Turbines	1091
Combined Cycle Gas Turbines	3013
Waste Incineration	89
Wind Turbines	3100
Wave Powers	500
Hydroelectricity	260
Interconnection	580

When simulating PHES in EnergyPLAN during this study, the primary focus was to integrate the maximum feasible wind penetration (MFWP) and hence, a technical optimisation was used. For a technical optimisation, PHES is charged during hours when critical excess electricity production (CEEP)[9] occurs in the energy system (i.e. if $e_{CEEP} > 0$) [178]. In this case the electricity demand for the PHES pump (e_{Pump}) is found as the minimum value in Equation 5, which considers the CEEP, e_{CEEP}, the available space in the PHES facility ($C_{Storage} - s_{PHES}$), and the maximum capacity of the PHES pump, C_{Pump}. Subsequently, the energy stored in the PHES facility after operating the pump is calculated using Equation 6, where s_{PHES} is the current volume of energy stored in the PHES facility and η_{Pump} is the pump efficiency:

$$e_{Pump} = min\left[e_{CEEP}, \frac{C_{Storage} - S_{PHES}}{\eta_{Pump}}, C_{Pump}\right] \tag{5}$$

$$s_{PHES} = s_{PHES} + \left(e_{Pump} * \eta_{Pump}\right) \tag{6}$$

Conversely, the PHES is discharged when it is possible to replace power plant production with power from the PHES facility (i.e. if $e_{PP} > 0$) [178]. Therefore, the electricity produced by the turbine, $e_{Turbine}$, is found as the minimum value in Equation 7, which considers the power plant capacity which can be replaced, e_{pp}, the current energy available in the PHES facility, s_{PHES}, and the maximum capacity of the PHES turbine, $C_{Turbine}$. Subsequently, the volume of energy remaining in the PHES after operating the turbine is identified using Equation 8, where $\eta_{Turbine}$ is the turbine efficiency:

$$e_{Turbine} = min[e_{PP}, (S_{PHES} * \eta_{Turbine}), C_{Turbine}] \tag{7}$$

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[9] CEEP is the amount of excess electricity produced that could not be used in the energy system. The consequences of CEEP are forced export (if adequate interconnection capacity exists) or stopping the wind turbines to reduce production (curtailment).

$$s_{PHES} = s_{PHES} - \frac{e_{Turbine}}{\eta_{Turbine}} \tag{8}$$

In summary, where possible the simulation will use wind power directly to satisfy the electricity demand, but when grid constraints prevent this, the PHES stores the excess wind power so it can be used at a later time. Two primary assumptions were made in order to ensure the electricity grid operated in a stable fashion. Firstly, it was assumed that the minimum output from electrical power plants was never below 700 MW during each hour simulated and secondly, as recommended by the Irish TSO [230], 30% of the electricity production during each hour had to be supplied from grid stabilising units such as thermal power plants and hydro stations. Finally, a full and detailed explanation of the equations and operating principals associated with the EnergyPLAN tool is available from the EnergyPLAN website [178].

8.3. The Technical Implications of PHES

As outlined in section 6.2.1 earlier, some of the key issues identified from the literature in relation to the integration of wind using PHES included its operation, size, and cost. Therefore, in this section the first two of these key issues, operation and size, were assessed by simulating various types and capacities of PHES on the 2020 Irish energy system with increasing penetrations of wind power.

8.3.1. Operation

Historically, PHES facilities have typically been constructed with a single penstock system as they were designed to maximise electricity generation from baseload power plants i.e. by charging during the night when electricity prices were low (due to a high percentage of baseload power) and discharging during the day when electricity prices were high (due to a high electricity demand). However, if energy storage devices are designed especially to integrate fluctuating renewable energy, there may be additional benefits, especially in relation to grid stabilisation, when using PHES that can charge and discharge at the same time. This can be achieved in a single PHES facility by installing two penstocks, as displayed in Figure 8-3, or also by installing multiple single penstock PHES facilities on the same energy system i.e. one can charge while the other is discharging at the same time. By using a double penstock system, the PHES introduces even more flexibility onto the energy system which could aid the integration of wind power. Therefore, both of these operating strategies were used to simulate a 2500 MW and 25 GWh PHES facility on the 2020 Irish energy system.

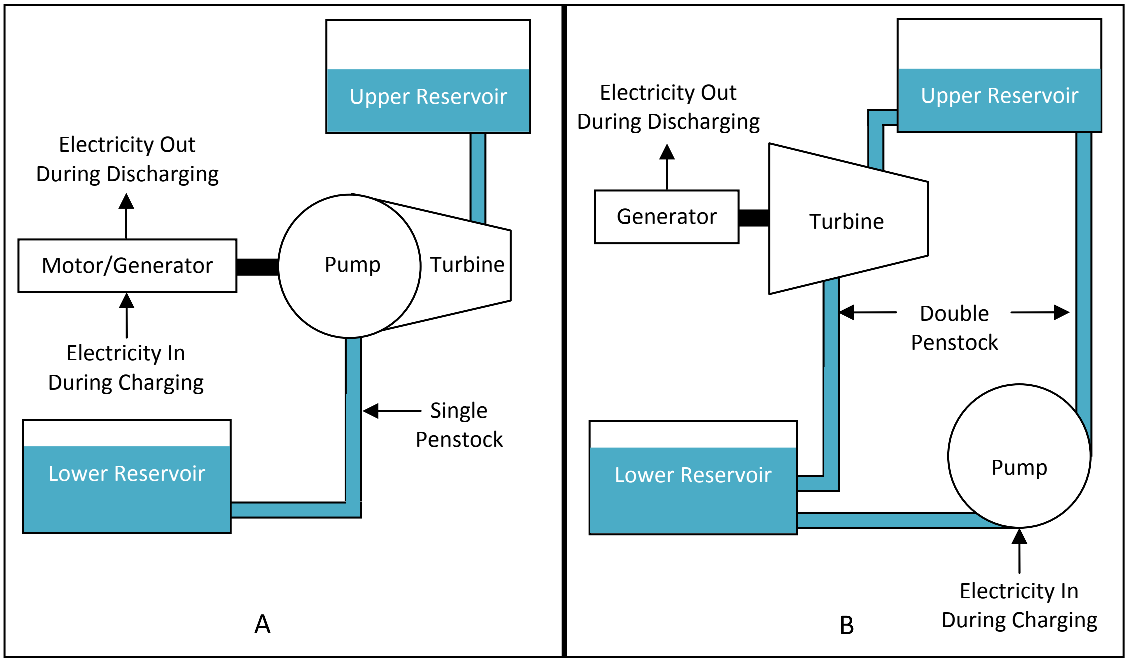

Figure 8-3: One PHES facility with (A) a single penstock system and (B) a double penstock system.

The CEEP recorded for both operating strategies when wind power is added to the Irish energy system is outlined in Figure 8-4, while Figure 8-5 displays the corresponding PES and CO_2 emissions. These results illustrate that PHES can reduce the amount of excess electricity created with the introduction of wind power, while also reducing the corresponding PES and CO_2 emissions. Also, it is evident from Figure 8-4 and Figure 8-5 that when the PHES facility operates as a double penstock system, there is less CEEP, PES, and CO_2 compared to the single penstock operating strategy. To identify the cause of this, the hourly operation of the system was analysed.

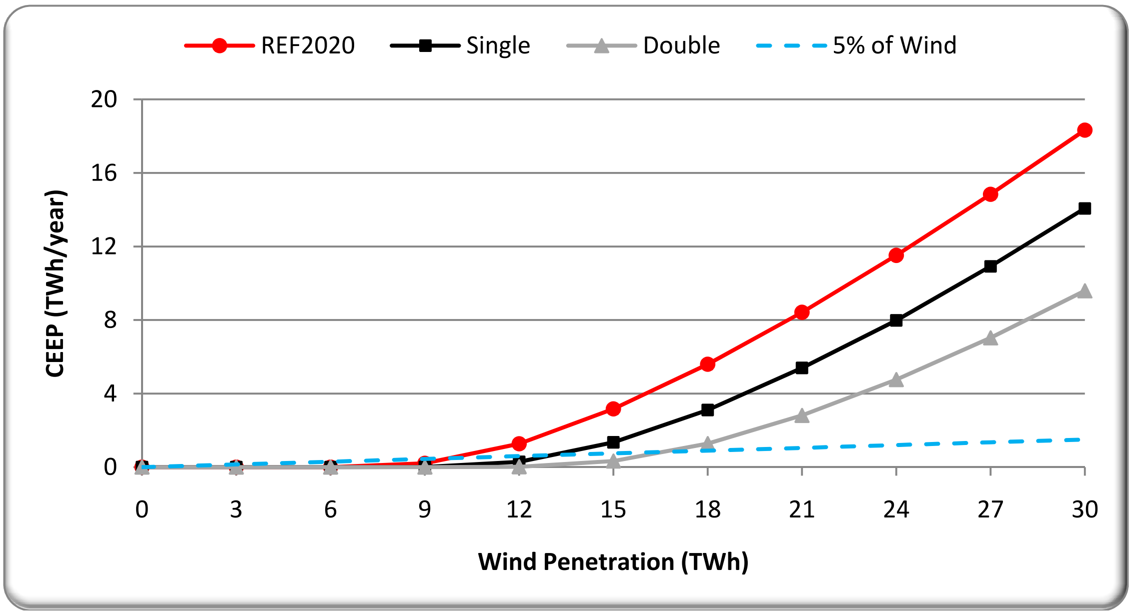

Figure 8-4: CEEP when a 2500 MW / 25 GWh single PHES and a 2500 MW / 25 GWh double PHES is added to the 2020 Irish energy system for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand. The 5% of wind limitation displayed is used to define a maximum feasible wind penetration.

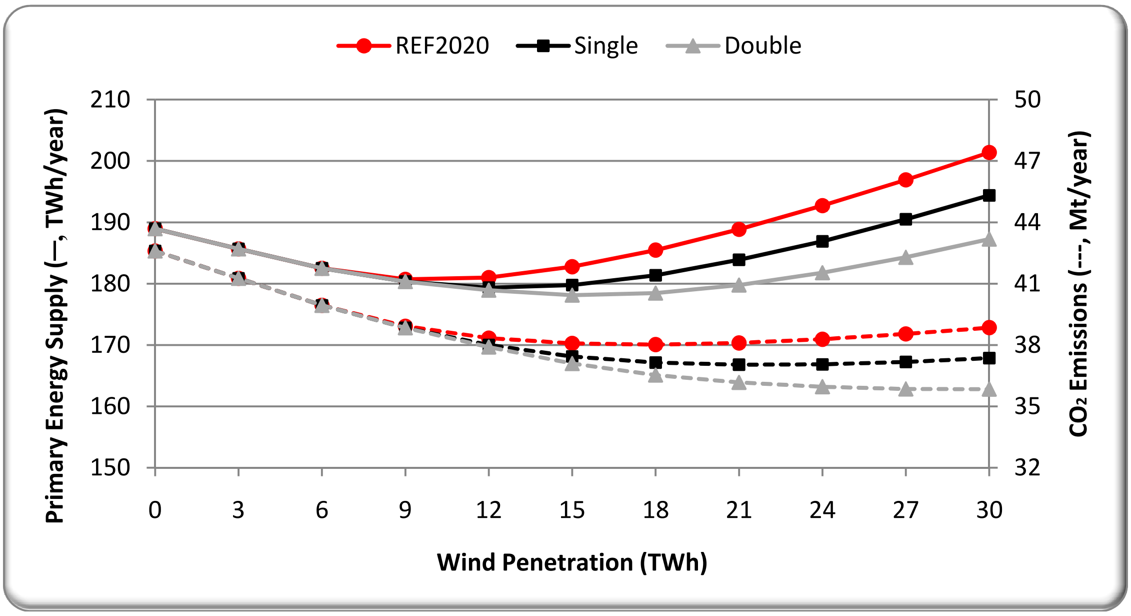

Figure 8-5: Primary energy supply and CO_2 emissions when a 2500 MW / 25 GWh single and double penstock system is added to the 2020 Irish energy system, for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand.

From these hourly values it became apparent that the grid stabilisation constraints were significantly limiting the effectiveness of the single penstock PHES. The primary objective of adding PHES is to minimise excess electricity production (i.e. reduce CEEP) and use it to replace thermal power production (i.e. reduce PES). However, as 30% of the production must come from grid stabilising units during each hour, wind power cannot always be used directly so it must be sent to the PHES facility. During these hours of excess wind, the single PHES cannot be used to provide grid stabilisation as it is being charged by the wind power and hence, the power plants (PP) must operate to provide grid stabilisation. Therefore, a single penstock PHES has to reduce CEEP and use the power plants to meet demand (Figure 8-6, Option A), or dump the CEEP and replace the power plant production (Figure 8-6, Option B). However, as displayed in Figure 8-6, both of these options will result in lower wind penetrations and correspondingly higher fuel consumption. In contrast, a double penstock system enables the PHES to store excess wind energy while at the same time providing ancillary services to the grid, which is also displayed in Figure 8-6. Therefore, during these hours a double penstock PHES facility can store CEEP by charging, while at the same time it can be discharged to replace power plant production (until such point that power plant production has reached its minimum limit, which was 700 MW in this study). This is the root cause for the lower CEEP, PES, and CO_2 emissions recorded in Figure 8-4 and Figure 8-5.

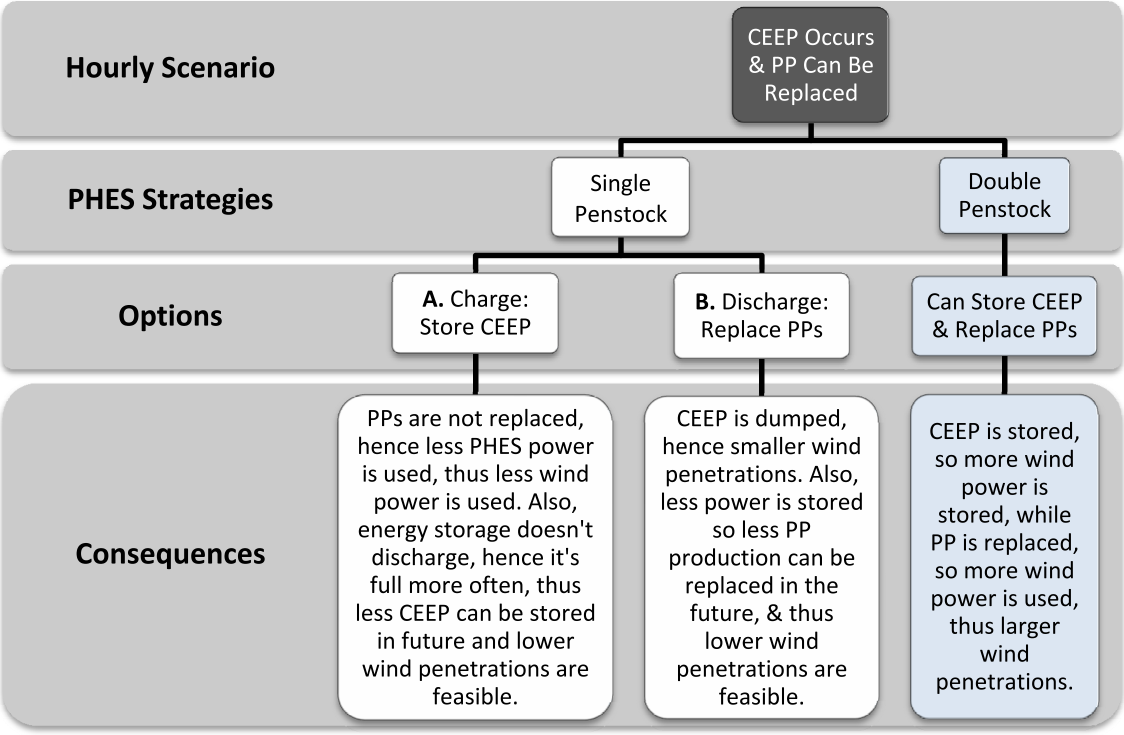

Figure 8-6: Consequences of using a single and double penstock system for PHES facilities when integrating wind power.

Finally, it is important to note that there is an underlying assumption in the modelling that only centralised power stations and hydro facilities can provide grid stabilisation. However, in future energy systems, grid stabilisation could be provided from wind turbines and decentralised units also [206], which could reduce the benefits of large-scale PHES. Due to the 40 year lifetime of PHES, this could be an important factor when constructing a new facility. Furthermore, when a single PHES was simulated with no grid constraints on the 2020 Irish energy system, it achieved greater reductions in CEEP, PES, and CO_2 emissions than the double penstock simulated here, thus outlining the significant role of grid constraints.

To summarise, this section has illustrated that under traditional grid constraint assumptions, adding conventional PHES to the Irish energy system will reduce CEEP, PES, and CO_2 emissions. A double penstock operating strategy is more effective than a single penstock system, as it can accommodate these grid constraints by charging and discharging at the same time. However, this analysis was completed using one PHES capacity only and so the next section investigates how alternative PHES capacities would influence the results.

8.3.2. Size

A PHES facility has three capacities: pump, turbine, and storage. When analysing PHES, many national-scale studies have not assessed the optimum relationship between these capacities for the integration of wind power [138, 140, 141], particularly in relation to Ireland [90, 91]. Therefore, the objective in this section is to identify how different combinations of these three PHES capacities will affect the wind penetration feasible on the 2020 Irish energy system, for both a single and double PHES.

Firstly, a definition was created to determine the maximum feasible wind penetration (MFWP) for each scenario analysed, which was: the MFWP occurs when the CEEP exceeds 5% of the total wind energy produced. This is illustrated graphically in Figure 8-4, where it can be seen that the MFWP is 30%, 43%, and 55% for the REF2020, Single PHES, and Double PHES scenarios respectively. Using this definition, the MFWP was identified for a range of PHES storage capacities by simulating each one with an infinite pump and turbine capacity. As a recent study in Ireland [89] has suggested that PHES storage capacities in excess of 100 GWh are now technically and economically feasible, the results were evaluated up to a storage capacity of 500 GWh. In line with this, the nine energy storage capacities considered in this thesis were, in GWh, 1.8 (reference), 3, 6, 12, 25, 50, 100, 250, and 500. After the MFWP was identified for each of these storage capacities, the hourly values were examined in each simulation to identify the pump and turbine capacity required to achieve this MFWP, which revealed a number of interesting trends.

The results in Figure 8-7 indicate that as the storage capacity of a single PHES increases from the reference value of 1.8 GWh to 25 GWh, the MFWP increases rapidly from approximately 30% to 40%. Afterwards, it slows down, taking about 125 GWh more to increase a further 10% to 50% and over 350 GWh more to reach a wind penetration of 60%. Interestingly, the pump and turbine capacities required are very similar for the first 25 GWh, but diverge away from one another after that. By 500 GWh, the pump capacity required to reach a 60% wind penetration is approximately 4500 MW, which is around 66% larger than the 2700 MW turbine required. Similarly for a double PHES, the results in Figure 8-8 indicate that it also increases the MFWP by 10% over the first 25 GWh. However, unlike a single PHES, the MFWP continues to increase at this rate up to a storage capacity of 100 GWh, when it reaches 80% of the total electricity demand. Subsequently, it takes an additional 150 GWh to rise a further 10% and finally, practically all of the electricity is provided using wind power with a storage capacity of 500 GWh. Once again, like the single PHES there is a clear divergence of capacities between the pump and turbine. However, this is even more severe for the double PHES facility because for each scenario considered the pump was approximately double the turbine capacity. After analysing the hourly operation of the systems simulated, it was clear that the pumping capacity is correlated to the excess electricity produced whereas the turbine is correlated to the power plant production it can replace. Therefore, as wind penetrations increase the pump size also increases so it can absorb more wind power which cannot be integrated onto the system. However, the turbine capacity doesn't increase this quickly, as the power plants it is replacing remain the same size. The relatively small increase in turbine capacity is thus due to the additional energy which is now stored in the PHES facility, as a result of the larger pump.

Furthermore, by comparing Figure 8-7 and Figure 8-8 (and as already discussed in section 8.3.1), it is evident that a double penstock PHES can enable much higher MFWPs than a single penstock PHES. However, the results also indicate that the pump and turbine capacities required by the double PHES to achieve its MFWPs are much larger than the capacities required by the single PHES. These findings created uncertainty in relation to the economics of a single and double PHES. One the one hand, a double PHES can integrate a lot more wind energy, but on the other it requires larger pump and turbine capacities. Consequently, an economic assessment of a single and double PHES was also carried out, which will be discussed later in section 8.4.

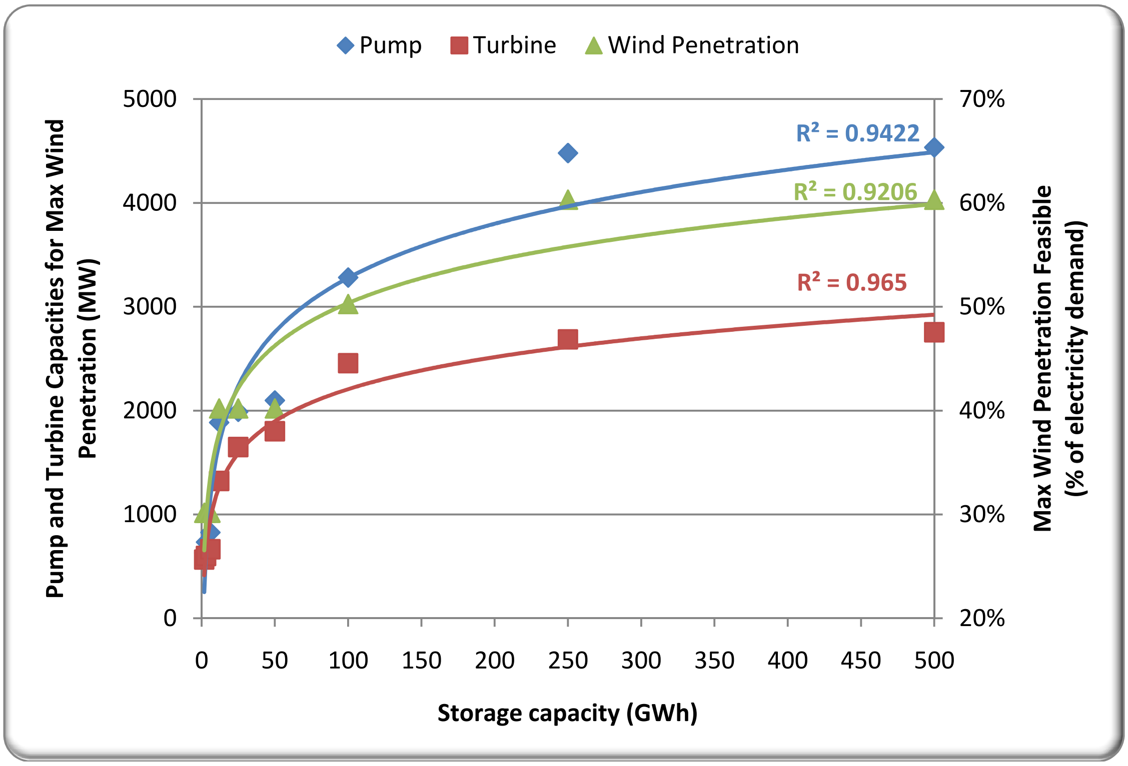

Figure 8-7: Maximum feasible wind penetration on the 2020 Irish energy system when various single PHES storage capacities are added to the system with infinite power capacities. Also outlined are the corresponding pump and turbine capacities required to achieve these maximum feasible wind penetrations identified at each storage capacity.

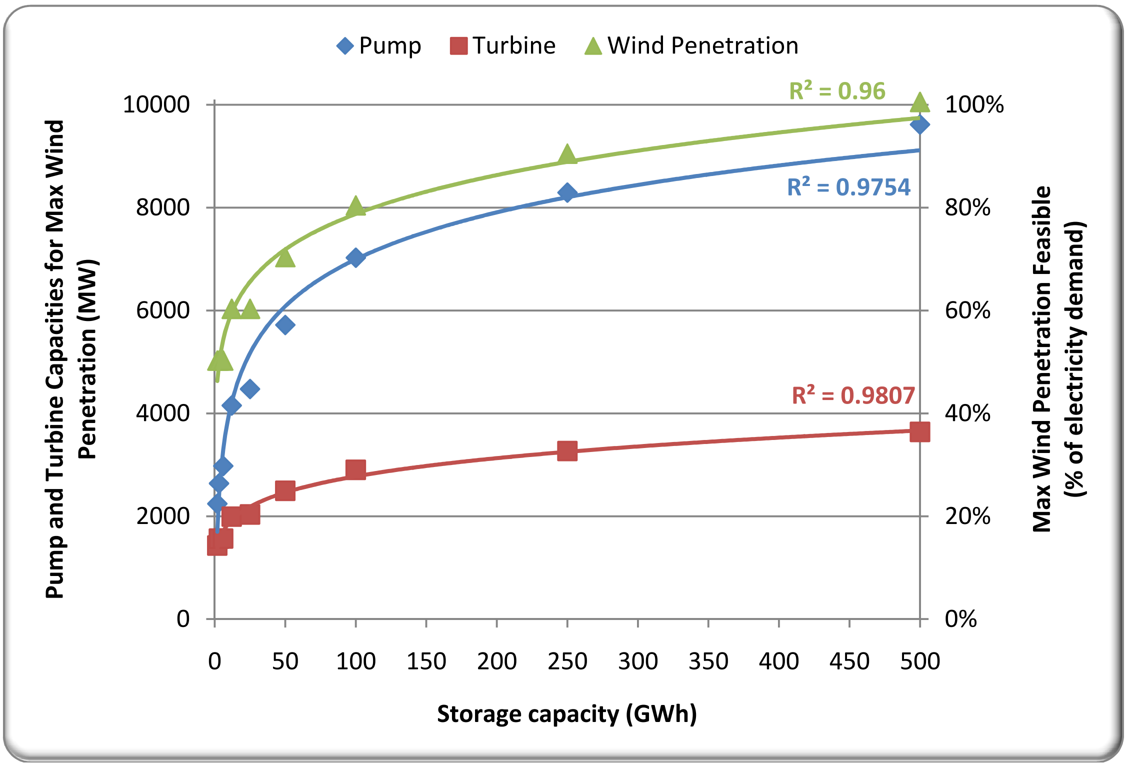

Figure 8-8: Maximum feasible wind penetration on the 2020 Irish energy system when various double PHES storage capacities are added to the system with infinite power capacities. Also outlined are the corresponding pump and turbine capacities required to achieve these maximum feasible wind penetrations identified at each storage capacity.

Finally, to ensure that the diverging trend between the pump and turbine capacities identified in Figure 8-7 and Figure 8-8 was not an created due to the definition for a MFWP, this was recalculated based on a number of different criteria. As already outlined above, the MFWP occurred when the total annual CEEP surpassed 5% of wind energy produced. Therefore, this was recalculated based on 10%, 15%, 20%, and 25% of wind power produced as well as 2%, 4%, 6%, 8%, and 10% of total electricity generated. As outlined in Figure 8-9 and Figure 8-10 for a single PHES as well as Figure 8-11 and Figure 8-12 for a double PHES, all of these criteria produced a similar trend to that already observed in Figure 8-7 and Figure 8-8 of this study, although the magnitude of the MFWP did change depending on the CEEP which was deemed acceptable. In addition, the COMP coefficient, which was developed in Appendix F to define a MFWP based on a trade-off between increasing CEEP and decreasing PES, was also used to evaluate the MFWP for each storage capacity and once again a similar pattern was identified, which is evident in Figure 8-13 and Figure 8-14. Therefore, it was concluded that the definition of a MFWP may alter the magnitude of the pump and turbine required, but the diverging trend between pump and turbine capacities as the MFWP increases is consistent. Overall, the limiting factor used in this study, which was a maximum CEEP equivalent to 5% of wind, is a relatively conservative definition as many of the others would increase the savings associated with additional energy storage.

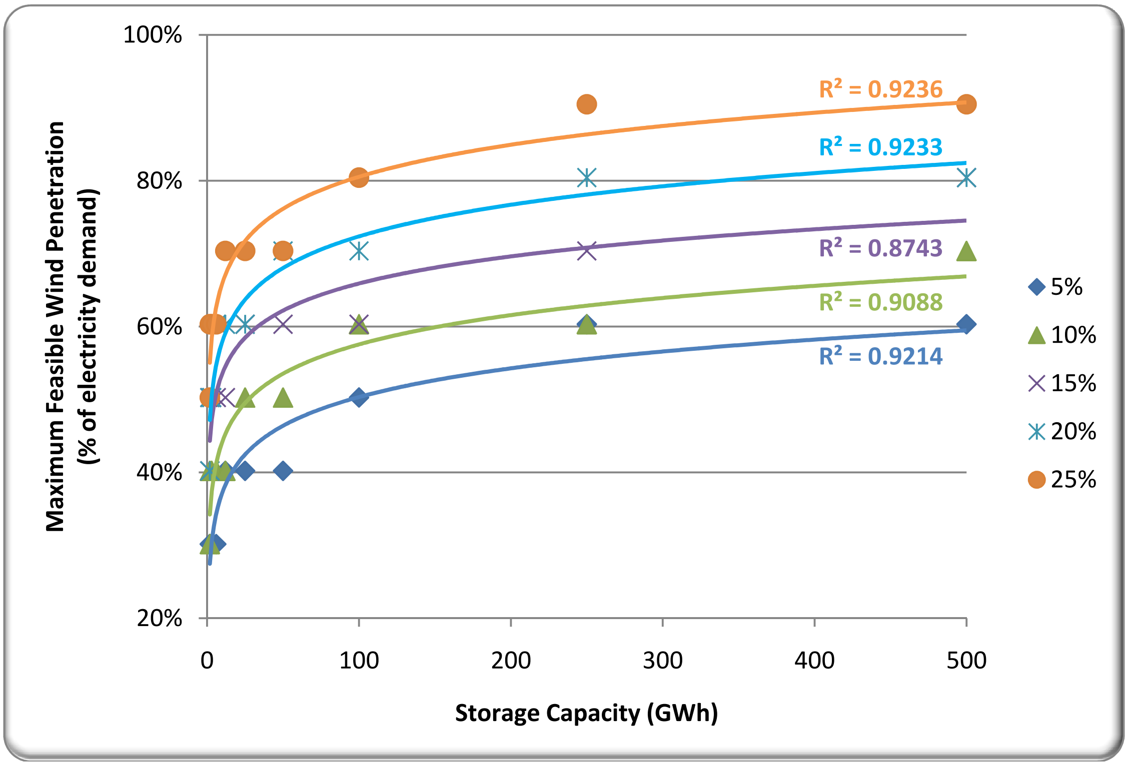

Figure 8-9: Maximum feasible wind penetration with various single PHES storage capacities on the 2020 Irish energy system based on different maximum allowable CEEP as a percentage of total wind power generated.

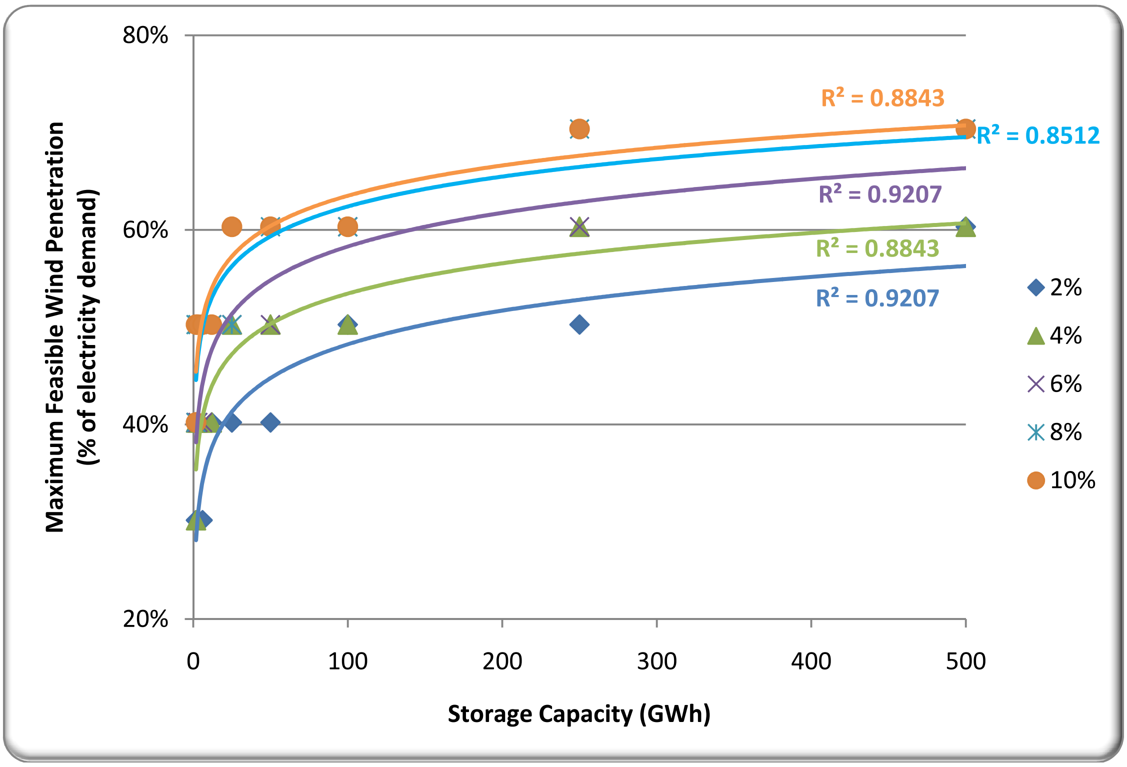

Figure 8-10: Maximum feasible wind penetration with various single PHES storage capacities on the 2020 Irish energy system based on different maximum allowable CEEP as a percentage of total electricity generated.

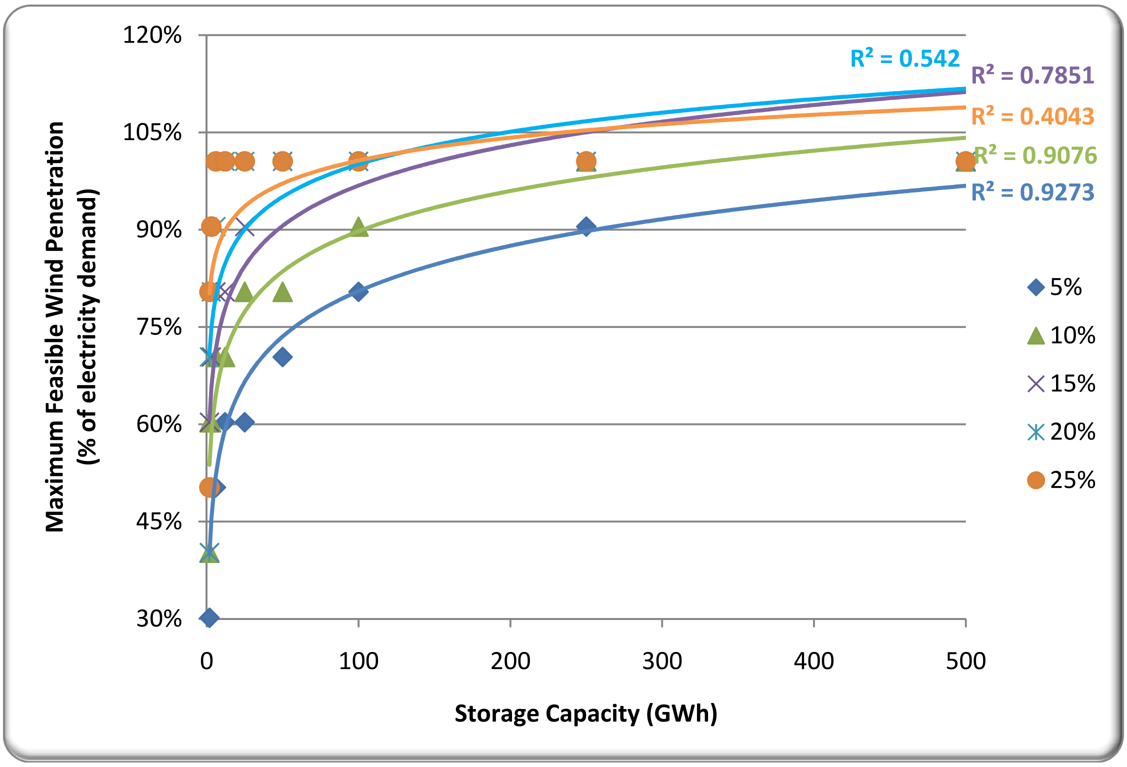

Figure 8-11: Maximum feasible wind penetration with various double PHES storage capacities on the 2020 Irish energy system based on different maximum allowable CEEP as a percentage of total wind power generated.

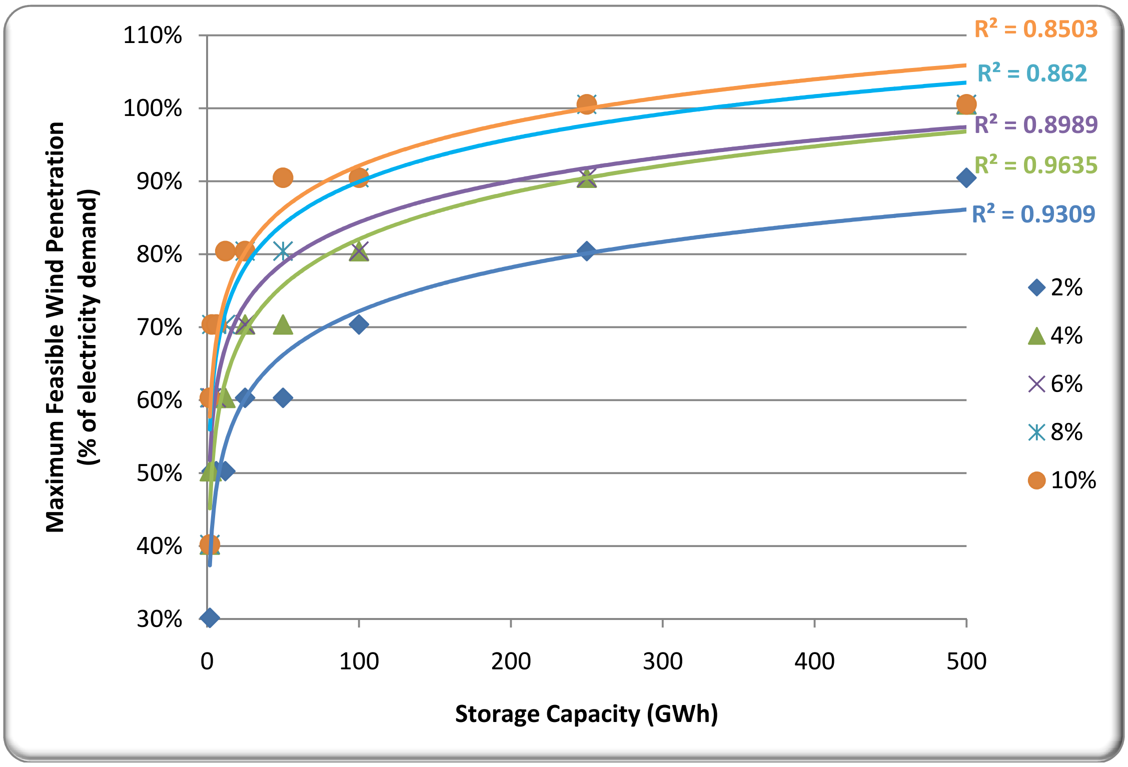

Figure 8-12: Maximum feasible wind penetration with various double PHES storage capacities on the 2020 Irish energy system based on different maximum allowable CEEP as a percentage of total electricity generated.

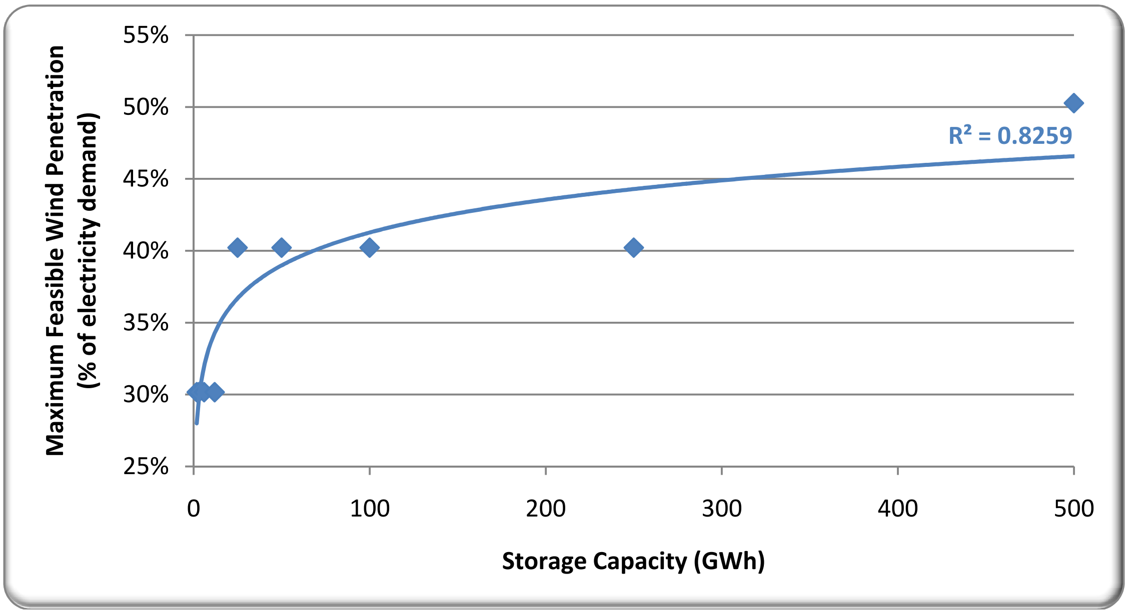

Figure 8-13: Maximum feasible wind penetration with various single PHES storage capacities on the 2020 Irish energy system based on the COMP coefficient developed in Appendix F.

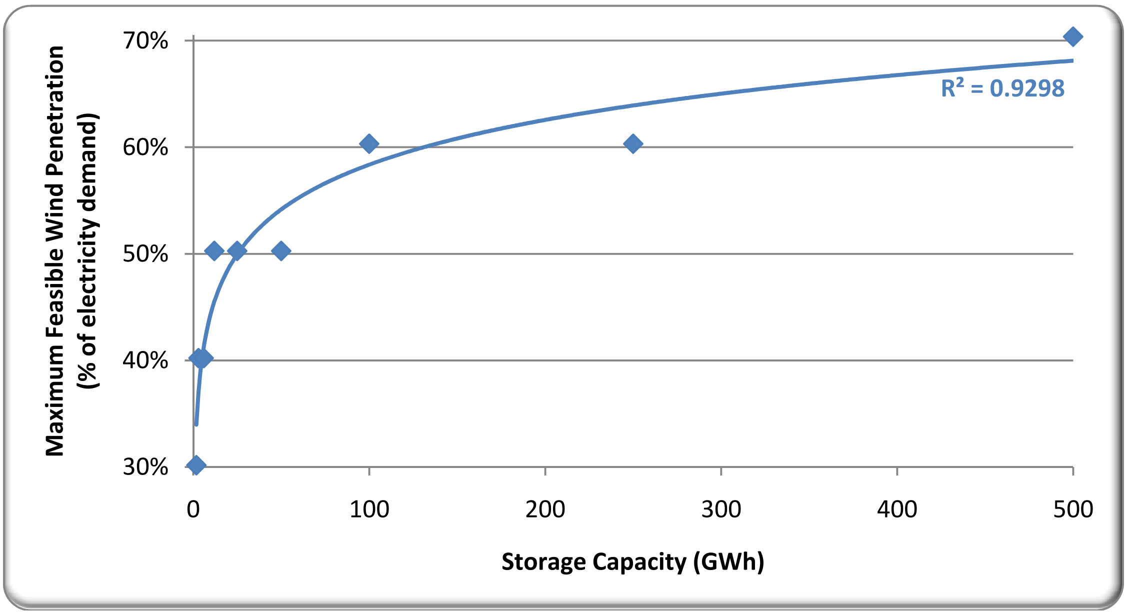

Figure 8-14: Maximum feasible wind penetration with various double PHES storage capacities on the 2020 Irish energy system based on the COMP coefficient developed in Appendix F.

8.3.3. Impact on Power Plant Operation

As almost 80% of the electricity generated in Ireland is from conventional power plants (see Table 8-13), it is important to consider the implications of large-scale wind and PHES on their operation. One of the most important implications to consider is the ramping requirement from the power plants caused by the addition of fluctuating renewable energy (i.e. wind). Therefore, to ensure that the results being produced by the EnergyPLAN model were realistic, the power plant fluctuations required were analysed on an hourly basis over a complete year (8784 hours) for different PHES scenarios and operating strategies. It was assumed for this analysis that the ramp-up demand on the power plants would be more important than the ramp-down demand and hence, it was the ramp-up demand which was analysed in detail, as displayed in Table 8-15 and graphed in Figure 8-15.

The results in Table 8-15 and Figure 8-15 were obtained using the power and storage capacities identified in section 8.3.2 above (see Figure 8-7 and Figure 8-8), which provided the MFWPs for the different PHES operating strategies. It is evident in part 1.1 of Table 8-15 that for a single penstock PHES both the scale and frequency of the ramp-ups required from power plants increases as additional wind and PHES are added to the reference scenario. However, after analysing the operation of the system during the hours before the ramp-ups occurred, it became apparent that a number of these ramp-ups happened when the PHES facility finished emptying after discharging over a prolonged period of time. Therefore, these situations could be anticipated in advance and hence they could be avoided. To account for this, ramp-up demands were analysed once again while ‘considering the PHES discharge’. It was assumed that if the PHES facility had energy available in the facility for each of the six hours prior to the hour where the ramping demand occurred, and the average energy in the PHES over this six hour period was greater than 500 MWh, then the ramping demand that occurred could have been avoided. Therefore, also displayed in Table 8-15 are the ramp-up demands for the single and double PHES for each scenario after this assumption was applied to the results.

Looking at the results in Table 8-15 and Figure 8-15 which did consider the discharge of PHES, it is clear that the ramping demands for power plants are larger when the MFWP is achieved on the REF2020 system, in comparison to those that occurred on 2009 energy system for both a single and double PHES. However, for all PHES operating strategies, wind capacities, and PHES capacities where the MFWP is achieved, the additional ramp-up demands placed on the power plants decreases with increasing storage capacities. Eventually at 500 GWh, the overall ramp-up demands on the power plants are larger in magnitude, but much less frequent than those that occurred during the operation of the 2009 Irish energy system (which had a wind penetration of only 10.5%). Therefore, it is assumed that adding large-scale wind and PHES to the existing Irish energy system will have a severe impact on the operation of existing power plants. However, if the discharge of the PHES facilities is controlled to prevent power plant fluctuations it will drastically reduce these implications, and as the storage capacities increase, it could eventually result in an energy system which is less challenging for power plants than the existing one.

Also, by comparing the single and double penstock operating strategies, it is evident from Table 8-15 and Figure 8-15 that for each storage capacity the double PHES requires similar ramping demands to the single PHES, even though the corresponding MFWPs are much larger for the double PHES. Consequently, not only can a double PHES accommodate the grid constraints specified, it can also integrate larger wind penetrations than a single penstock system while having similar implications on the power plant ramp-up demands. Finally, it is critical to recognise that EnergyPLAN is not designed for analysing the detailed operation of specific components such as power plants. Consequently, even though this analysis gives a realistic indication of the results, an energy tool designed for this specific issue is necessary for a more robust conclusion.

Table 8-15: Power plant ramping requirements for the MFWP identified at each storage capacity, using either a single or a double penstock system. Data is displayed graphically in Figure 8-15.

PHES Capacity		MFWP (% of electricity)	Average of Top 20 Power Plant Ramp-Ups (MW)	Number of Hours With PP Fluctuations*		
Pump-Turbine (MW)	Storage (GWh)			>1000 MW	<1000 MW & >500 MW	<500 MW & >250 MW
272: REF2009	1.8: REF2009	10.5%[#]	706[#]	1[#]	96[#]	717[#]
1. Single Penstock PHES						
1.1. Before Considering the PHES Discharge						
272: REF2020	1.8: REF2020	30%	946	7	266	812
600-500	1.8: REF2020	30%	951	6	322	824
700-600	3	30%	950	6	331	789
800-600	6	30%	934	5	307	792
1800-1300	12	40%	1344	93	413	707
1900-1600	25	40%	1470	75	332	683
2000-1800	50	40%	1594	51	291	657
3200-2400	100	50%	1889	129	286	599
4400-2600	250	60%	2194	168	276	493
4500-2700	500	60%	2186	128	246	489
1.2. After Considering the PHES Discharge						
272: REF2020	1.8: REF2020	30%	921	6	254	736
600-500	1.8	30%	918	5	267	758
700-600	3	30%	918	5	258	738
800-600	6	30%	918	5	255	730
1800-1300	12	40%	903	3	215	632
1900-1600	25	40%	904	3	210	612
2000-1800	50	40%	893	3	207	600
3200-2400	100	50%	952	3	158	491
4400-2600	250	60%	868	3	116	325
4500-2700	500	60%	862	3	108	314
2. Double Penstock PHES After Considering the PHES Discharge						
272: REF2020	1.8: REF2020	30%	922	5	260	759
2200-1400	1.8: REF2020	50%	980	7	248	724
2600-1500	3	50%	980	7	241	699
2900-1500	6	50%	960	5	229	681
4100-1900	12	60%	952	4	198	563
4400-2000	25	60%	952	4	193	547
5700-2400	50	70%	935	3	160	440
7000-2900	100	80%	898	2	131	349
8200-3200	250	90%	871	1	95	229
9600-3600	500	100%	848	1	50	143

***Total of 8784 hours.**

[#] Based on historical 2009 data [231, 232].

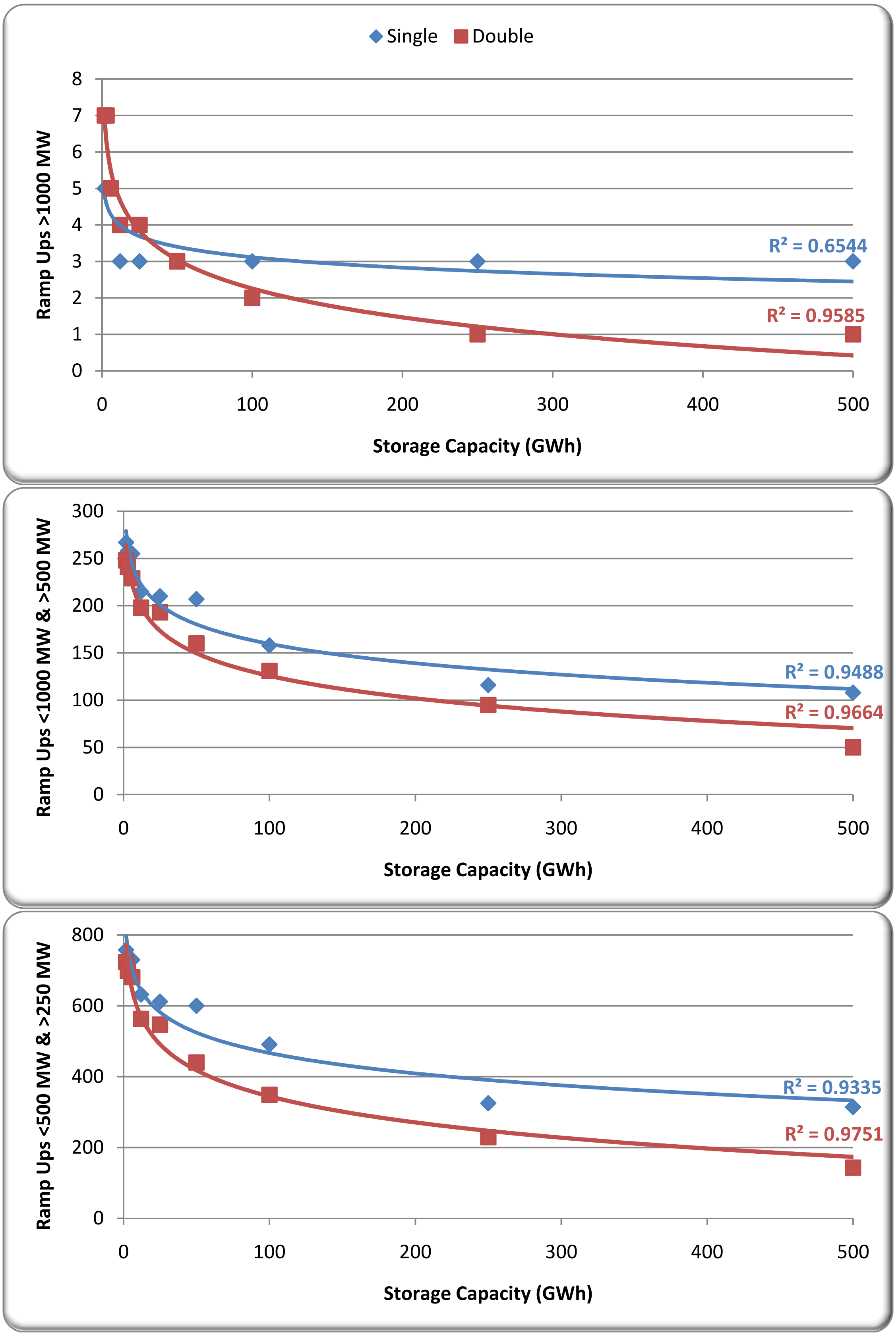

Figure 8-15: Scale and frequency of ramp-up demands placed on power plants for the MFWP identified at each storage capacity, when using either a single or a double penstock system: data provided in Table 8-15.

8.3.4. Summary

Overall, this section illustrates that large-scale PHES can enable higher wind penetrations on the Irish energy system, while also reducing the total energy required and the resulting CO_2 emissions. In addition, compared to their current operation, there are larger and more frequent ramping demands placed on power plants when the MFWP is achieved. However, as the storage capacity of PHES is increased, these ramping demands reduce and can even become less severe than those recorded for the year 2009. Finally, it was also evident in this section that the PHES pump and turbine capacities required to integrate wind power are not the same as each other. For both a single and double penstock operating strategy, it is evident that the pump capacity is related to the installed capacity of wind generation, while the turbine capacity is related to the install power plant capacity. In addition, a double PHES system can integrate larger wind penetrations than a single PHES, even at much smaller storage capacities. However, to do so a double PHES requires much larger pump and turbine capacities. Due to the higher capital costs associated with a double PHES, it is difficult to conclude which operating strategy is the most effective at integrating wind power. Therefore, the following section investigates if the extra flexibility from a double penstock system is worth the additional investment required.

8.4. The Economic Implications of PHES

The technical assessment of PHES for the integration of wind energy has revealed a number of complex relationships between the capacities required and the corresponding MFWPs feasible for a single and double PHES. Therefore, this section estimates the cost of constructing and operating the scenarios proposed in section 8.3 under a variety of different scenarios.

8.4.1. Costs for One PHES Capacity

The annual operating costs of the Irish energy system are made up of investment repayments, fuel costs, fixed O&M costs, variable O&M costs, as well as the exchange of electricity over the interconnector. A detailed description of the equations used within EnergyPLAN to calculate these costs are outlined on the EnergyPLAN website [178] and in Appendices E, F, and H. For these calculations, a range of assumptions have to be made in relation to investment costs, operation and maintenance costs, and lifetimes to analyse the costs of adding wind power and PHES to the 2020 Irish energy system. Those assumed for wind turbines and PHES are all displayed in Table 8-16, while the costs assumed for all the other components[10] on the Irish energy system are outlined in Appendices E and F. Although there are a wide range of costs reported for a single PHES [103, 167], no historical data was identified for the double PHES. Therefore, it was assumed that the double PHES would cost twice as much as a single PHES, considering the additional penstock, grid infrastructure, and components that would be required. For the initial cost assessment, fuel prices corresponding to an oil price of \$100/bbl for 2020 were assumed (see Table 8-17), along with an interest rate of 6% which has been used when assessing other energy infrastructure in Ireland [233]. Also, based on 2020 projections by the IEA, a CO_2 cost of \$50/t was also incorporated into the calculations [4].

Table 8-16: Costs assumed for PHES and wind turbines [103, 167, 234, 235].

Plant Type*	Pump-Turbine Investment (€M/MW)	Storage Investment (€M/GWh)	Fixed O&M (% of Investment)	Variable O&M (€/MWh)	Lifetime (Years)
Single PHES	0.50	7.5	1.5	1.5	40
Double PHES#	1.00	7.5	1.5	1.5	40
Wind turbines	1.14	0.0	1.8	0.0	20

***Transmission costs were not considered as the Irish TSO, EirGrid, has not specified which technologies are responsible for individual costs of transmission.**

#However, it was assumed that a double penstock would require more transmission than a single penstock, which is incorporated in the investment cost.

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[10] All other investment costs remain the same in the analyses completed in this study and hence they are not essential to the PHES analysis.

Table 8-17: Fuel prices assumed for 2020 in the analyses (€/GJ) [4, 236].

Crude Oil ($/bbl*)	Crude Oil	Fuel Oil	Gas Oil/ Diesel	Petrol/JP	Coal	Natural Gas	Biomass
100	13.60	9.60	17.00	18.00	3.19	8.16	7.00
150	20.40	14.40	25.50	27.00	4.23	12.49	7.00

***Assumed exchange rate of €1 = $1.282.**

Using these assumptions, the cost of a 2500 MW 25 GWh PHES on the 2020 Irish energy system while operating as both a single and a double penstock system was simulated for wind penetrations of 0% to 100% (0-30 TWh) of the electricity demand. As displayed in Figure 8-16, the results indicate that the PHES facility does not increase the wind penetration enough to warrant the initial investment required, with the reference scenario proving to be the most economical. In addition, the results suggest that the double penstock is not worth the additional investment required as it is more expensive than the single penstock operating strategy up to a wind penetration of 18 TWh (60%). However, this analysis was completed using only one PHES capacity and hence, the next section calculates the cost of integrating wind energy using the range of different PHES capacities identified earlier in section 8.3.2.

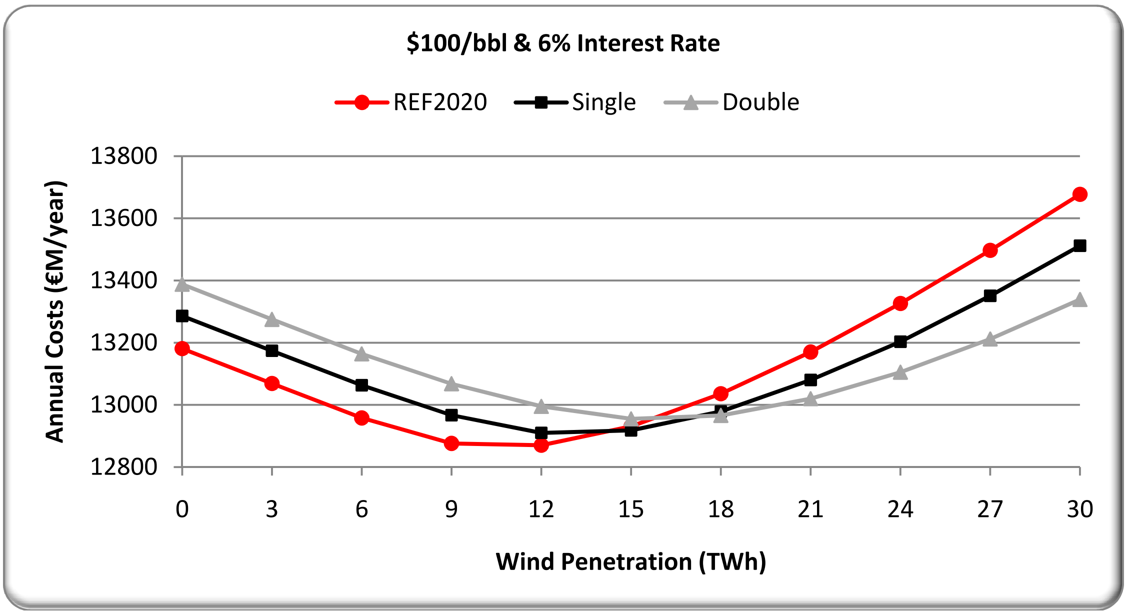


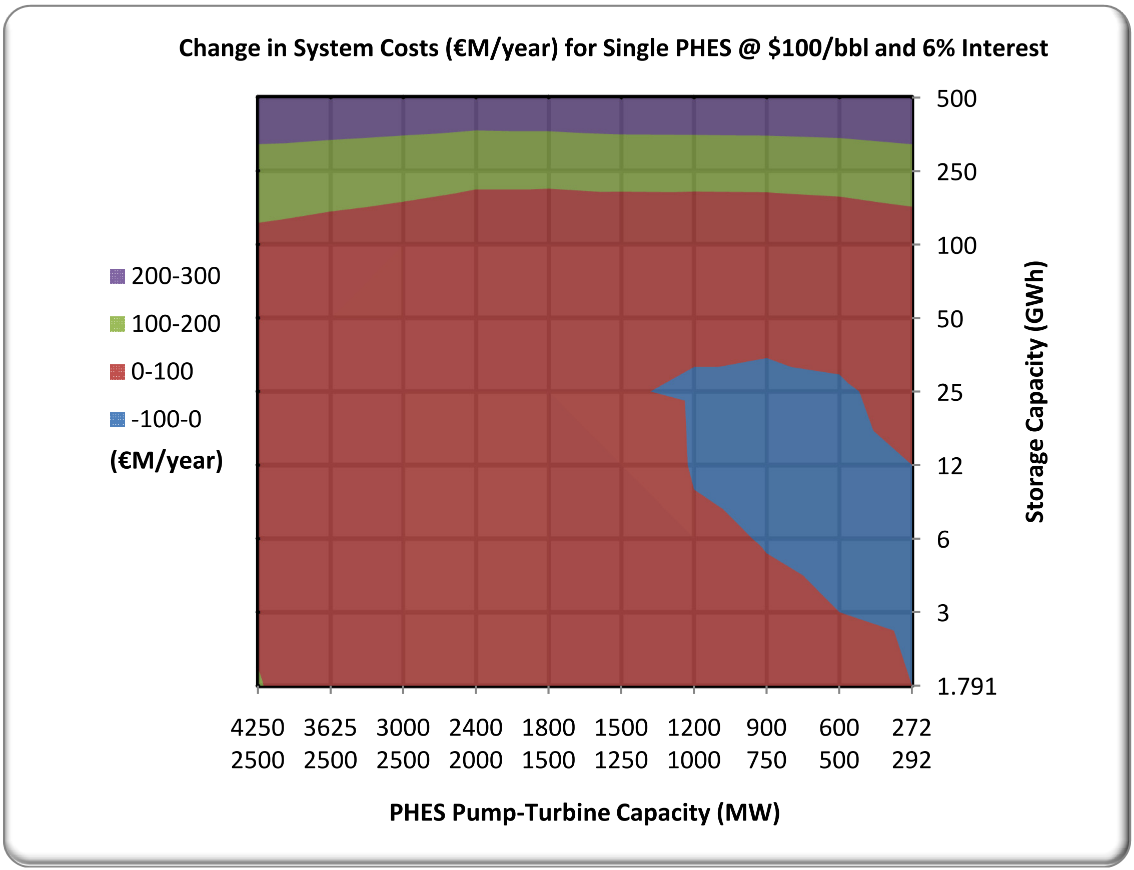
Figure 8-16: Cost of operating the Irish energy system in 2020 for the reference scenario, a 2500 MW / 25 GWh single PHES scenario, and a 2500 MW / 25 GWh double PHES scenario, for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand, assuming fuel prices based on an oil price of $100/bbl and an interest rate of 6%.

8.4.2. Costs for Various PHES Capacities

Based on the ratios identified between the pump and turbine capacities in section 8.3.2 above, a selection of pump-turbine combinations (which are outlined in Table 8-18) were chosen to assess the operating costs over a range of different PHES storage capacities. These pump-turbine capacities were simulated for all 9 storage capacities considered and once again in each simulation the wind penetration was varied from 0-100% in steps of 10% on the 2020 Irish energy system. Subsequently, the cheapest wind penetration was identified for each combination of the PHES capacities, which is illustrated in Figure 8-17 for a single PHES and in Figure 8-18 for a double PHES.

Table 8-18: Pump and turbine capacities assumed when evaluating the economic viability of a single and double PHES system for various storage capacities.

Single PHES			Double PHES		
Pump	**Turbine**	**Ratio** ($C_{Pump}/C_{Turbine}$)	**Pump**	**Turbine**	**Ratio** ($C_{Pump}/C_{Turbine}$)
272	292	Reference	272	292	Reference
600	500	1.2	642	292	2.2
900	750	1.2	1650	750	2.2
1200	1000	1.2	2750	1250	2.2
1500	1250	1.2	3850	1750	2.2
1800	1500	1.2	4950	2250	2.2
2400	2000	1.2	6050	2750	2.2
3000	2500	1.2	7150	3250	2.2
3625	2500	1.45	8250	3750	2.2
4250	2500	1.7			



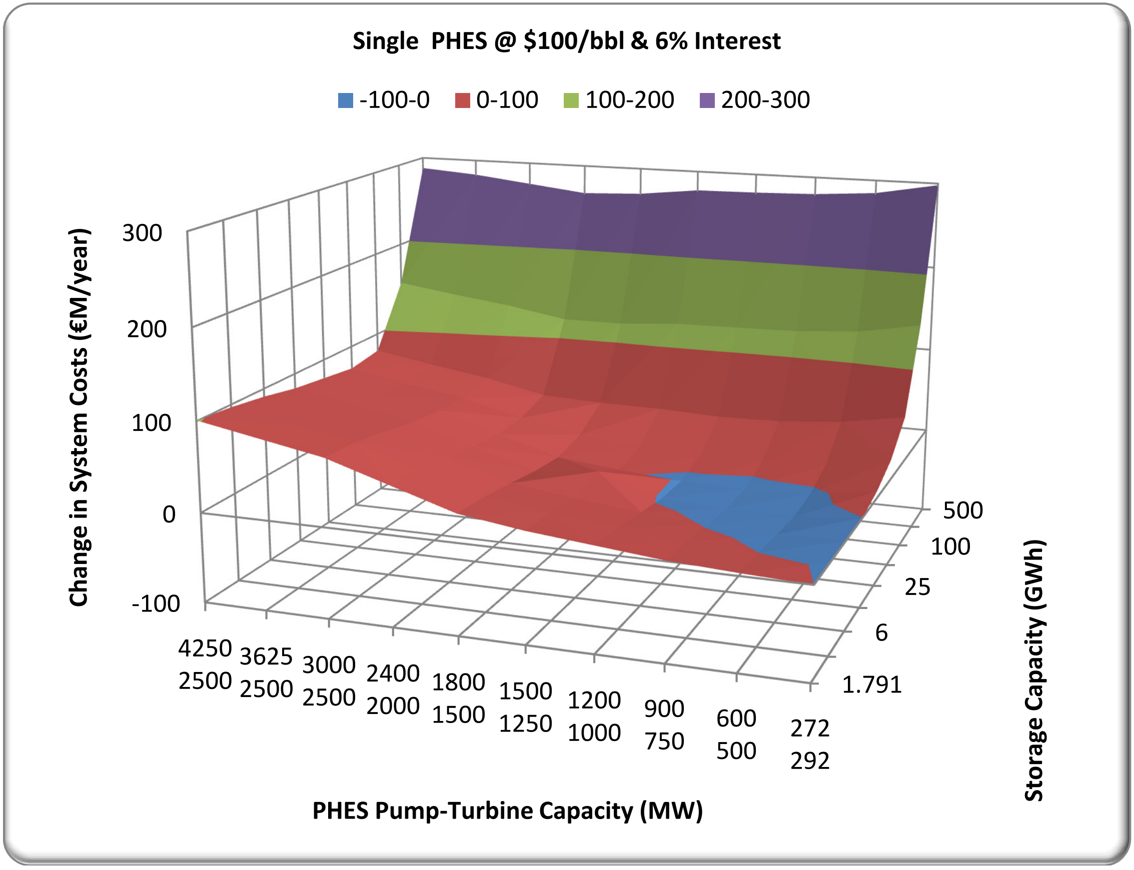
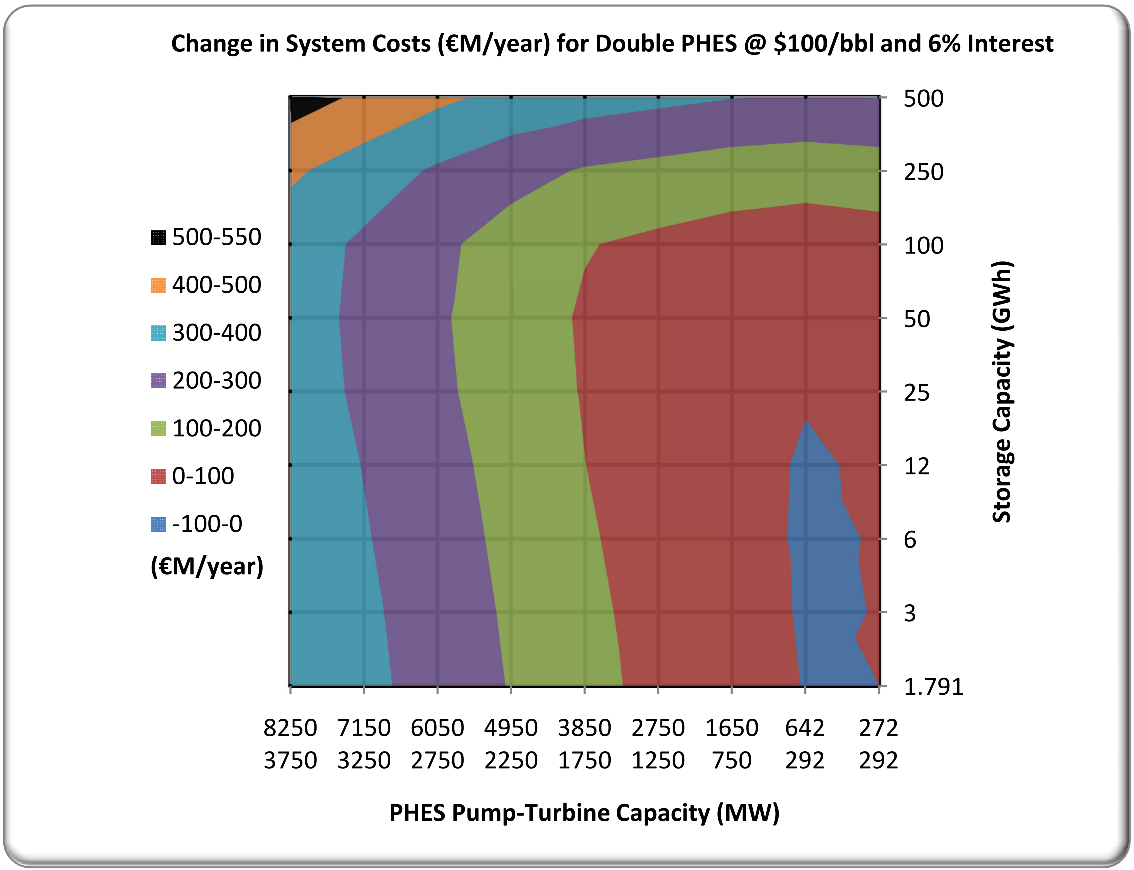


Figure 8-17: Change in energy system costs when various single PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and using an interest rate of 6%.



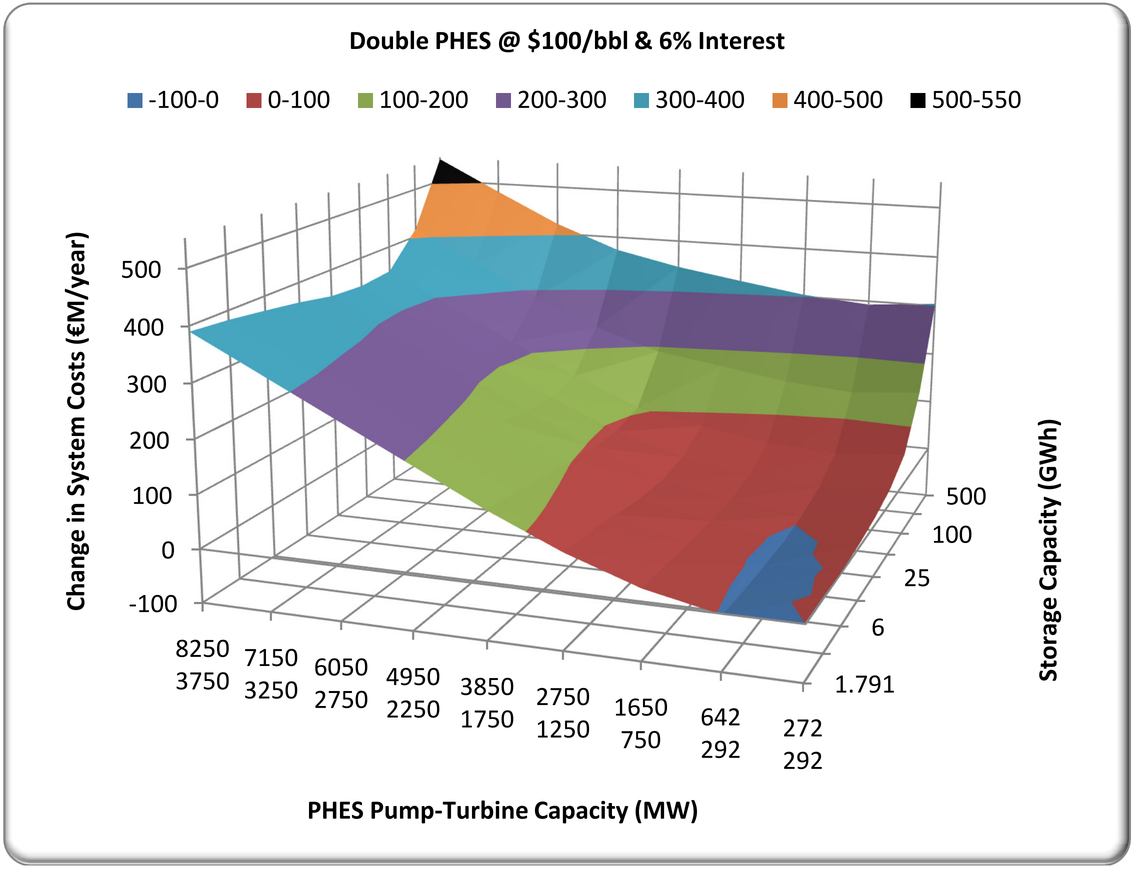


Figure 8-18: Change in energy system costs when various double PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and using an interest rate of 6%.

From the results, it is evident that the sizing of a PHES has dramatic implications on the overall operating costs of the system. Contrary to the results identified in Figure 8-16, the results in both Figure 8-17 and Figure 8-18 indicate that PHES could reduce the overall operating costs of the Irish energy system. However, the scale of these cost reductions are quite small and as such, Figure 8-19 indicates that the cheapest scenario for both a single and a double PHES only reduced the operating costs by approximately €9M/year and €3M/year respectively. Hence, there were no significant economical gains from the addition of PHES. Finally, it is also clear from Figure 8-17 and Figure 8-18 that the total operating costs of the system can be increased dramatically if the PHES capacities are not optimised for the system in question, especially for a double PHES. Therefore, it can be concluded that wind and PHES are capable of reducing the operating costs of the Irish energy system, but under 2020 cost predictions and considering the scale of these reductions along with the risk of increasing the operating costs, PHES is not yet an attractive alternative. Finally, to further investigate the validity of these conclusions, a sensitivity analysis was completed on a range of key parameters.

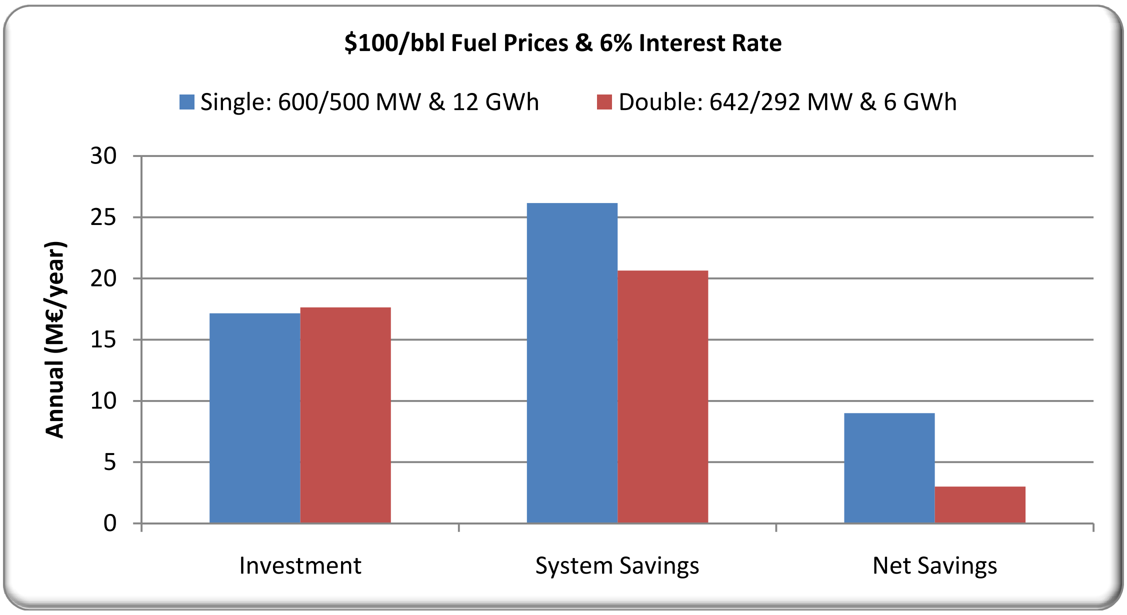


Figure 8-19: The investment and savings for the single and double PHES capacities which provided the largest reduction in system costs, when analysed using fuel prices corresponding to $<u>100</u>/bbl and an interest rate of <u>6%</u>.

8.4.3. Sensitivity Analysis

The key parameters assessed in this sensitivity analysis include changes in the wind energy produced, a lower interest rate on investments, an increase in fuel prices, and a lower investment cost for the double PHES facility.

Wind Generation

There are two aspects to wind which were analysed in this sensitivity analysis: hourly distribution and total annual generation. The hourly wind distribution data in this study was based on historical data recorded in Ireland from the year 2009 [22]. To ensure that this particular wind distribution was not an artefact leading to erroneous conclusions in this study, the results were repeated based on hourly wind data recorded in Ireland from the year 2007. Using this data, there was no significant change in the trends identified in this study.

Also, changes in the total annual electricity generation from wind were assessed. As the installed wind capacity in Ireland has increased by an average of 35% each year between 1999 and 2009, it is difficult to conclude what variation occurs in total wind production from one year to the next using historical data. However, by analysing Danish wind data from 2003 to 2008[11] [237], it is evident that the total wind power produced from the same capacity of wind turbines can vary by up to +/-20% from one year to the next. Therefore, this has been used as a proxy in this study. The annual operating costs were recalculated based on an expected wind production which produced an actual wind production of +/-20% for three different scenarios: the REF2020 scenario with no additional PHES, the REF2020 system with a 2500 MW 25 GWh single PHES facility, and finally the reference REF2020 scenario with a 2500 MW 25 GWh double PHES facility. As expected, Figure 8-20 indicates that a 20% increase in the expected wind production will reduce the annual operating costs for each scenario while a 20% decrease in wind production will inflate costs. Due to the insignificant role of additional PHES below a wind penetration of 9 TWh (30%), the change in annual costs is the same for all three scenarios until this point. Afterwards, the reference scenario shows the least variation in costs, followed by the single PHES, and the double PHES shows the largest deviation in annual operating costs due to a change in annual wind production. However, for all three scenarios the increase in costs for a +20% wind production is very similar to the corresponding decrease in costs due to a -20% production. In fact, in all scenarios simulated the increase in annual operating costs was never greater than the corresponding reduction in annual operating costs. This indicates that over the 40 year lifetime of a PHES facility, the additional costs that occur during years of low annual wind production should be cancelled out by years of savings in years of high annual wind production.

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[11] The installed wind capacity in Denmark was practically the same from 2003 to 2008, as the maximum and minimum capacity recorded for each of these years were 3163 MW and 3116 MW respectively.

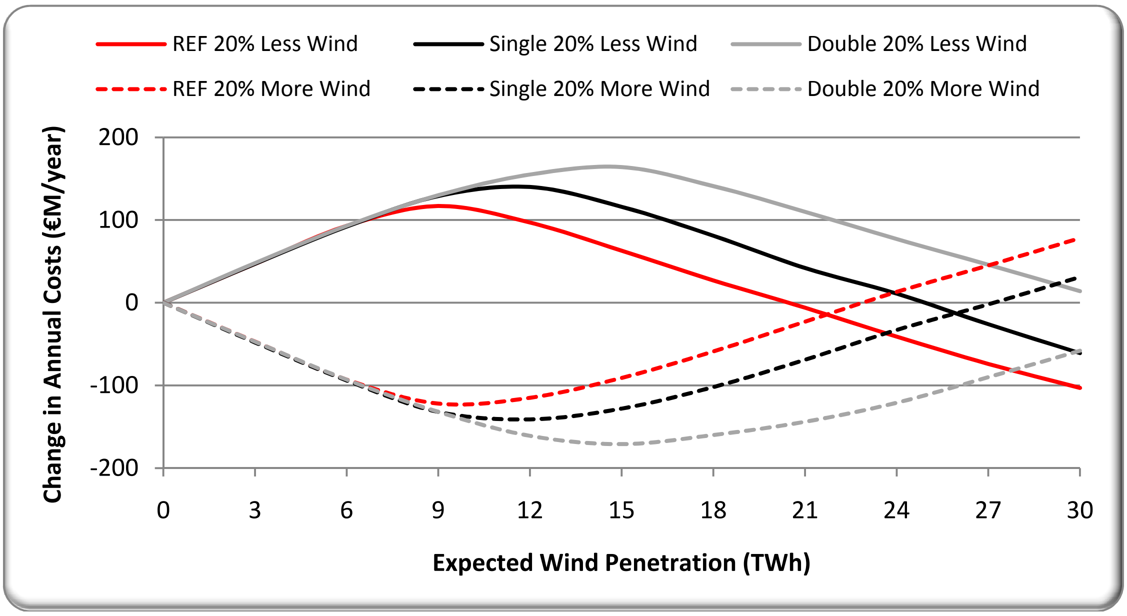


Figure 8-20: Change in annual costs (using a 6% interest rate and $100/bbl fuel prices) for an expected wind production of 0-30 TWh (0-100%) for the 2020 reference scenario on its own, with a single 2500 MW 25 GWh PHES, and with a double 2500 MW 25 GWh PHES.

3% Interest Rate

The economic calculations in this study were based on an interest rate of 6%, but it could be argued that a 3% interest rate is more applicable due to the 40 year lifetime of PHES and the societal gains from utilising more wind energy. Therefore, the costs were recalculated using a 3% interest rate instead, which are outlined in Figure 8-21 for the 2500 MW 25 GWh facility. As the initial investment costs for wind power and PHES are relatively high, a comparison between Figure 8-16 and Figure 8-21 indicates that a 3% interest would significantly improve the economical feasibility of a wind-PHES system in Ireland. This is even more apparent for the double penstock PHES, which could enable a wind penetration of approximately 60% using a 3% interest rate at a similar cost to the REF2020 scenario, which only has a wind penetration of 40%. Based on the trend identified here, the costs were also recalculated for the range of PHES capacities discussed in section 8.4.2 and displayed in Table 8-18. As outlined in Figure 8-22 to Figure 8-24, with an interest rate of 3% the optimum capacities for both a single and double penstock PHES could reduce the overall operating costs of the Irish energy system by approximately €25M/year and €35M/year respectively in 2020. In addition, the scale of PHES which provides the most economical scenario has increased significantly to 1800/1500 MW and 50 GWh for the single PHES and to 2750/1250 MW and 50 GWh for the double PHES.

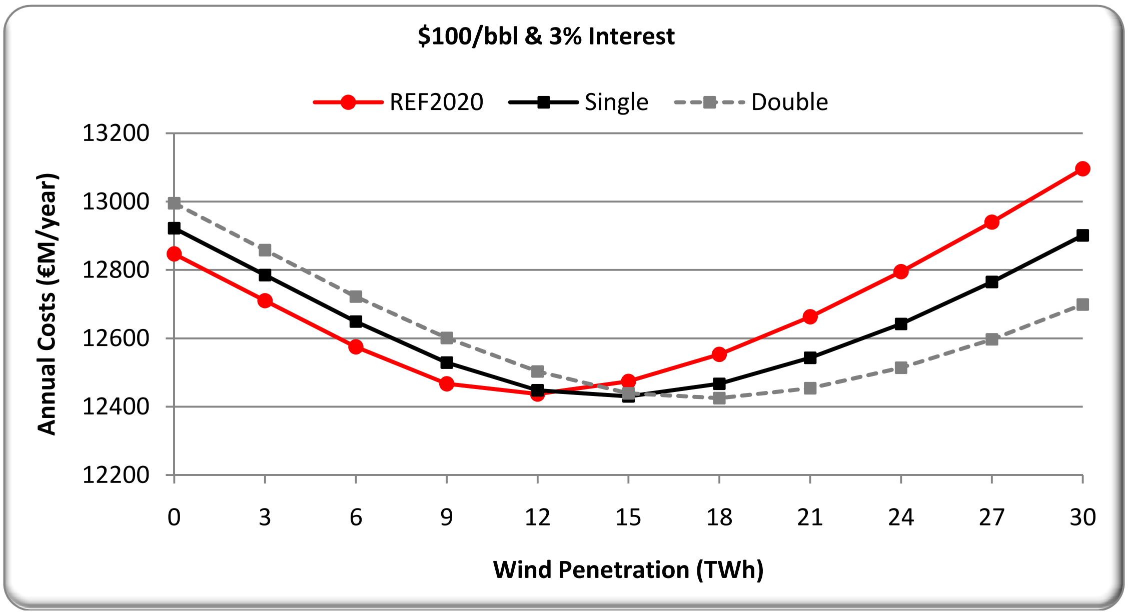


Figure 8-21: Cost of Irish energy system in 2020 for the reference scenario, a 2500 MW / 25 GWh single PHES scenario, and a 2500 MW / 25 GWh double PHES scenario, for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand assuming fuel prices based on an oil price of $100/bbl and an interest rate of 3%.

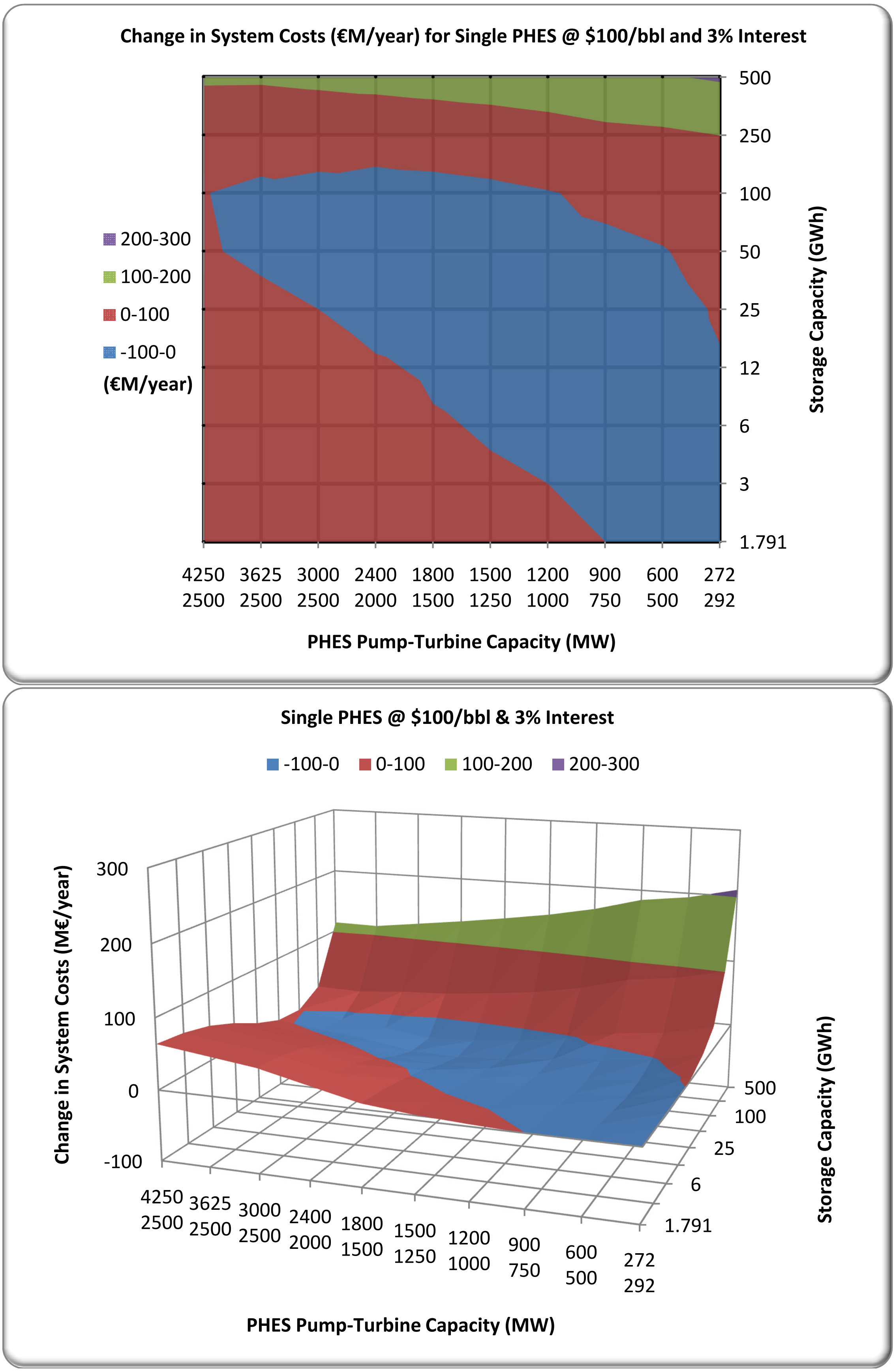
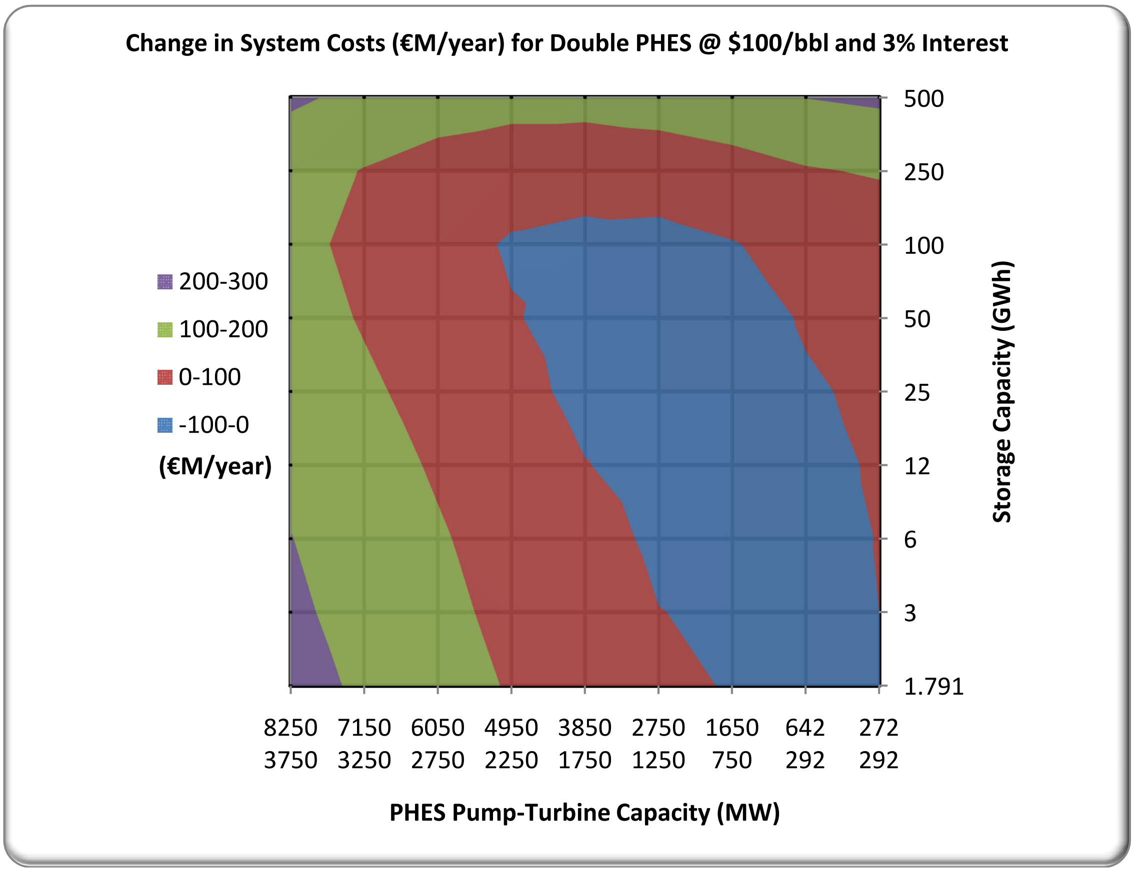


Figure 8-22: Change in energy system costs when various single PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and using an interest rate of 3%.



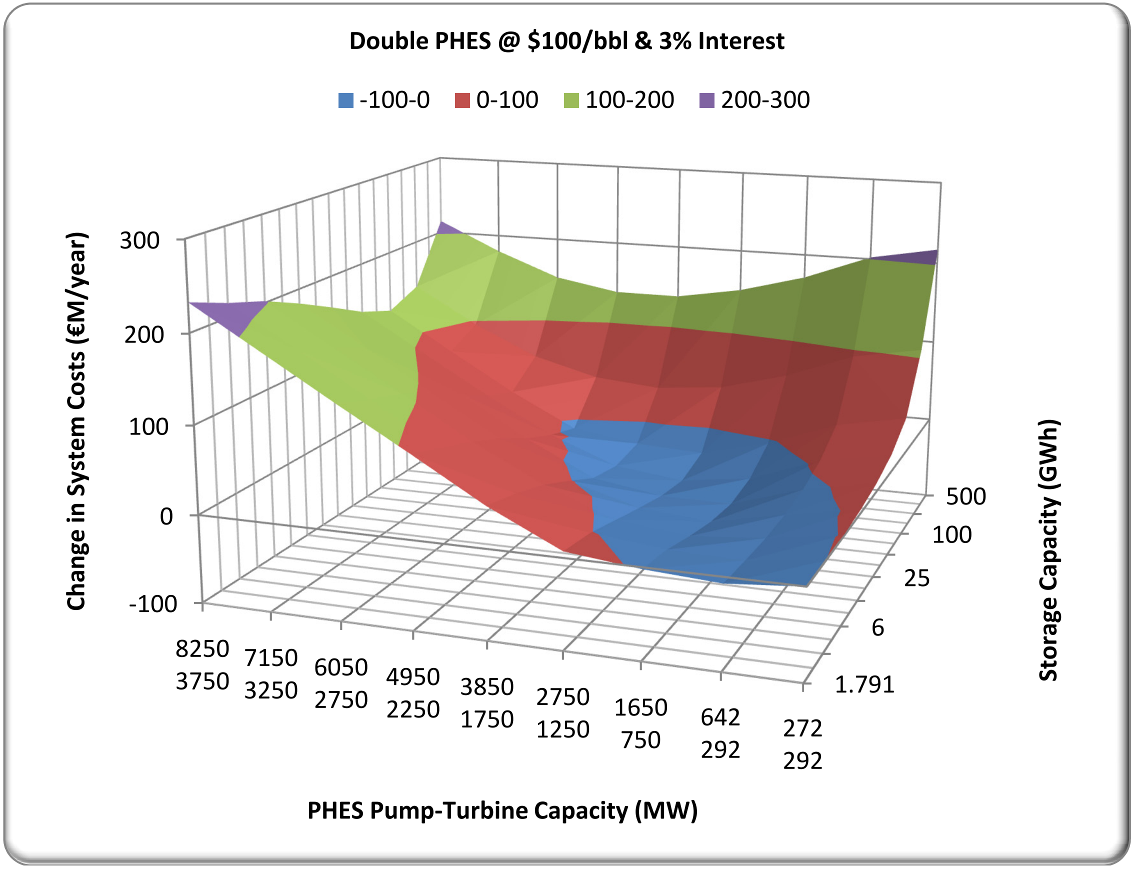


Figure 8-23: Change in energy system costs when various double PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and using an interest rate of 3%.

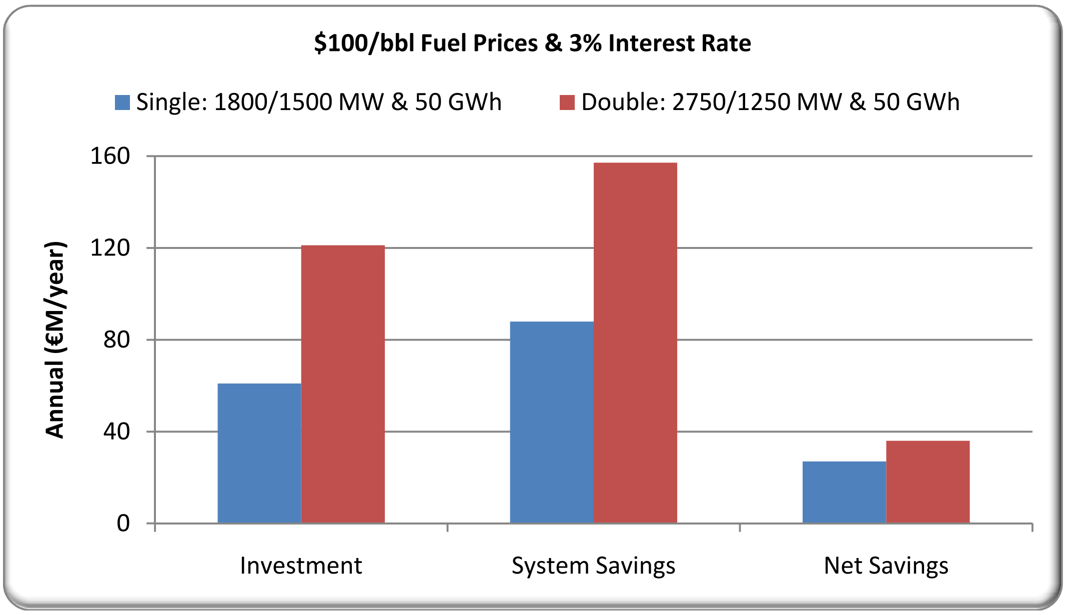


Figure 8-24: The investment and savings for the single and double PHES capacities which provided the largest reduction in system costs, when fuel prices correspond to $<u>100</u>/bbl and for an interest rate of <u>3%</u>.

$150/bbl Fuel Prices

By 2020, global fuel prices are expected to reach an oil price equivalent of $100/bbl [4]. However, as already discussed in section 2.1 of this thesis, fuel prices can be extremely unpredictable due to many political and supply concerns [6]. To demonstrate the consequences of a fuel price increase, the results were recalculated based on an oil price of $150/bbl and an interest rate of 6%, with corresponding prices for other fuels outlined in Table 8-17. The results from the analysis were very similar to those observed for an interest rate of 3% and fuel prices corresponding to $100/bbl of oil. Once again a 2500 MW and 25 GWh double penstock PHES could enable a 60% wind penetration at a similar cost to a 40% wind penetration on the 2020 reference scenario, similar to the results presented for a fuel price of $100/bbl and a 3% interest, which is evident from Figure 8-25. Also, the optimum capacities for the single and double PHES were the same when using $150/bbl and 6% as those identified when using $100/bbl and 3%, which from Figure 8-26 was 1800/1500 MW and 50 GWh for the single PHES and from Figure 8-27 was 2750/1250 MW and 50 GWh for the double PHES. Once again, the reductions in operating costs in 2020 were €25M/year and €35M/year for the single and double respectively. The only key difference between the results was the scale of initial investments required. At a 3% interest rate and $100/bbl the initial investment for the single and double PHES were €60M/year and €120M/year respectively. As illustrated in Figure 8-28, at 6% and $150/bbl the investment costs were €85M/year and €170M/year, thus increasing the risk associated with constructing PHES.

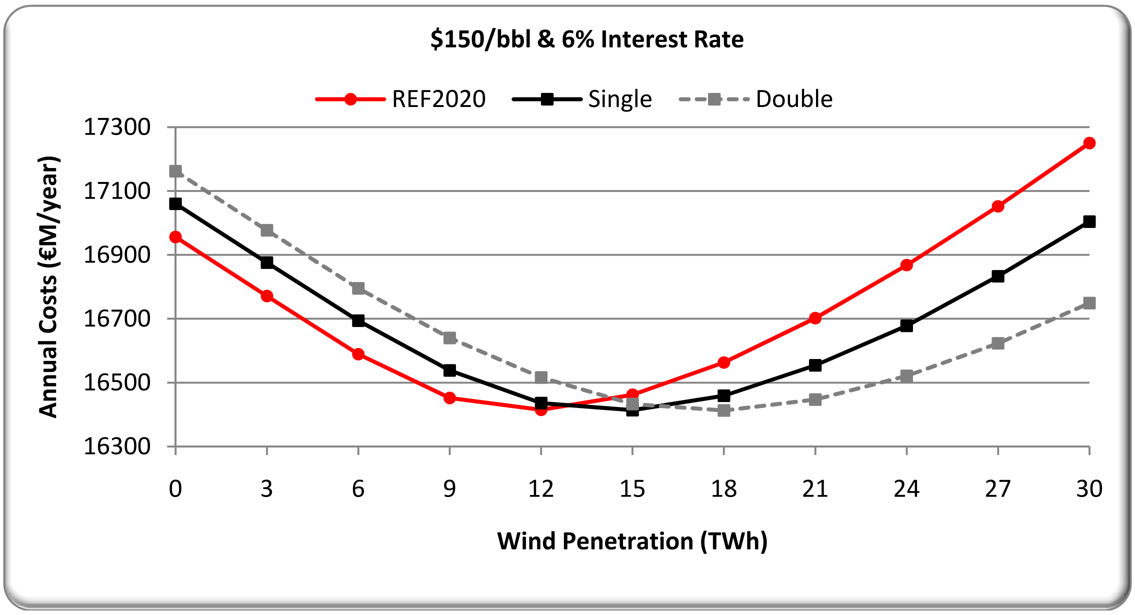
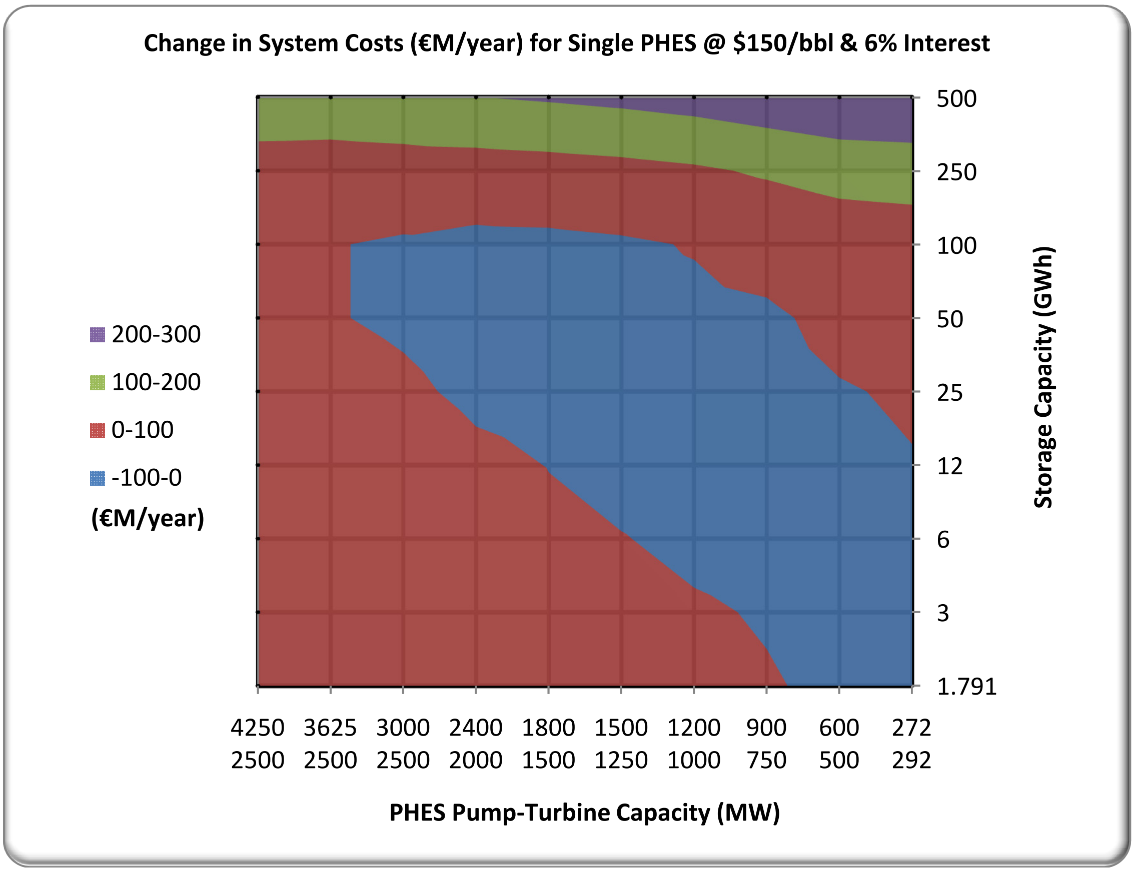


Figure 8-25: Cost of Irish energy system in 2020 for the reference scenario, a 2500 MW 25 GWh single PHES scenario, and a 2500 MW 25 GWh double PHES scenario, for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand assuming fuel prices based on an oil price of $100/bbl.



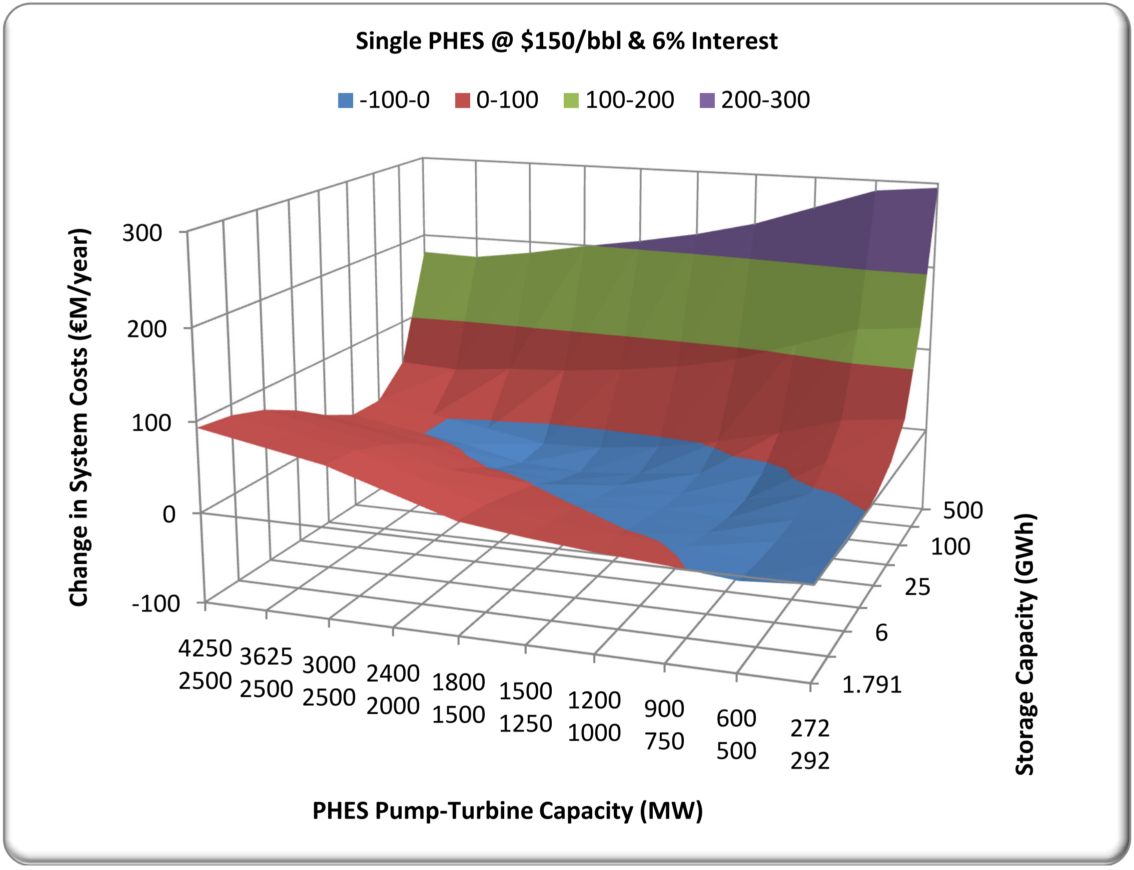


Figure 8-26: Change in energy system costs when various single PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $150/bbl and using an interest rate of 6%.

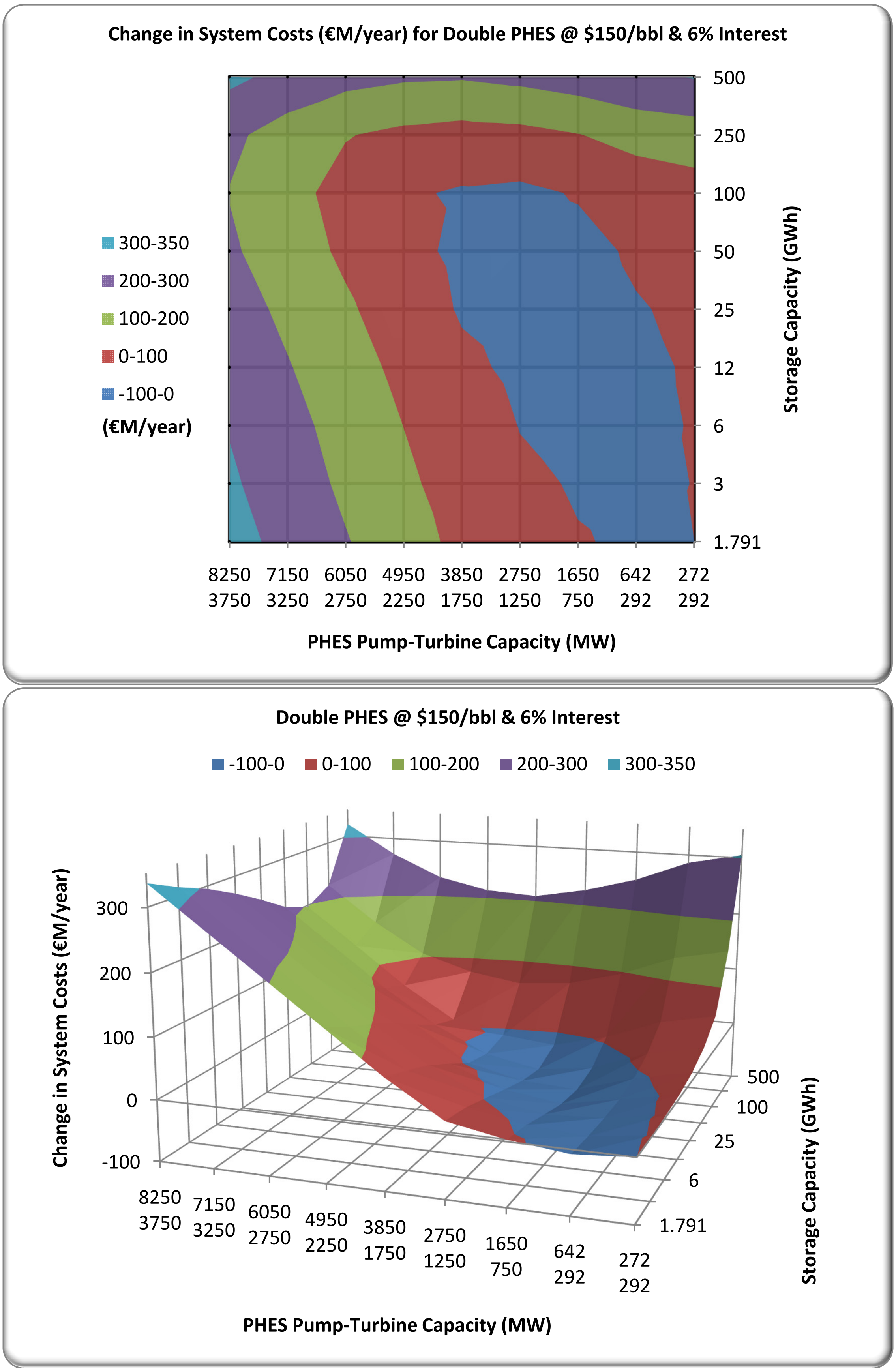


Figure 8-27: Change in energy system costs when various double PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $150/bbl and using an interest rate of 6%.

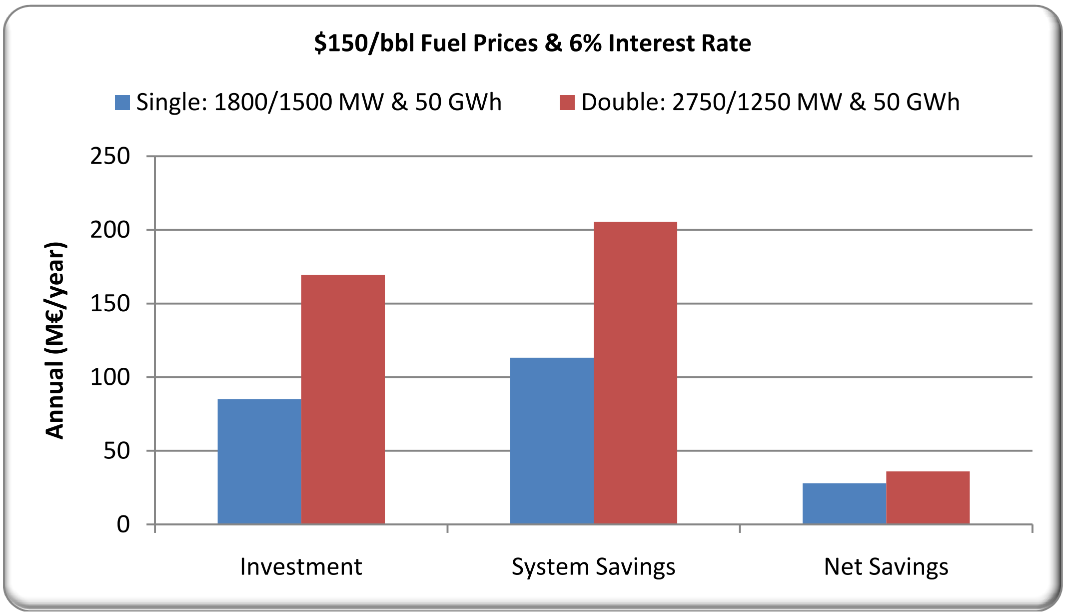


Figure 8-28: The investment and savings for the single and double PHES capacities which provided the largest reduction in system costs, when fuel prices correspond to $<u>150</u>/bbl and using an interest rate of <u>6%</u>.

Double PHES Investment Costs

To complete this economic assessment, it was assumed that the double penstock PHES (€1M/MW) would cost twice as much to construct compared to the single PHES (€0.5M/MW). This assumption was based on the additional penstock, transmission, housing, and communication systems that would be necessary in a double PHES. However, no evidence was found to support this assumption and therefore the results were analysed for a double PHES investment cost of €0.75M/MW also. For the 2500 MW 25 GWh facility, the results in Figure 8-29 indicate that this lower investment cost for a double PHES does not alter the economic trend experienced for increasing penetrations of wind energy, but as expected it does improve the overall economic viability of a double PHES.

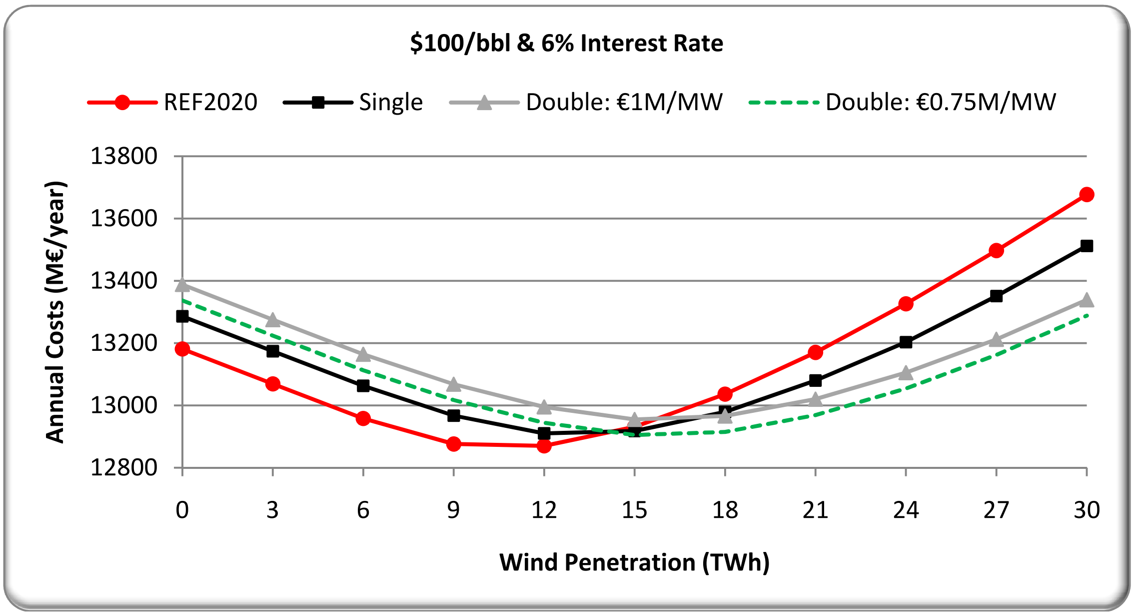
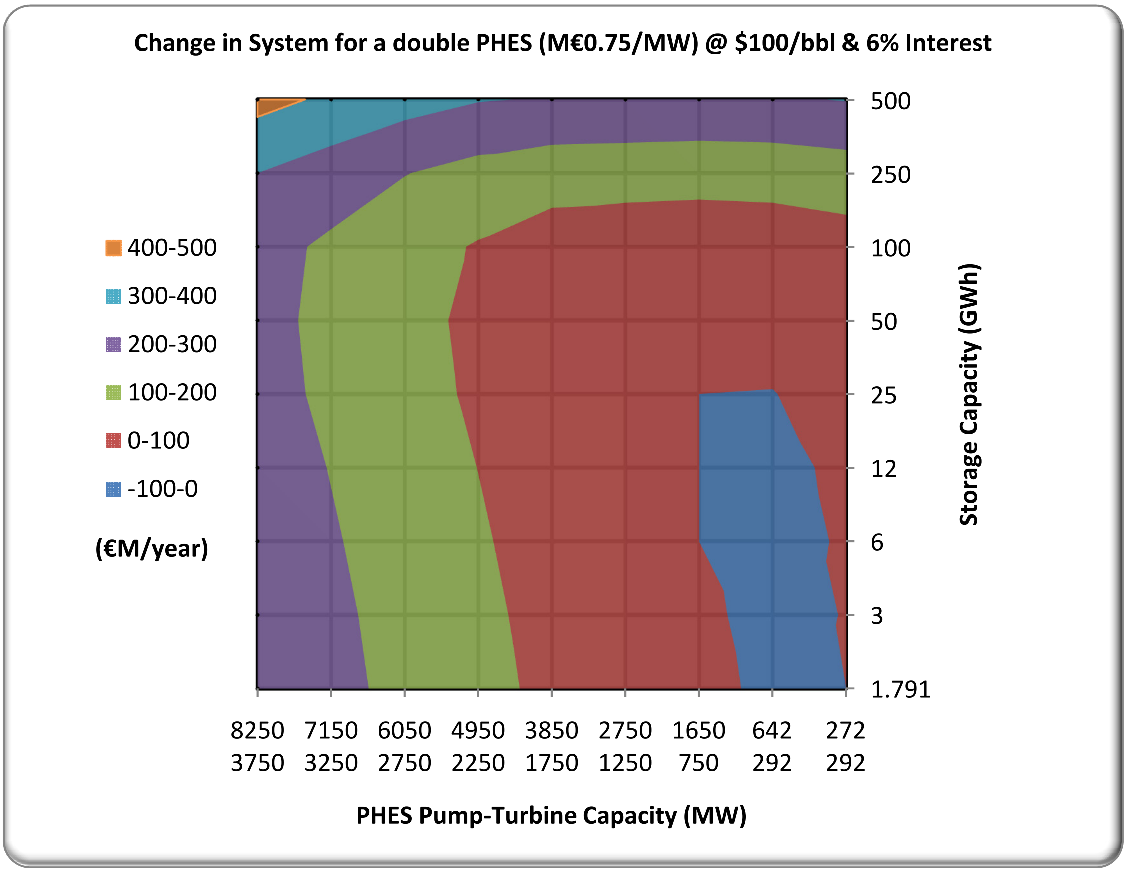


Figure 8-29: Annual costs for the Irish energy system in 2020 for the reference scenario, a 2500 MW 25 GWh single PHES scenario, and two 2500 MW 25 GWh double PHES scenarios (each with different investment costs), for wind penetrations of 0% to 100% (0-30 TWh) of electricity demand assuming fuel prices based on an oil price of $100/bbl and using an interest rate of 6%.

In line with this, Figure 8-30 indicates that if a double PHES can be constructed at €0.75M/MW, then it would become economically viable over a larger range of capacities than those reported in section 8.4.2. However, the results do not change as dramatically as those already displayed for a lower interest rate of 3% (Figure 8-23) and for higher fuel prices corresponding to $150/bbl (Figure 8-27). To conclude, it is important that the uncertainty surrounding the double PHES construction costs is considered when assessing the results in this study, but the implications of these seem less severe than those reported for the interest rate and the fuel prices.



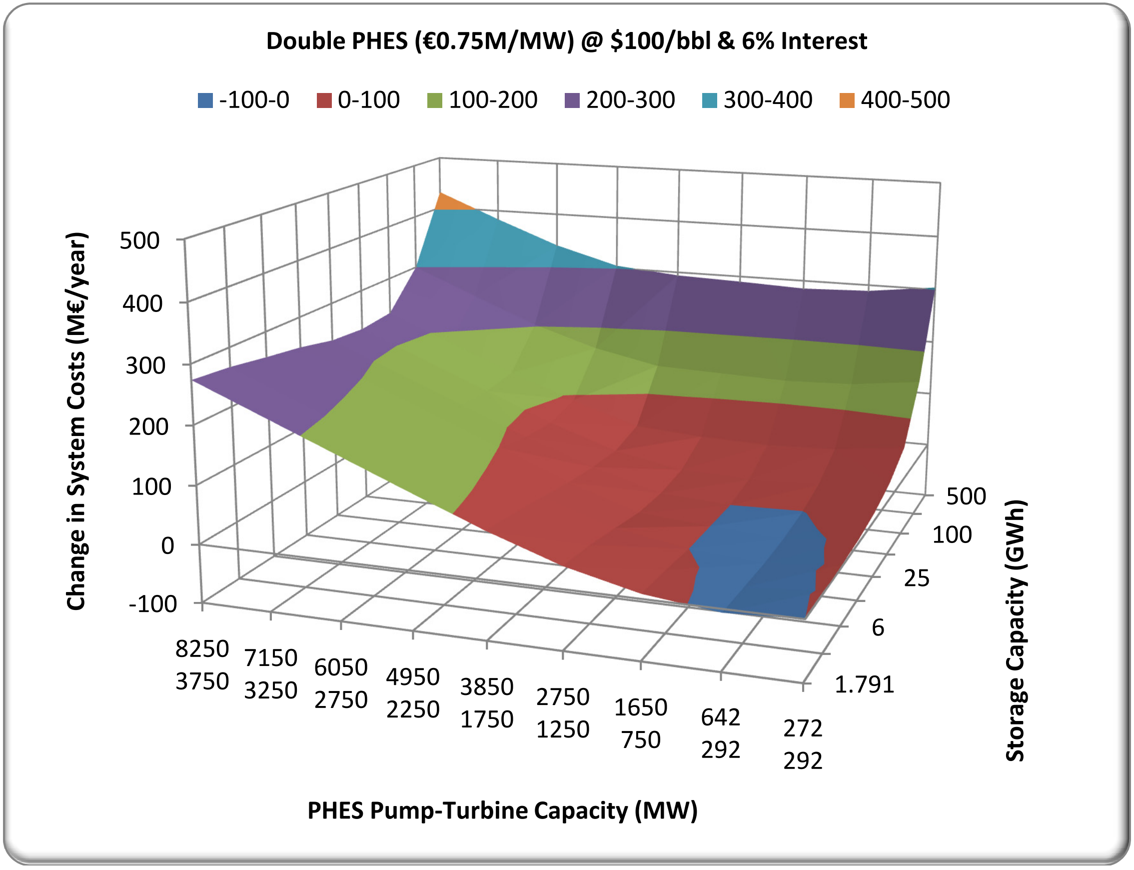


Figure 8-30: Change in energy system costs when various €0.75M/MW double PHES capacities from Table 8-18 are added to the 2020 Irish energy system compared to the reference, assuming fuel prices corresponding to $100/bbl and an interest rate of 6%.

To recap briefly, this sensitivity analysis has verified that the wind distribution does not alter the results significantly and although any reduction in the total annual electricity generation from wind would increase the operating costs, this is equivalent to the savings identified due to a corresponding increase in annual wind generation. Also, the economic viability of PHES in conjunction with wind power is significantly enhanced by using a 3% interest rate to assess its economic viability or if global fuel prices reach $150/bbl. Under both of these scenarios and based on the costs assumed in Table 8-16, a double PHES system would enable a 60% wind penetration on the Irish energy system at the same cost as a 40% wind penetration on the reference scenario. In addition, the uncertainty surrounding the additional investment required for a double penstock PHES is important to consider when assessing the results in this section, although the sensitivity analysis indicates that the interest rate and fuel price assumptions have a greater impact on the results. Finally, before concluding that PHES is a suitable alternative for Ireland, it must also be compared to alternative technologies that could also be utilised.

8.4.4. Comparing PHES to Alternatives

As outlined in section 8.4.2, for $100/bbl and a 6% interest rate the cheapest single and double penstock capacities both corresponded to an investment of approximately €17M/year. Therefore, the results from the PHES analysis were compared to the same investment in two other technologies: domestic heat pumps (HP) and the creation of a district heating network utilising a new combined heat and power (CHP) plant. The capacities, costs, and investments required for these alternatives are outlined below in Table 8-19.

Table 8-19: Capacity and cost assumptions for the alternative scenarios considered on the 2020 Irish energy system.

Alternative	Size	Unit	Costs Per Unit (€M)	Life-time (years)	Fixed O&M (% of investment)	Total Costs (€M/year)	Ref.
Heat Pumps	**135**	**MW$_e$**	**1.2**	**15**	**0.6**	**17.5**	**[238]**
CHP						**17.6**	
Convert PP	125	MW$_e$	0.80	30	2.00	9.3	[167, 238]
Thermal Storage	1	GWh	1.34	20	1.00	0.13	[225]
Peak Boilers	125	MW$_{th}$	0.15	20	3.00	2.2	[238]
Network	15	km	2.00	40	1.00	2.3	[239]
Central Heating	1500	Conversions	0.0054	40	0.90	0.6	[238]
Heat Exchangers	15000	Customers	0.00275	40	0.90	3.11	[238]
Single PHES						**17.1**	
Pump	330	MW$_e$	0.25	40	1.5	6.7	[103, 167]
Turbine	210	MW$_e$	0.25	40	1.5	4.2	[103, 167]
Storage	10.2	GWh	7.50	40	1.5	6.2	[95]
Double PHES						**17.6**	
Pump	370	MW$_e$	0.50	40	1.5	15.07	[103, 167]
Turbine	0$^{\#}$	MW$_e$	0.50	40	1.5	0.00	[103, 167]
Storage	4.2	GWh	7.50	40	1.5	2.57	[95]

***Equates to 10% of total customers.**
$^{\#}$Capacity required is already installed in Ireland.

As displayed in Figure 8-31, under predicted 2020 fuel prices of $100/bbl and a 6% interest rate, an investment of €17M/year in domestic heat pumps provides the same savings for the Irish energy system as the optimum single PHES unit. The CHP alternative provided larger savings than the optimum double penstock PHES, but it was not as cost-effective as the optimum single PHES for 2020. However, it should be stressed that the PHES capacities have been optimised in this study, while the CHP capacities are just estimates based on the heating demands that had to be met and predicted costs [239]. Again, the sensitivity analysis discussed above was repeated on these alternatives. As outlined in Figure 8-31, an increase in fuel prices to $150/bbl or a reduced interest rate of 3% will improve the savings associated with all four alternatives. Although the single PHES is the most economical alternative when this occurs, it is the double PHES which is the most sensitive to changes in fuel prices and interest rates. Finally, each of the scenarios were analysed for a 20% reduction and increase of total annual wind energy generation. As already outlined in section 8.4.3, PHES is very sensitive to changes in the total annual wind generation, which is evident once again in Figure 8-31. In contrast, the cost savings related to the HP and CHP scenarios are practically the same for the reference as those calculated for a +/-20% change of annual wind generation. Consequently, the results indicate that even if optimum capacities of PHES are identified, there are alternatives that are as cost effective under predicted 2020 conditions and which are less sensitive to changes in fuel prices, interest rates, and annual wind production.

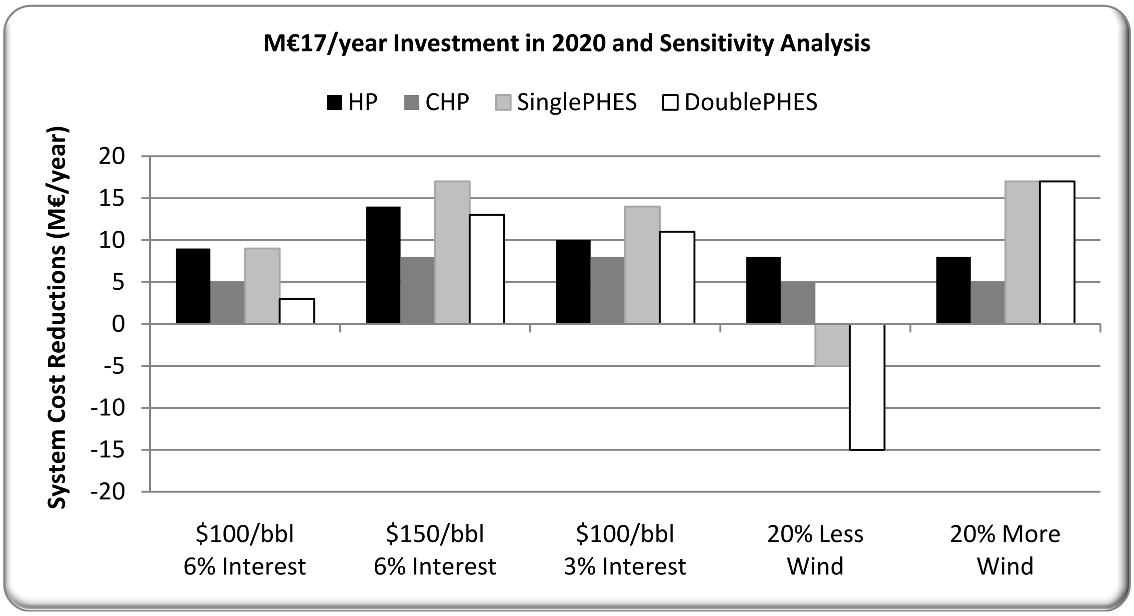


Figure 8-31: Annual system cost reductions compared to reference when approximately €17M/year is invested in domestic heat pumps (HP), a CHP system with district heating (CHP), as well as the optimum single and double PHES facilities from section 8.4.2. All capacity and cost assumptions are outlined in Table 8-19 and a wind penetration of 40% was used as it was the most economical for each alternative.

Nonetheless, considering Ireland's significant dependence on imported fuel (see Figure 4-4), it is not only important to consider the economic implications of energy alternatives, but also the affect which they have on Ireland's energy consumption. Displayed in Figure 8-32 are the changes in a number of key energy parameters when each of the alternatives proposed are introduced to the 2020 Irish energy system. From these results it is evident that PHES improves Ireland's security of supply by more than HP or CHP. To do this, PHES reduces CEEP by enabling the integration of more wind power and thus correspondingly reduces the PES, fossil fuel demand (FFD), and CO_2 emissions. Although HP reduced the costs of operating the Irish energy system more than PHES, they do so by reducing the consumption of fossil fuels instead of increasing the use of wind energy (i.e. insignificant reduction in CEEP). Therefore, it could be argued that the additional cost of PHES is worth the larger reductions in FFD, due to the socio-economic benefits for Ireland such as increased security of supply and less CO_2 emissions. These benefits were considered in this thesis by using a predicted CO_2 cost of $50/t, but since this is a global guideline [4] and Ireland is the 12th largest net importer of energy in the world (see Figure 4-7), this assumption may not be sufficient to reflect these benefits. In summary, PHES may not be the most economical alternative for 2020, but its additional socio-economic benefits could be worth the additional cost.

Finally, this analysis reflects two key broader concerns for Ireland: firstly, energy alternatives need to be evaluated in more detail while also considering the entire energy system and secondly, developing Irish specific energy planning costs and indices for evaluating these alternatives, especially in relation to socio-economic benefits, should be determined so optimum alternatives can be identified. In addition, it is essential that the initial HP and CHP analyses presented in this thesis are expanded based on the potential cost reductions identified as the optimum solution could in fact contain a mixture of all the technologies assessed here.

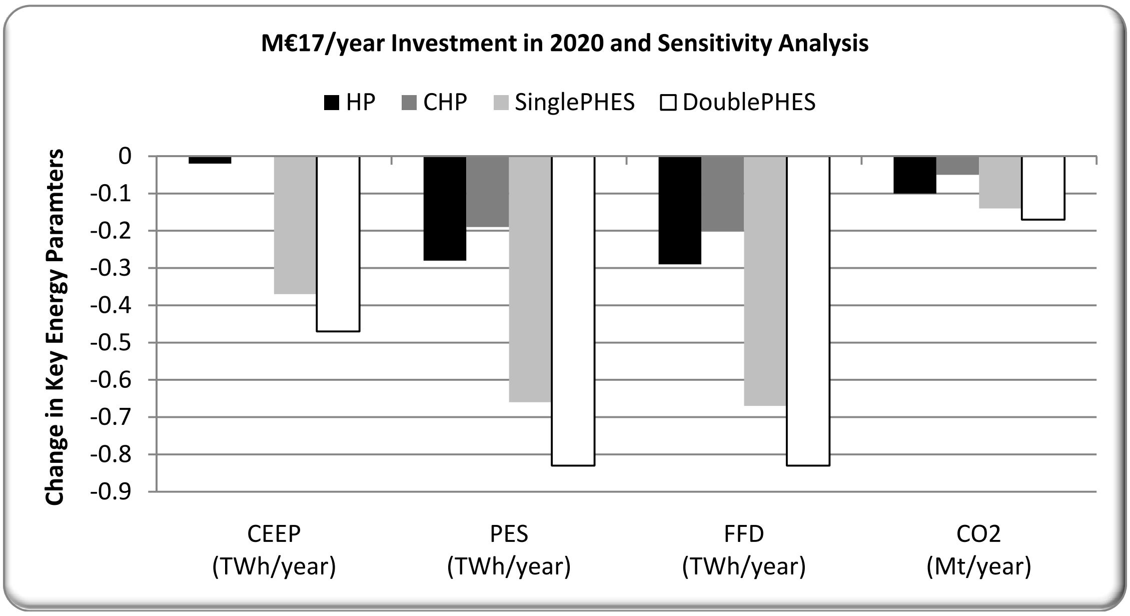


Figure 8-32: Change in key energy parameters compared to reference when approximately €17M/year is invested in domestic heat pumps (HP), a CHP system with district heating (CHP), as well as the optimum single and double PHES facilities from section 8.4.2. All capacity and cost assumptions are outlined in Table 8-19 and a wind penetration of 40% was used as it was the most economical for each alternative.

8.5. Conclusions

To conclude, this chapter has outlined that wind power and PHES can be used together to reduce the operating costs of the Irish energy system. However, under the conservative assumption that societal benefits are accounted for with a predicted CO_2 price of \$50/t, the savings calculated are too small based on a conventional 6% interest rate and the predicted fuel prices for 2020 to warrant the initial investment in PHES, especially as it could also increase the operating costs. However, if the interest rate for assessing PHES is reduced to 3% to reflect its lifetime of 40 years and the socio-economic benefits of additional wind, then PHES can enable up to 20% additional wind in Ireland without increasing the annual operating costs of the energy system. Equally, if global fuel prices increase to a level which reflects \$150/bbl, then the same outcome will occur.

More specifically in relation to PHES, the analysis identified a divergence between the pump and turbine capacities required for a PHES when used to integrate increasing amounts of wind power. As wind penetrations increase the pumping capacity required also increases so the PHES can soak up excessive wind production, but the turbine capacity doesn’t increase as quickly because the power plant production which it is replacing remains the same. The slight increase in turbine capacity required is primarily related to the additional energy available in the PHES due to the increased pumping capacity. Finally, a single penstock and double penstock operating strategy have been analysed throughout this study to assess if the additional capacity required for a double penstock system is offset by the additional wind penetrations feasible. The results suggest that as wind penetrations increase, the double penstock system is a more economical alternative and it enables Ireland to utilise more indigenous wind energy. However, it is also more sensitive to changes in fuel prices, interest rates, and total annual wind production.

As well as analysing PHES, this study also assessed two alternative technologies which could be used to reduce the operating costs of the Irish energy system, which were domestic heat pumps and a district heating network with CHP. After comparing these alternatives to PHES, it was evident that domestic heat pumps are just as economical as an optimum PHES in Ireland based on projected fuel prices for 2020 and an interest rate of 6%. In addition, the savings associated with domestic HP are not as sensitive to changes in fuel prices, interest rates, or annual wind productions as PHES and thus, would be a more attractive investment. In addition, the PHES capacities proposed have been optimised over the course of this study, but the HP and CHP capacities proposed are only estimates based on the demands that have to be met. Conversely though, the single and double PHES systems can integrate more indigenous renewable energy as well as provide larger reductions in PES, FFD, and CO_2 than the HP and CHP scenarios. Therefore, these additional socio-economic benefits associated with PHES may be worth the additional cost. As a result, a more detailed analysis of these alternatives is necessary and also, it is essential that numerous alternatives across all sectors of an energy system are considered when evaluating solutions for the future.

Finally, there are a number of limitations which need to be considered when interpreting the results of this study. Firstly, it is clear that PHES is a key asset for wind energy as it enables the grid to operate securely while also incorporating high wind penetrations. However, in the future wind turbines and decentralised plants could make a more significant contribution to grid stabilisation and hence the value of PHES could be diminished. Also, the EnergyPLAN tool used in this study is a scenario tool which simulates an energy system on an hourly basis, which does not account for the dispatch of individual power plants or the current flow on individual power lines. Therefore, a more detailed energy tool will be required to fully establish the implications of using different grid constraints on the Irish energy system. This type of study would also provide another essential comparison between the alternatives considered i.e. the role out of domestic heat pumps could require less transmission upgrades than the construction of large centralised PHES facilities. Overall, the ultimate necessity for the future which can be drawn from this study is the demand for more detailed analyses of a wide range of alternatives for an energy system, as significant savings can be realised using existing technologies especially by integrating the electricity, heat, and transport sectors.

Chapter 9

9. The Dispatch of PHES on Electricity Markets

In a deregulated electricity market, an energy storage facility is typically defined as a merchant unit, which maximises its profits subject to technical constraints, or as a system asset, which is managed by the system operator to assist in maintaining system security and in reducing operational costs [91]. As a merchant unit, an energy storage facility will earn most of its revenue from the sale of electricity to the market [91, 143]. Hence, this chapter investigates how an energy storage facility can operate to maximise its revenue from the purchase of low-cost off-peak electricity and the sale of high-cost peak electricity on the market. In total, three practical operation strategies (24Optimal, 24Prognostic, and 24Historical) are compared to the optimum profit feasible for a PHES facility with a 360 MW pump, 300 MW turbine, and a 2 GWh storage utilising price arbitrage on 13 electricity spot markets. A more detailed discussion of this work is provided in Appendix H.

9.1. Electricity Markets

Electricity markets typically operate as a gross mandatory pool into which all electricity generated or imported must be sold, while all wholesale electricity for consumption or export must be purchased from this pool. Using this structure, the Single Electricity Market (SEM) was created for the island of Ireland in November 2007 and hence, it is a suitable case study for analysing the role of PHES on electricity markets.

In the SEM, each trade day comprises of 48 half hourly trading periods and participation in the pool is mandatory for all generators with a maximum export capacity greater than 10 MW [240]. Competitive bidding takes place one day ahead of delivery during which all dispatchable generators provide price and quantity information for each trading period. The spot market demand is cleared for each trading period and dispatch schedules are determined [241]. The clearing price is the price per MWh declared by the highest price generator required to meet demand. This determines the system marginal price (SMP) which will be awarded to all scheduled generators in a given trading period. Wind is Ireland's largest renewable energy resource with an installed capacity of approximately 1260 MW [231] compared to a maximum demand of approximately 5000 MW [22]. Like the majority of the EU-27 member states, Ireland exercises explicit priority dispatch of renewables [242]. Therefore, during dispatch scheduling wind generated electricity is treated as a negative load, which results in all available wind power being accepted onto the grid. Consequently the availability of wind during each trade period determines the net load to be supplied by conventional generation plant to maintain grid equilibrium. A graphical illustration of the scheduling process is illustrated in Figure 9-1. Using this procedure, a schedule of Ex-Ante (EA) prices is published at 16:00 one day ahead of the trade date in question. Four days after the trade date, final Ex-Post (EP) prices are published which includes the price of imbalances, constraints, and imperfections that could not have been predicted during the EA calculations [240].

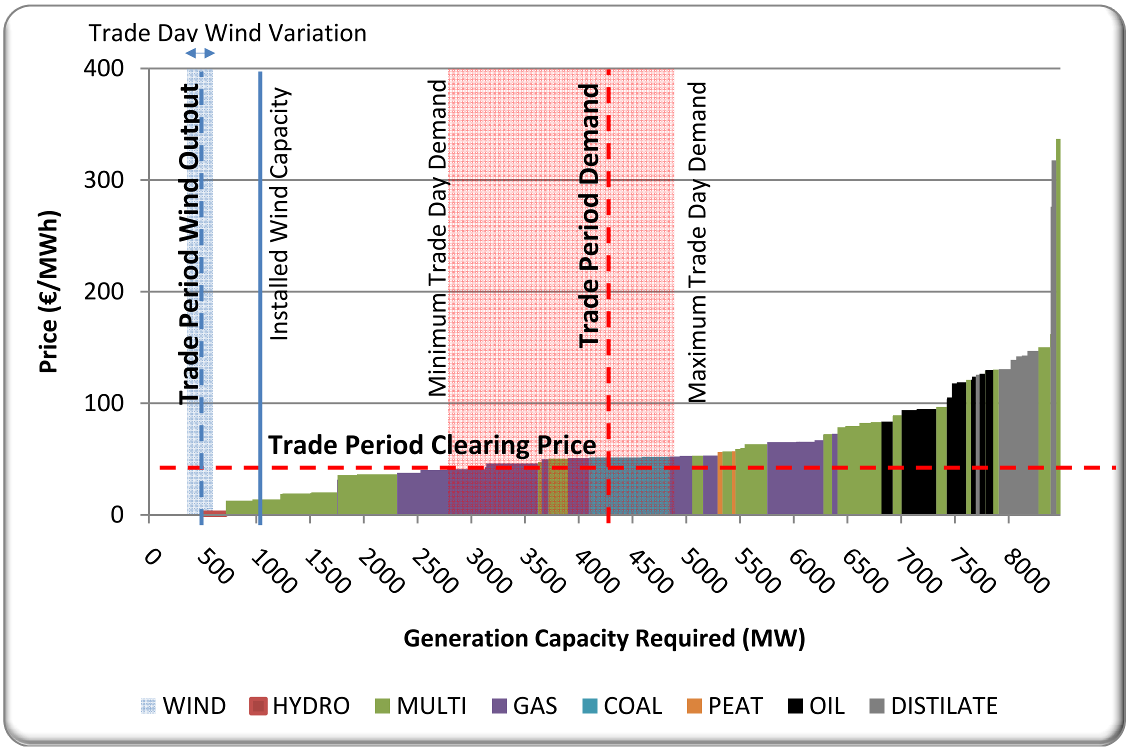


Figure 9-1: Generator bidding process on the Irish electricity market divided by fuel. It illustrates the clearing price and the priority dispatch of wind [243]: prices are based on generator submissions to the SEM on 01/Jan/2008 [232].

As the demand for electricity, the production from wind turbines, and the availability of conventional generation varies for each trading period, the SMP varies also. In 2008 for example, the lowest SMP price in Ireland was €2.54/MWh, the maximum SMP was €696.85/MWh, and the average SMP was €80.53/MWh, as displayed in Figure 9-2.

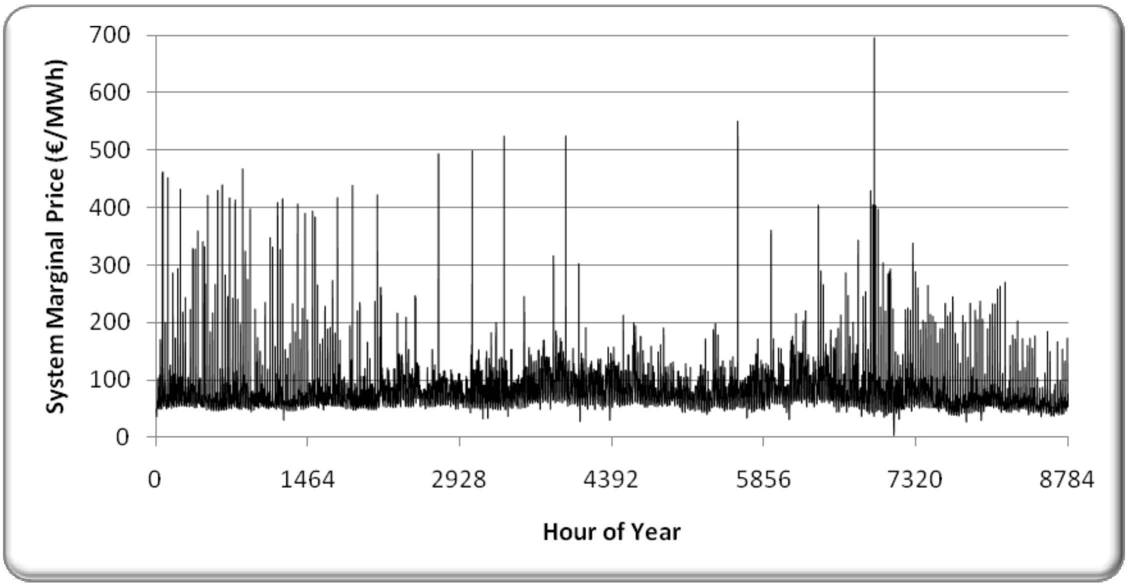


Figure 9-2: System marginal price for each trading period on Irish electricity market in 2008 [232].

This price differential usually occurs on a daily basis also, primarily due to the daily fluctuation in electricity demand on the grid, as displayed in Figure 9-3. Although some PHES facilities can take advantage of seasonal variations in electricity prices, most PHES facilities have been designed to utilise this daily price difference [160]. Various studies (which have been discussed in section 6.2.2) investigated new methods for dispatching PHES to maximise the profit available based on this price differential. However, none of the operation strategies identified could be utilised by a single PHES unit on a wholesale electricity market. Hence, using the Irish electricity market as a case study, the objective in this chapter was to develop a new dispatch strategy for PHES on wholesale electricity markets, which would enable it to maximise its profits based on electricity price arbitrage[12]. This is done by identifying the maximum feasible profit that a PHES facility can achieve on an electricity market with perfect pricing foresight for one year, then comparing this to a range of realistic operating strategies which could be put into practice, and subsequently investigating the economic viability of a PHES facility utilising price arbitrage on various electricity markets.

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[12] As well as the electricity market, there is also an ancillary services and capacity payments market in Ireland. However, due to the limited capacities of PHES, it can only be optimised on one market each day. Hence, to analyse the profits on these markets, a separate analysis would be required.

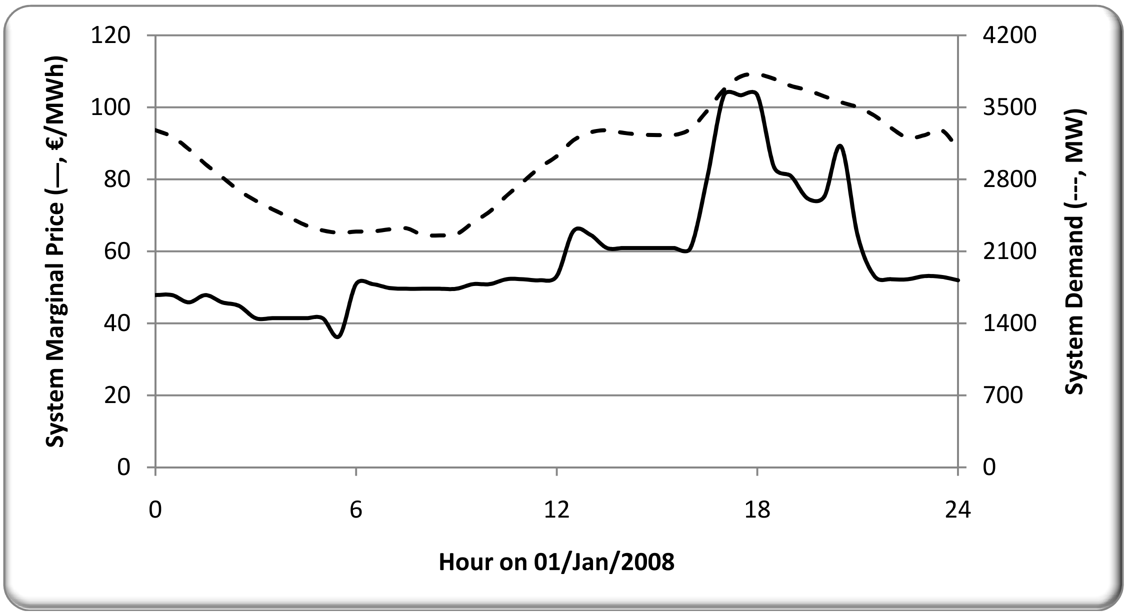

Figure 9-3: System marginal price and electricity demand for each trading period in Ireland on the 1st January 2008 [232].

9.2. Methodology

In total four different operation strategies were created for energy storage on a liberalised electricity market, which are called ‘Optimal’, ‘24Historical’, ‘24Prognostic’, and ‘24Optimal’. The Optimal operation strategy identifies the maximum theoretical operational income given an hourly time series of electricity prices over a one year period. Hence, it assumes perfect foresight of electricity prices for the year. The Optimal algorithm is described, formulated, and illustrated in Appendix H. In practice, energy storage plants could not implement the Optimal operation strategy since the fluctuations of spot market prices in the coming hours and days are not known for a whole year. Therefore, three additional strategies were created, which could utilised by an energy storage operator:

1. 24Historical strategy: decisions on buying and selling electricity are solely based on the knowledge of the average price over 12 historical and 12 future prices.
2. 24Prognostic strategy: decisions on buying and selling electricity are based on the average price of the upcoming 24 hours. Such a strategy requires the presence of good price prognoses.
3. 24Optimal strategy: operation of the energy storage facility is optimised using the same procedure as the optimal strategy, but it optimises the energy storage for the next day only. After optimising the first day, the procedure then repeats itself until the entire year is complete. Once again, such a strategy requires the presence of good price prognoses.

The concept behind the historical and prognostic strategies is to take the average price of a user-specified period and bid on the market correspondingly. The bid on the market occurs so that the price difference between the buying and bidding prices is equally distributed around the average price. The price is updated on an hourly basis, as opposed to a fixed average over a specified period. This implicitly assumes that the system operator can update market bids on an hourly basis, which distinguishes the 24Prognostic and the 24Optimal strategies, as the latter uses a fixed 24 hour time period i.e. the next day. The equations derived for the prognostic and historical strategies are outlined in Appendix H, while Figure 9-4 demonstrates their concept for a 24-hour period. The centre line represents the price average for the shown 24 hour-period. Based on that, the buying and selling prices are defined.

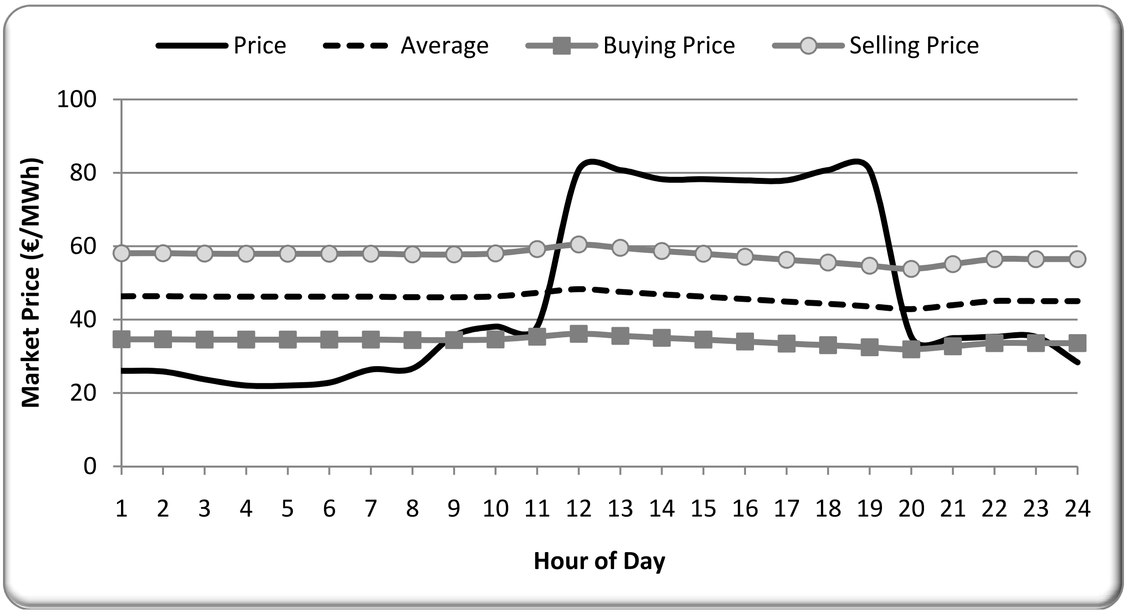

Figure 9-4: Concept used by the 24Historical and 24Prognostic strategies considered.

Two deterministic modelling tools have been used to analyse the operation of a PHES facility on an hourly basis over one year. The first tool is contained within EnergyPLAN [178] and it was developed by Lund and Salgi [207] to evaluate two practical operation strategies for CAES, which were called '24Historical' and '24Prognostic'. Here, the EnergyPLAN tool is used to model these two strategies when applied to PHES. In addition, the new operating strategy called '24Optimal' has been developed in MATLAB [244]. Finally, the 'Optimal' strategy which was also developed in [207], was simulated in both tools to model PHES and subsequently, their results were compared to ensure they were both operating in the same way.

Using each of the strategies defined above, the profit feasible from a PHES facility with the parameters outlined in Table 9-1 was identified for each of the electricity markets displayed in

Table 9-2. Previous studies have indicated that these are the typical capacities of existing PHES facilities [103, 160], while chapter 7 concluded that these capacities could be constructed in Ireland in the future. Also, using a pumping capacity of 360 MW and a turbine capacity of 300 MW enables the PHES facility to both charge and discharge for approximately 6 hours and hence, the facility can take advantage of daily low and high prices which typically occur on an electricity market.

Table 9-1: Capacity assumptions for the PHES facility used to test the various operating strategies.

PHES Parameter [source]	Value	Unit
Pumping capacity	360	MW
Turbine capacity	300	MW
Storage capacity	2000	MWh
Pumping efficiency [160]	92	%
Turbine efficiency [160]	92	%

Table 9-2: Electricity market data used for analysing the profit feasible from the PHES facility described in Table 9-1.

Electricity Market Operator	Region	Symbol	Link
Australian Energy Market Operator	New South Wales, Australia	AU	http://www.aemo.com.au
Energy Exchange Austria	Austria	AA	http://en.exaa.at
Elexon*	Britain	GB	http://www.elexon.co.uk
Alberta Electric System Operator	Alberta, Canada	CAA	http://ets.aeso.ca
Independent Electricity System Operator	Ontario, Canada	CAO	http://www.ieso.ca
Single Electricity Market Operator	Island of Ireland**	IE	http://www.sem-o.com
Gestore Mercati Energetici	Italy	IY	http://www.mercatoelettrico.org
Electricity Authority	New Zealand, North Island	NZN	http://www.ea.govt.nz
Nordpool Spot	Nordic region***	NP	http://www.nordpoolspot.com
Operador do Mercado Ibérico de Energia	Portugal	PL	http://www.omip.pt
Operador del Mercado de Electricidad	Spain	SP	http://www.omel.es
ISO New England	New Hampshire, New England, USA	USANE	http://www.iso-ne.com
New York ISO	Capital–F, New York, USA	USANY	http://www.nyiso.com

***Based on the market index price.**

****Based on final EP2 prices.**

*****Includes Denmark, Finland, Norway, and Sweden.**

9.3. Results and Discussion

Firstly, the profit for the energy storage facility was identified for each of the electricity markets as displayed in Figure 9-5. From the results it is evident that the 24Optimal strategy can obtain almost all of the profit that is feasible from each market: on average the 24Optimal strategy obtained 97% of the profit which was identified using the Optimal strategy. In comparison, the 24Prognostic and 24Historical strategies achieved 81% and 83% respectively of the Optimal strategy profits. However, it is likely that this large proportion of maximum profits achieved by the 24Optimal strategy is related to the 6 hour charge/discharge cycle of the PHES facility considered (see Table 9-1). To illustrate this, the results were recalculated for a storage capacity of 8 GWh instead of 2 GWh. As displayed in Figure 9-6, the profits achieved for an 8 GWh PHES facility using the 24Optimal strategy are only 82% of those achieved when the Optimal strategy is used. In addition, the 24Prognostic and 24Historical returned higher profits for the 8 GWh by achieving an average of 87% and 83% of the Optimal profits respectively. However, as PHES facilities are typically constructed with a charge/discharge cycle of approximately 6-8 hours [160], the 24Optimal strategy is very applicable to most existing PHES facilities. This is significant as the 24Optimal strategy shows that PHES units with charge/discharge cycles of approximately 6 hours do not need an intra-day market to maximise their profits from electricity arbitrage, but instead they need accurate electricity prices one day in advance.

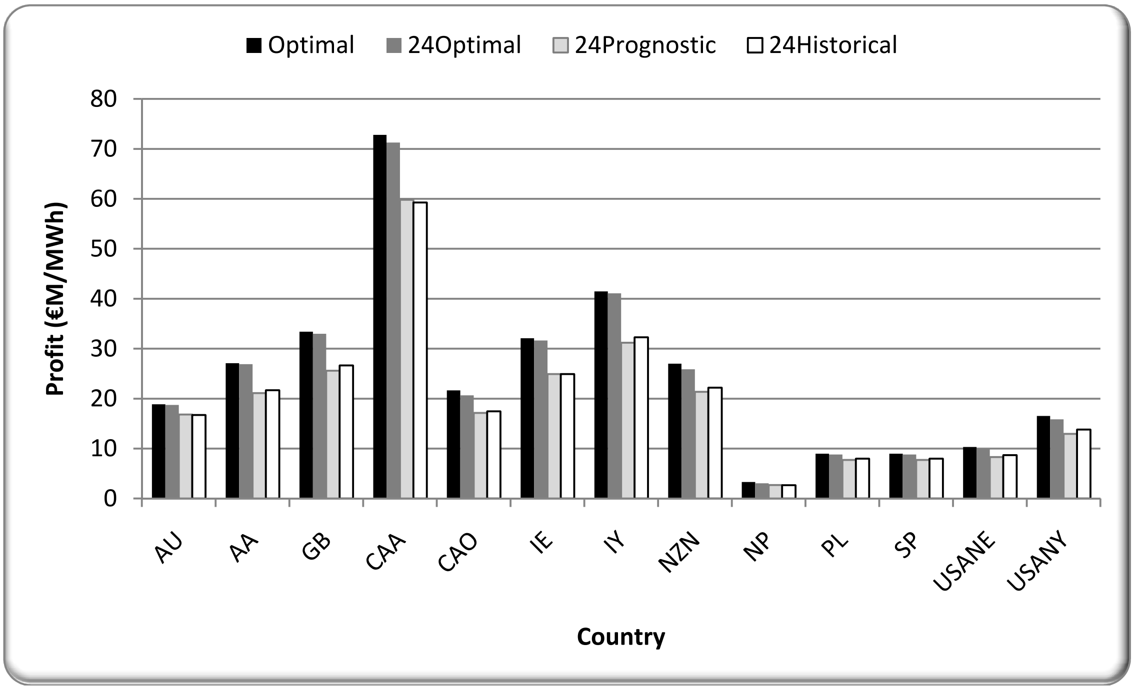

Figure 9-5: Profit for 2008 on each of the electricity markets (see Table 9-2) considered for all four optimisation strategies with a 2 GWh storage capacity.

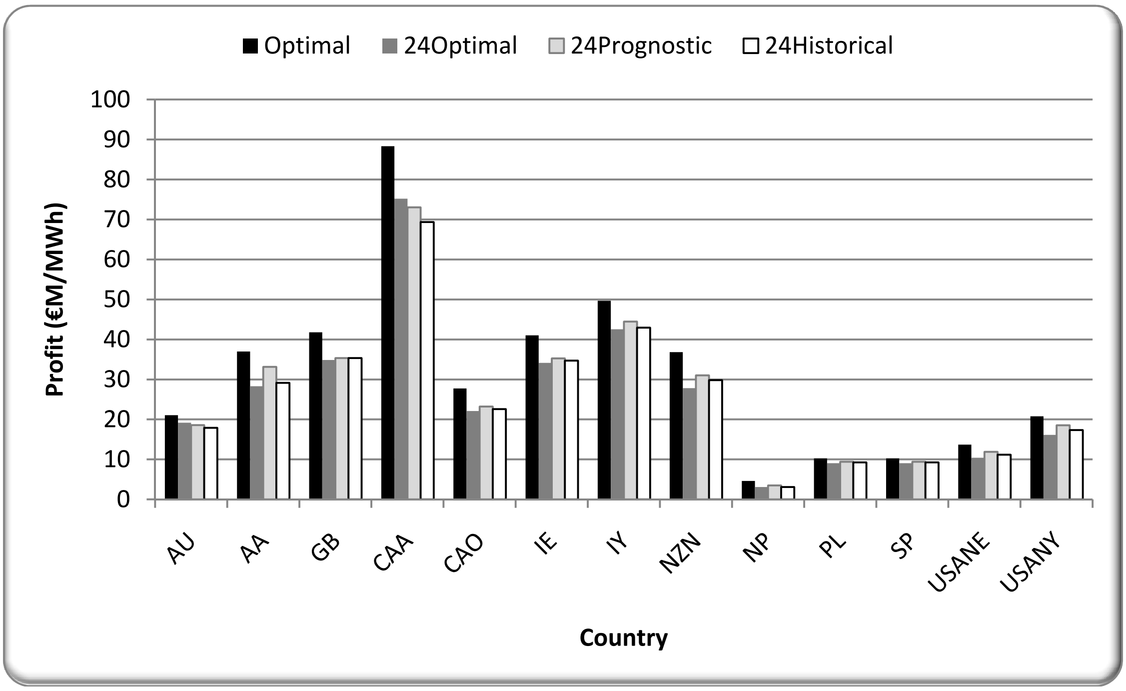

Figure 9-6: Profit for 2008 on each electricity market (see Table 9-2) considered for all four optimisation strategies with an 8 GWh storage capacity.

Although some markets already provide exact electricity prices one day in advance[13], the Irish electricity market does not. Instead, the day-ahead market in Ireland only provides indicative prices called that Ex-Ante (EA) prices. Four days after the day of trading, final prices, called Ex-Post2 (EP2) prices, are produced which include the cost of balancing the system. Therefore, if the 24Optimal strategy was utilised on the Irish market, the energy storage facility would be optimised using indicative EA prices, but charged the final EP2 prices. As outlined in Figure 9-7, when the 24Optimal strategy is optimised and charged based on the final EP2 prices, it makes the most profit. Also, although the profits from the PHES facility are reduced when the facility is optimised and charged based on predicted EA prices, the least profit occurs when the energy storage facility is optimised based on predicted EA prices, but charged the final EP2 prices (i.e. the current situation).

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[13] The Nordpool market provides exact electricity prices one day in advance and uses a regulating market to account for changes that occur on the following day.

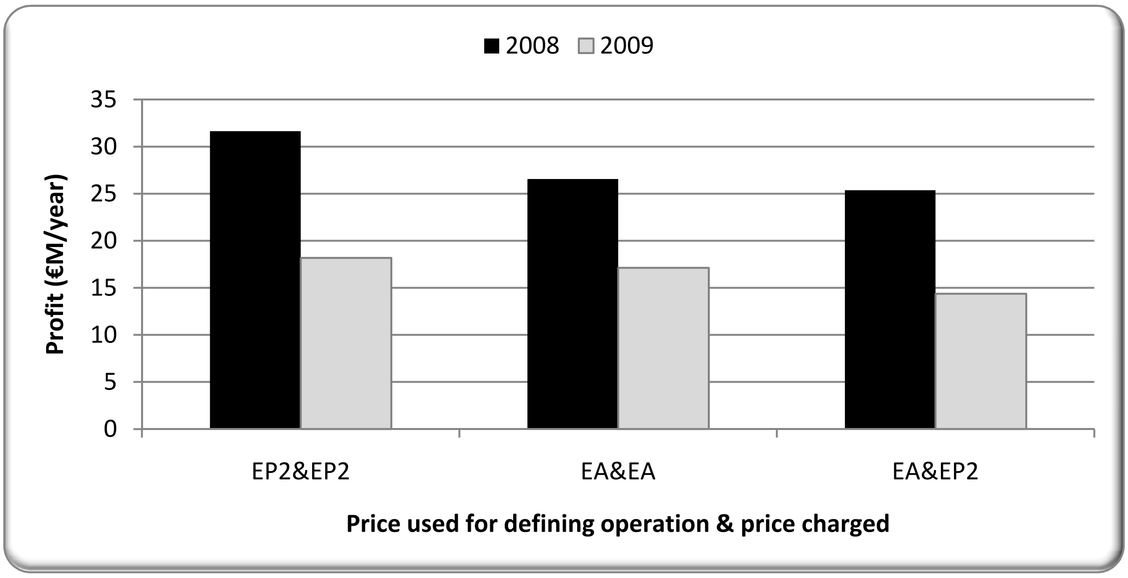

Figure 9-7: PHES facility profit using the 24Optimal strategy on the Irish electricity market when it is optimised and charged different prices in 2008 and 2009.

After closer inspection of the price distributions, two primary reasons were identified for this profit reduction. Firstly, some extreme events can occur during the year where the predicted prices can change dramatically during the operation of the PHES. As outlined in Figure 9-8, between hours 2060 and 2168 in 2008, the electricity price was predicted to be relatively low at approximately €60/MWh and hence, the PHES facility decided to operate the pump. However, the actual price was very high at approximately €260/MWh and as a result, instead of making a predicted profit that day of ~€25,000, the facility made a loss of ~€200,000.

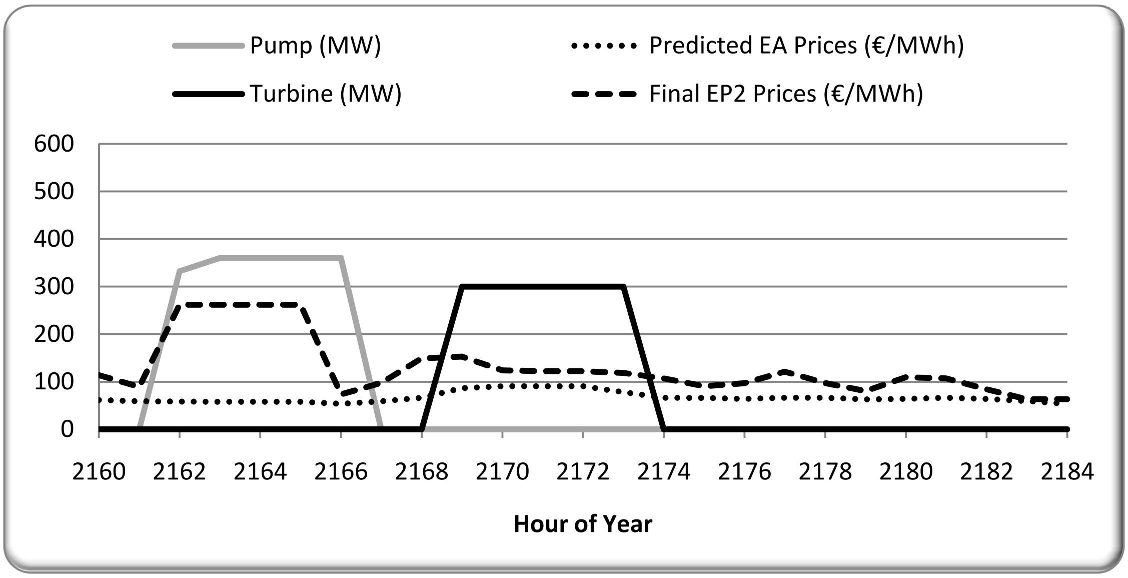

Figure 9-8: Pump and turbine operation based on predicted Irish market prices in 2008.

Secondly, less extreme reductions in the daily profit are also experienced due to the relationship between predicted EA prices and final EP2 prices. As displayed in Figure 9-9, prices which are predicted to be low are more likely to increase, while prices which are predicted to large are more likely to decrease [82]. Therefore, the hours when the PHES is pumping are more likely to increase and thus increase costs, while the hours when the PHES is generating are more likely to decrease and thus decrease income. In conclusion, for a PHES to maximise its profits, the operator needs to obtain the final electricity price in advance or else have very accurate price predictions.

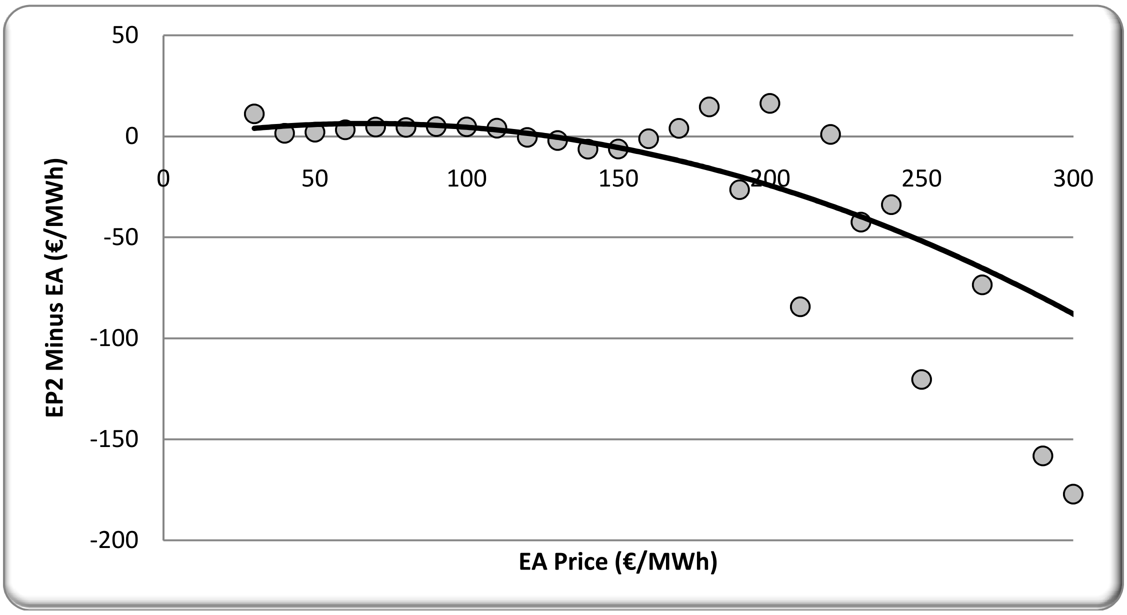

Figure 9-9: Average price difference between predicted EA prices and final EP2 prices on the Irish electricity market in 2008.

Finally, the profits identified for the PHES facility using the 24Optimal strategy were compared with the annual investment costs required using the assumptions outlined in Table 9-3 along with Equation 4 in section 7.2, which consists of the total investment costs *I*, the installed capacities *C*, lifetimes *n*, an interest rate *i*, and the annual fixed O&M costs as a percentage of the total investment. As Deane *et al.* [103] outlined in a review of existing and proposed PHES facilities around the world, there is no 'general' cost for a PHES facility as it is very site dependent: the authors concluded that the investment costs could vary from 0.47 to 2.17 €M/MW. Therefore, to account for this variability, a low and high investment scenario was investigated based on this data. In addition, this analysis was carried out over a five year period and hence, it was only completed for the electricity markets which provided the price data necessary. Finally, as the lifetime of PHES is approximately 40 years (and up to 100 years for some components), the annual investment cost will be sensitive to the interest rate. Therefore, an interest rate of 3% and 6% was also used for both the high and investment costs.

Table 9-3: Low and high cost assumptions for the PHES facility.

PHES Parameter	Cost [source]	Unit
	Common economic assumptions	
Variable O&M costs	1.5 [95]	€/MWh
Fixed O&M costs	1.5 [167]	% of investment
Lifetime	40 [95, 167]	Years
Interest Rate	6 [233]	%
	Low Investment Assumptions	
Pump investment	0.235 [95, 103]	€M/MW
Turbine investment	0.235 [95, 103]	€M/MW
Storage investment	7.884 [95]	
	High Investment Assumptions	
Pump investment	1.085 [103]	€M/MW
Turbine investment	1.085 [103]	€M/MW
Storage investment	15.77 [95]	€M/GWh

As displayed in Figure 9-5 previously and Figure 9-10 below, the profit feasible from the PHES varies considerably for one electricity market to the next. However, Figure 9-10 also indicates that the profit on the same market can vary substantially from year to year. For five of the six markets analysed, the total profit varied by over 50% over the five year period analysed, which makes PHES a risky investment. In addition, Figure 9-10 emphasises the importance of locating a suitable site for constructing the PHES facility. If the initial investment costs are low and the PHES facility is constructed in a suitable market, then the profit fluctuations will not result in significant losses. However, as a PHES facility has a typical lifetime of approximately 40 years, it is likely that any potential investor would need some additional profit stability. A low interest rate is one policy which could improve the long-term feasibility of PHES. When the interest rate is increased from 3% to 6% on the initial investment, the annual repayments correspondingly increase by approximately 40%. If the initial investment costs are high at 2.17 €M/MW, then this equates to approximately €17M extra investment each year. However, even though a low interest rate would improve the economics of PHES, the results indicate that a suitable electricity market and low investment costs are still the most significant factors.

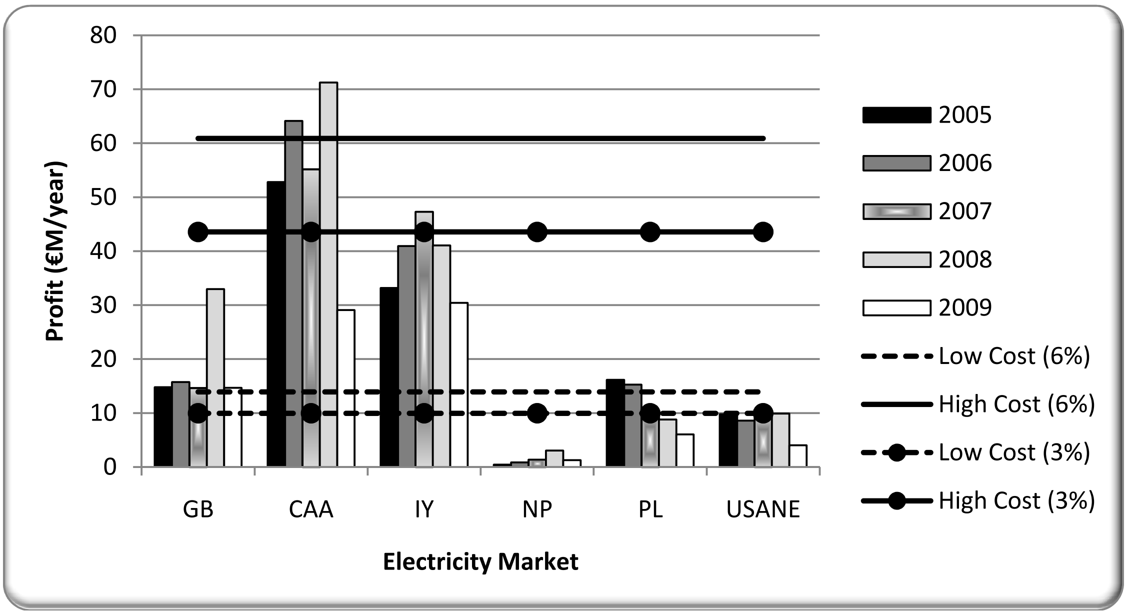

Figure 9-10: PHES profit using 24Optimal strategy on the electricity markets with data available for 2005 to 2009, along with high (€2.17M/MW) and low (€0.47M/MW) annual investment costs based on a 3% and 6% interest rate.

9.4. Conclusions

The results indicate that the 24Optimal operation strategy is the most profitable practical method of dispatching a typical PHES facility. Under this strategy the PHES is optimised based on the day-ahead electricity prices and by doing so, almost all (~97%) of the profits feasible can be obtained when the charge and discharge cycles are each approximately 6 hours. This indicates that long-term foresight of electricity prices is not essential for most PHES facilities to maximise their profits using electricity price arbitrage. However, a further analysis based on the Irish electricity market indicated that for the 24Optimal strategy to be effective, the day-ahead electricity prices must be the actual prices which the PHES facility is charged or the PHES operator must have very accurate price predictions. Otherwise, the predicted profit could be significantly reduced and even become a loss. Finally, using the 24Optimal strategy, the PHES profit from energy arbitrage on some electricity markets can surpass the annual investment repayments required. However, the annual profit from the PHES facility varied by more than 50% on five out of six electricity markets considered over the five year period analysed: 2005 to 2009. Therefore, even with low investment costs, a low interest rate, and a suitable electricity market, a PHES facility is still a risky investment in most markets without a more predictable profit or some additional revenue, which could come from ancillary services, capacity payments, or a balancing market.

Chapter 10

10. Conclusions

The Irish energy system, wind energy, and pumped hydroelectric energy storage (PHES) were used to assess the role of large-scale energy storage and the integration of fluctuating renewable energy in this study. The Irish energy system was deemed suitable for three key reasons: it has a significant wind resource which could supply over 200% of Ireland's electricity demands with existing technologies, its ambitious wind energy targets which includes 34-37% of electricity from wind by 2020, and its isolated structure due to limited interconnection (chapter 4). Hence, utilising large-scale energy storage offers unique benefits for the Irish energy system. After an extensive review of all the energy storage technologies available, PHES was chosen as the most suitable for Ireland since it is the most mature, largest, and cheapest form of energy storage currently available (chapter 5). However, three key issues were often reported in the literature in relation to PHES: firstly there were very few suitable sites remaining for the construction of PHES, secondly it is unclear how much additional wind energy could be integrated onto the Irish energy system with PHES and thirdly, the role of energy storage on existing electricity markets was ambiguous (chapter 6). Hence, creating solutions for these issues defined the structure of this research.

To identify suitable PHES locations (chapter 7), a new software tool was developed which can search a user-specified terrain with user-specified parameters and recognise a suitable site for constructing PHES. The results from this software can be used in the Energy Capacity and Cost Calculator also developed in this study, which will estimate the size and cost of the facility found. After using these tools to search County Clare in Ireland, which is approximately 3150 km^2, at least 8 locations suitable for the construction of PHES were identified with capacities as large as 570 MW and 22.5 GWh. Therefore, this research has illustrated that Ireland has a significant freshwater PHES resource, so the next step was to quantify the implications of constructing it.

The implications of PHES were defined under two distinct objectives in this study: firstly, what is the maximum technical wind penetration feasible with PHES and secondly, what is the most economical wind penetration that can be achieved with PHES on the Irish energy system (chapter 8). Based on previous literature in this area, it was clear that a model of the Irish energy system would be necessary to answer these questions (section 6.2.1). Hence, a review of existing energy tools was carried out to identify a tool which could not only model the technical and economical implications of wind energy and PHES, but could also be applied to the Irish energy system (section 8.1.1). After assessing approximately 68 energy tools, EnergyPLAN was deemed the most suitable tool available for this study as it could model an entire national energy system, it could be applied to Ireland, it was free, online training was available, and previous studies completed using EnergyPLAN were very applicable to this study (section 8.1.2). Using EnergyPLAN, a model of the Irish energy system was created based on the year 2007 to ensure it could simulate Ireland accurately, and based on the year 2020 so the implications of PHES could be assessed (section 8.2).

With the 2020 model, the maximum feasible wind penetration was identified on the Irish energy system for various capacities and operating strategies of PHES, plus the implications of these wind penetrations on existing power plants was also examined (section 8.3). Here it was concluded that the grid constraints required to maintain grid stabilisation are closely linked to the benefits of PHES. Using a double penstock PHES operating strategy, it is possible to accommodate these grid constraints while also supplying up to 100% of Ireland's electricity using wind power. In contrast a single penstock operating strategy could only enable up to 60% of Ireland's electricity from wind power. However, the capacity analysis indicated that a double PHES would require much larger pump and turbine capacities than a single PHES. Therefore, the economic assessment was essential to identify whether the additional wind penetrations feasible from a double PHES were worth the additional pump and turbine capacities required.

Based on predicted 2020 fuel prices which reflect an oil price of \$100/bbl, a CO_2 cost of \$50/t, and an interest rate of 6%, results indicate that PHES is not a viable alternative for Ireland (section 8.4.2). However, if an interest rate of 3% was used to assess PHES and wind energy, due to their lengthy lifetimes and socio-economic benefits, then PHES would be an economical alternative in Ireland for 2020 (section 8.4.3). Similarly, if fuel prices increased to reflect an oil price of \$150/bbl, this would also be the case. Nonetheless, a comparison between PHES and two other alternatives, which were domestic heat pumps and a district heating network with CHP, indicated that these alternatives can provide similar savings to PHES while also being more robust against fuel prices, interest rates, and annual variations in wind generated electricity (section 8.4.4). In addition, as the benefits of PHES are dependent on grid constraints, the value of PHES could depreciate as distributed forms of energy generation begin to contribute to grid stabilisation. Conversely though, PHES does enable Ireland to utilise more indigenous wind power and obtain larger reductions in energy consumption, fossil fuels, and CO_2 than both the HP or CHP alternatives. Hence, depending on the socio-economic value which Ireland places on these issues, PHES could indeed be worth the additional economic cost. Therefore, PHES could be a viable alternative for Ireland under certain circumstances, but initial results indicate that heat pumps and district heating could offer more significant long-term economic savings at lower risk and hence, further work is necessary in these areas to ensure the optimum solution.

Separate to the results obtained in chapter 8, a number of conclusions can be made in relation to the methodology developed for evaluating energy storage on the Irish energy system. Firstly, it is crucial to consider the structure of an energy system when evaluating energy storage. Typically, most energy alternatives are assessed to identify how fuel consumption can be minimised by replacing fossil fuel technologies with renewable alternatives. Energy storage is only considered here because it is an additional source of flexibility in an energy system and hence, more renewable energy can be utilised. Therefore, energy storage is only useful if the energy system being evaluated requires additional flexibility. Considering this, energy storage should be assessed in the context of a future long-term system. In other words, the existing Irish energy system may need flexibility, but will the technologies available in 2020, 2030, or 2050 also need it? Secondly, when evaluating energy storage, it is vital that it is compared to a range of alternatives. Evaluating technologies as a solitary solution will not produce the optimum result for Ireland, as benefits and drawbacks are all relative. In line with this, the third key conclusion about the methodology utilised in chapter 8 concerns the sectors considered. When evaluating alternatives to energy storage, it is essential that all sectors of the energy system are considered, especially due to the potential flexibility that can be created by merging the supply and demand across the electricity, heat, and transport sectors. In other words, the electricity sector is no longer an independent entity within a national energy system, as the construction of technologies such as energy storage will have to be compared with technologies such as heat pumps and thermal storage in the heating sector, as well as electric vehicles in the transport sector. To summarise, when evaluating energy storage in the future, it is important to consider a long-term horizon, if flexibility is necessary, alternative investments, and the entire energy system.

Finally, if PHES is required on the Irish energy system in the future, it will need to be accommodated on the electricity market and hence this was also investigated (chapter 9). At present, there are three electricity markets in Ireland: ancillary services, capacity payments, and energy. As PHES must create the energy it needs before the time of delivery, it can only be optimised for one market at a time and hence the focus in this study was the energy market.

Therefore, the objective was to maximise the profits of a PHES facility utilising electricity price arbitrage. For this analysis a PHES with a 360 MW pump, 300 MW turbine, and a 2 GWh storage capacity was used as case study, which chapter 7 indicated could be constructed in Ireland. During the investigation a new 24Optimal operating strategy was created for PHES on electricity markets, which enables them to achieve approximately 97% of the profits that could ever be obtained. Utilising this operating strategy in Ireland, the PHES facility could have earned approximately €18M in 2008 and €32M in 2009. The annual repayment costs for the same facility would be between €10M/year and €60M/year, depending on the initial capital costs and the interest rate required. Hence, if one of the PHES sites identified in chapter 7 can be constructed at a cost of approximately €0.5M/MW, then this facility could make a profit on the Irish electricity market by utilising electricity price arbitrage. However, chapter 9 also indicates that to do so the market should offer the PHES facility a fixed price one day in advance or else the operator will require very accurate price predictions. Otherwise, its income could be cut by approximately 20%. To build on this study, the profits feasible on the ancillary services and capacity payments markets should also be assessed in the future.

Overall, the results in this study have verified that Ireland can build large-scale PHES, it can provide all of its electricity using PHES and wind energy, and it can accommodate PHES on its electricity market. However, it is also important to recognise the limitations in these results. The sites identified in chapter 7 will require a more detailed assessment to determine their exact size, cost, and environmental impact. EnergyPLAN is a planning tool and hence a more detailed model of the grid would be necessary to fully evaluate the consequences of large-scale PHES and wind energy. Also, the PHES profits feasible from the ancillary services and capacity payments markets should also be assessed before altering the market to accommodate it. Therefore, even though the results portrayed throughout this thesis provide a good indication of the final results, their specific limitations need to be appreciated also. All of these issues could form the basis for more research in the future, but this research will continue by focusing on the most significant conclusion reported: Ireland needs to develop a long-term energy plan that utilises its significant fluctuating renewable energy resources such as wind, wave, tidal, and solar, by assessing alternatives which generate flexibility by integrating the electricity, heat, and transport sectors. As Paul Cunningham concluded after discussing Ireland's Green Economy with numerous researchers, entrepreneurs, and politicians [245]:

Chapter 10

"Ireland has immense natural resources, its people innovative skills; what we need now is a measureable and verifiable green action plan, co-ordinated thinking, and the determination to push it through. If we get this right, the green economy and green technologies can benefit every single one of us."

11. Future Work

Throughout this study a number of new methodologies, software tools, and definitions have been developed. Most significantly for the Ireland though is the new model of the Irish energy system created in EnergyPLAN, which can be used to analyse a broad range of different technologies in the future, primarily as it considers the electricity, heat, and transport sectors. The benefits of this have already been illustrated in section 8.4.4, when PHES was compared to domestic heat pumps and a district heating system with CHP. Therefore, the primary focus for the future will be to investigate the feasibility of alternative energy technologies for Ireland which will ultimately lead to a 100% renewable energy system. This process has already begun by carrying out a technical assessment of a biomass, hydrogen, and electricity based 100% renewable scenarios for Ireland.

11.1. 100% Renewable Alternatives

Once the 2007 model of the Irish energy system was created and validated against historical data, an initial draft of a 100% RES for Ireland was developed. In total, four 100% renewable energy scenarios were made for Ireland including a:

1. Biomass Energy System (BES): a 100% renewable energy system based on biomass.
2. Hydrogen Energy System (HES): a 100% renewable energy system using hydrogen.
3. Electricity Energy System (EES): a 100% renewable energy system maximising the use of renewable generated electricity.
4. A combination of each (COMBO): a 100% renewable energy system based on the results from the BES, HES, and EES scenarios.

For each scenario a number of assumptions were made about the future energy demands and production units required. Although these assumptions would have to be validated further before an accurate solution is proposed, they do provide an indication of the trends that can be expected if various technologies are used as an integral part of a 100% renewable energy system for Ireland. Listed below are the assumptions used in three of the 100% renewable energy systems investigated for Ireland:

Assumptions for the biomass energy system (BES)

1. All electricity, heat, and transport demands were maintained at 2007 levels.
2. Energy storage is increased to 3000 MW and 15 GWh.
3. Eliminate existing electric heating.

4. Supply 10% of individual heating with solar thermal.
5. Supply 35% of individual heating with biomass boilers: accounts for all homes in rural areas.
6. Supply 55% of individual heating using district heating: accounts for heating demand in all towns and cities with more than 1500 people.
7. Introduce 251 MW (0.92 TWh) of tidal power.
8. The entire fuel demand in industry is supplied using biomass.
9. All transportation fuel is supplied by biofuels, including jet fuel. Biomass is converted to bio-ethanol at a ratio of 1:1.35 (for private cars and jet fuel) and to biodiesel at a ratio of 1:1 (for road freight).

Assumptions for the hydrogen energy system (HES)

1. All electricity, heat, and transport demands were maintained at 2007 levels.
2. An electrolyser of 10,000 MW and storage of 240 GWh is added to produce, store, and provide hydrogen to the power plant, transport, and heating sectors.
3. Supply 10% of individual heating with hydrogen micro CHP.
4. Supply 10% of individual heating with solar thermal.
5. Supply 10% of individual heating with heat pumps.
6. Supply 15% of individual heating with biomass boilers.
7. Supply 55% of individual heating using district heating: accounts for heating demand in all towns and cities with more than 1500 people.
8. Introduce 251 MW (0.92 TWh) of tidal power.
9. Introduce 3000 MW (3.33 TWh) of wave power.
10. The entire fuel demand in industry is supplied using biomass.
11. Transportation fuel is primarily supplied by hydrogen: all private cars and jet fuel is replaced by hydrogen, while 50% of road freight is fuelled by hydrogen and 50% biodiesel.

Assumptions for the electricity energy system (EES)

1. All electricity, heat, and transport demands were maintained at 2007 levels.
2. Energy storage is increased to 3000 MW and 15 GWh.
3. Supply 10% of individual heating with solar thermal.
4. Supply 35% of individual heating with heat pumps: accounts for all homes in rural areas.

5. Supply 55% of individual heating using electric heating: accounts for heating demand in all towns and cities with more than 1500 people.
6. Introduce 251 MW (0.92 TWh) of tidal power.
7. Introduce 1000 MW (1.11 TWh) of wave power.
8. The entire fuel demand in industry is supplied using biomass.
9. All road transportation is fuelled by electricity and biomass: The private car fleet is fuelled by 80% electricity and 20% bio-ethanol (which can include electric, hybrid, or bio-ethanol cars). All road freight is fuelled using biodiesel and all jet fuel is supplied using bio-ethanol.

Once these assumptions were reflected in the model of the Irish energy system, the capacity of wind power was increased incrementally to identify the maximum wind penetration that could be achieved, as this is the most economical renewable energy resource available in Ireland (see section 4.2). The process used to define the maximum wind penetration feasible is described in more detail in Appendix I.

Using the scenarios described above and methodology defined in Appendix I, the PES and the energy generated from all of the different technologies were calculated for all three scenarios, as displayed in Figure 11-1. From the outset it is evident that all three scenarios (BES, HES, and EES) have a lower primary energy supply than the 2007 reference. This is primarily due to the introduction of more efficient systems such as CHP and district heating in the BES and HES, as well as fuel cell transportation in the HES, and electric vehicles in the EES. Of the three alternatives, the EES has the lowest primary energy supply at 590 PJ, while the BES has the highest at 660 PJ. This is due to the large amount of biomass required to replace fossil fuels in the transport sector. In addition, unlike hydrogen and electric vehicles, bio-ethanol vehicles do not aid the integration of higher wind penetrations. The PES of the HES was also very similar to the BES at 629 PJ. This illustrates that a hydrogen economy is also very demanding on resources, especially in comparison to the EES. The main reason for this decrease in PES in the EES is the efficient use of electricity. In the HES, electricity is transformed to hydrogen and then typically transformed back to electricity at a later stage, which results in a very inefficient system. In contrast, the EES uses electricity directly so the losses are reduced, primarily in the transport sector.

The biomass consumption varies considerably within each scenario also, in terms of total consumption and also in terms of its specific uses. As expected, the BES uses the most biomass at 611 PJ, which is 92.5% of the PES. In the HES and the EES the biomass consumption is much less than the BES at 513 PJ and 472 PJ respectively. However, the use of biomass in both the HES and the EES is very different. The HES uses a large amount of biomass in the power plants, to create electricity to produce hydrogen for heating and transportation. In contrast, the EES uses a lot of biomass directly in the transport sector.

Also from these results, it is evident that the biomass energy system can utilise very little wind energy compared to the HES and the EES. In total, the BES was only able to integrate 10.4 TWh of renewable generated electricity, while the HES was able to integrate 29 TWh and the EES 29.7 TWh. This is due to the much larger electricity demands and energy storage capacities available in the HES and the EES. The HES uses a lot of electricity to generate hydrogen which can then be stored for use in power plants, hydrogen micro-CHP, and transport. The EES uses a large amount of electricity for electric heating and transportation, while electric vehicles can also act as large sink for excess renewable energy.

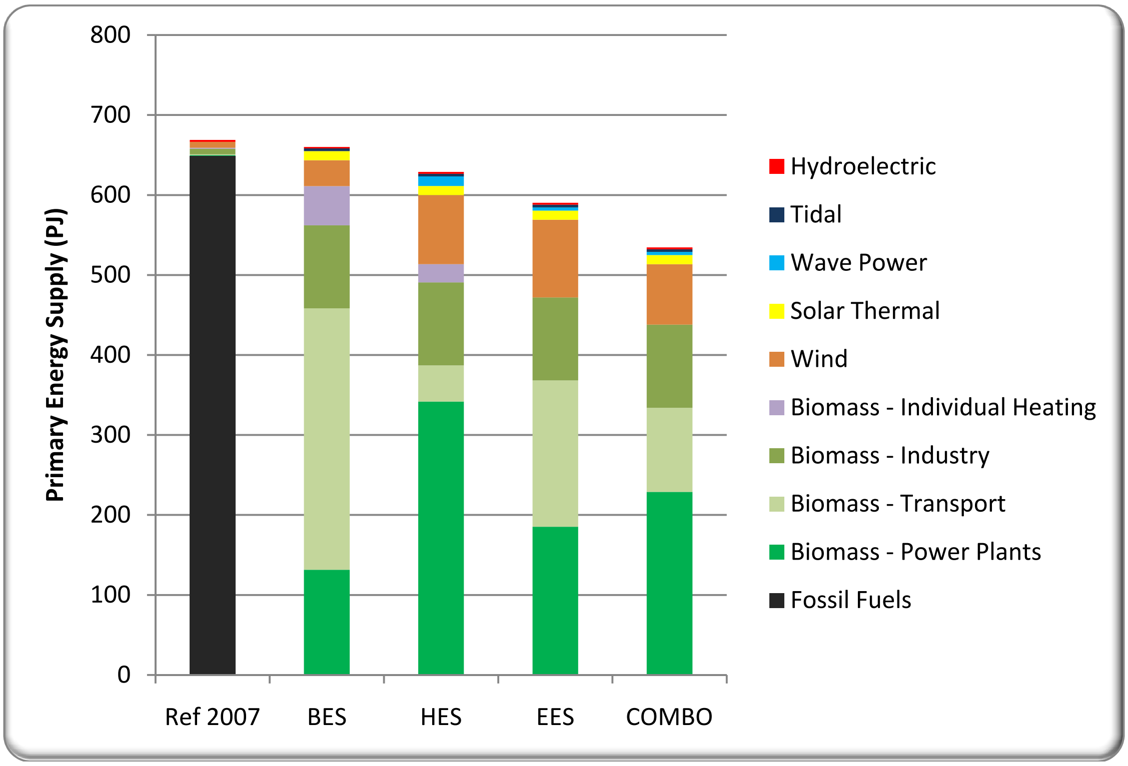

Figure 11-1: Primary energy supply in reference, BES, HES, EES and COMBO scenarios.

Based on the results from the BES, HES, and ESS, a COMBO scenario was created with the following characteristics:

1. All electricity, heat, and transport demands were maintained at 2007 levels.

2. No energy storage is added: enough is provided by the electric vehicles in the transport sector.
3. Supply 10% of individual heating with solar thermal.
4. Supply 35% of individual heating with heat pumps: accounts for all homes in rural areas.
5. Supply 55% of individual heating using district heating: accounts for heating demand in all towns and cities with more than 1500 people.
6. Introduce 251 MW (0.92 TWh) of tidal power.
7. Introduce 1000 MW (3.33 TWh) of wave power.
8. The entire fuel demand in industry is supplied using biomass.
9. Transportation is fuelled by electricity, hydrogen, and biomass. The private car fleet is fuelled by 80% electricity and 20% bio-ethanol, road freight is supplied by 50% bio-ethanol and 50% hydrogen, and jet fuel is supplied using 50% hydrogen and 50% bio-ethanol.

The objective was to combine the efficient use of biomass in the BES scenario with the efficiency of rural heating in the EES. Therefore, CHP and district heating was used instead of electric heating in the EES, while heat pumps were maintained as the primary heat technology in rural areas. For the transport sector, the efficiency of electric vehicles was maintained for private transport, and a mix of hydrogen and biomass was used for road freight and aviation fuel. From Figure 11-1, it is evident that this results in the most efficient energy system of all. The PES is reduced by 20% to 534.5 PJ and 23.7 TWh of renewable generated electricity is used. Finally, the biomass required in the COMBO scenario is reduced to 438 PJ, which is 71% of the biomass demand in the BES. This is also 59.6% of the potential biomass resource in Ireland, although this is a total potential and not a residual potential i.e. it does not account for land that may be unavailable to avoid affecting food production or other industries [43]. Therefore, even though the biomass requirement in the COMBO scenario is low, it still might be too much depending on the residual biomass that is available in Ireland.

In addition to the issues discussed above, it is also worth noting that energy savings were not considered in detail in this analysis. It was assumed that energy demands would remain the same as 2007: this may be too low as energy demands are likely to increase in the future, or it may be too high as it may be possible to reduce demands below 2007 levels depending on the energy savings feasible. In the future, energy conservation will need to be considered in more detail, when identifying the least-cost 100% renewable energy system for Ireland.

11.2. Conclusions

In summary, this work illustrates that an Irish energy system with district heating, heat pumps, and a transportation mix of electricity, hydrogen, and biomass, is the most efficient and resource-friendly method of converting Ireland to a 100% renewable energy system. However, this analysis was carried out from a technical and resource perspective and not an economic perspective, which may alter the results. Also, the assumptions used to create the alternatives in this study are crude and the combinations of technologies used to supply the demands are not at optimum capacities. However, although the results obtained in this study are not ideal, they do illustrate the options available to Ireland in achieving a 100% renewable energy system.

On a more detailed level, the economic assessment in section 8.4.4 also illustrated the potential savings for the Irish energy system associated with PHES, heat pumps, and district heating with CHP. It was evident from these results that there is a significant potential within the heating sector to reduce the operating costs of the Irish energy system and hence, it is imperative that these reductions are quantified. It is clear from these results that the true value of any energy technology can only be determined when contrasted against its alternatives.

Overall, this research focused primarily on the benefits of large-scale energy storage, but the most significant finding in this work is the need for a more detailed analysis of energy system alternatives for Ireland. Therefore, it is hoped that this work can motivate a larger interest in identifying accurate predictions and costs (especially socio-economic) for the future of the Irish energy system, specifically among experts within each of the relevant areas and hence improve the overall accuracy of the models created. It is imperative that Ireland quantifies the benefits of existing technologies such as CHP, district heating, heat pumps, biomass boilers, and electric rail more accurately, as well as the potential of future technologies such as electric vehicles and the hydrogen economy. Future studies will focus on these technologies with the overall objective of defining a realistic pathway towards a 100% RES for Ireland. This will contribute to an increasing body of 100% RE research that has already been carried out for regions such as Australia [246], New Zealand [247, 248], Japan [200], America [247, 249], Denmark [225-229], Portugal [142], and Europe [186, 250, 251].

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