

Power-to-Gas Energy Storage and its Effects on reducing Emissions and improving Energy Security for Ireland

Thesis submitted for the
MASTERS OF SCIENCE IN ENVIRONMENTAL SYSTEMS
School of Engineering
Galway Mayo Institute of Technology

Author
Henrik Kolberg

Supervisor
DR. DENIS O'MAHONEY
Departments of Mechanical & Industrial Engineering
Galway- Mayo Institute of Technology, Ireland

STATUTORY DECLARATION

Plagiarism is defined as the taking and using as one's own the thoughts, writing or invention of another (Oxford English Dictionary).

I wish to affirm that the substance of this thesis is the result of my own effort and that I have rigorously referenced and acknowledged all sources of information, writing and ideas used in this dissertation. No part of this thesis has been submitted for any degree or award concurrently. I declare that this thesis is my original work except where otherwise stated.

Signed:

Date: 17/09/2012

ABSTRACT

The safeguarding of a reliable, environmental benign and economically meaningful energy supply is one of the key challenges Ireland is facing towards 2020 and beyond. The country is transforming its energy system from conventional power generation relying on fossil fuel imports towards a sustainable system utilising renewable and domestic sources of supply. The increased number of non-synchronous power generation stipulates the development of energy storage technologies as the amount of electricity supplied to the network has to equal the amount of electricity consumed. With an increased share of renewable generators that produce intermittent power output the utilisation of energy storage technologies for the compensation of fluctuations and peak demand is urgently required.

Power-to-Gas energy storage is a concept able to store surplus energy in the megawatt range by using the existing network infrastructure of gas. The system is linking the inflexible power network with the natural gas grid. The Power-to-Gas concept represents a complete system solution in its ability to store surplus electricity in chemical form. In a first step hydrogen is produced through the process of electrolysis. In a subsequent reaction hydrogen is united with carbon dioxide in order to produce synthetic methane. The synthetic natural gas (SNG) is able to replace fossil gas reserves on a like-for-like basis.

The basic process ingredients of water, electricity and carbon dioxide reduce any dependencies on rare material components and promote its universal application in connection with non-synchronous power generators. This thesis highlights the performance characteristics of Power-to-Gas energy storage and examines the potential environmental and economical impacts of the technology for Ireland.

ACKNOWLEDGEMENTS

I would like to thank everyone who contributed to the completion of this thesis. Special thanks go to Dr. Denis O'Mahoney, whose encouragement and guidance I am very grateful for. My thanks are extended to Elaine Hattie (Bord Gais Networks), Brendan Kelly, Noelle Ameijenda & Nezar Kamaluddin (EirGrid Plc), Aoife Crowe and John Lynch (CER) and Dermot Campfield (SEMO) who have taken their time to answer to my inquiries.

Finally, I will thank my family for their constant support throughout the five years of study and my wife Ulrike for her patience and endless love.

Thank you.

TABLE OF CONTENTS

Statutory Declaration	1
Abstract	2
Acknowledgements	3
Table of Contents	4
List of Figures	7
List of Tables	9
Glossary of Abbreviations	10
1 Introduction	12
1.1 Background	12
1.2 Motivation	12
1.3 Hypothesis	13
1.4 Aim & Objectives	13
1.5 Approach & Methodology	14
1.6 Scope & Demarcation	14
2 Energy Security & Climate Change	15
2.1 Introduction	15
2.2 Sustainable Development	15
2.2.1 Energy Use in Ireland	16
2.3 Drivers of Energy Management	19
2.3.1 Energy Security	20
2.3.2 Kyoto Protocol	21
2.3.3 Legislative Framework & Policy	21
3 Integrated Assessment – The Role of Wind Energy	24
3.1 Wind Energy and Sustainability	24
3.2 Economic Impacts from the Promotion of Wind Energy	25

3.2.1	The Cost of Financial Support Schemes	26
3.2.2	Employment Opportunities	29
3.2.3	Attracting Foreign Direct Investment	31
3.3	The Irish Supply System	32
3.3.1	Integration of Wind Energy in Energy Supply Systems	33
3.3.2	Curtailment and Network Constraints	35
3.4	Base load Energy Systems	37
3.4.1	Base load Provision by Dispersion of Wind Farms	37
3.4.2	Base load Provision from Hybrid Systems	38
4	Wind Gas – Energy Storage in the Gas network	40
4.1	Concept of Wind Gas / Synthetic Natural Gas (SNG) from Wind	40
4.1.1	Conversion Technology	41
4.1.2	Conversion Efficiency & Costs	42
4.2	Localisation and Operation	48
4.2.1	Characteristics of Synthetic Natural Gas	51
5	Hybrid Power plant Design for Ireland	54
5.1	Basic Design Parameters	54
5.1.1	Analysis of Wind Power Storage Requirements	56
5.1.2	Analysis of Balancing Load Requirements	57
5.1.3	Power-to-Gas Hybrid Plant Simulations	58
5.1.4	Load Balancing Requirements in 2011 & 2020	64
5.2	Evaluation of Economic Benefits	65
5.2.1	Impact on Fuel Prices	65
5.2.2	Impact on Plant Competitiveness	66
5.2.3	Commercial Viability Analysis	67
5.3	Evaluation of Environmental Benefits	68
5.3.1	CEEP Based Assessment	69
5.3.2	Mandatory Storage Requirement for Intermittent Supply Sources	71

6 Discussion and Conclusion	74
6.1 Discussion of Main Findings	74
6.1.1 Difficulties	75
6.2 Conclusions.....	76
7 Further Research	77
8 References	78
Appendices	84

LIST OF FIGURES

Figure 1: All-Island Fuel-Mix 2010 (Source: CER, 2011).....	17
Figure 2: Energy Efficiency in Electricity Generation (DCENR, 2009)	18
Figure 3: Historical annual gas supplies ROI (Gaslink, 2011)	19
Figure 4: European Wind Resource, May 2011 (AWS Truepower)	24
Figure 5: REFIT Reference Price vs. SMP (13/07/2012).....	27
Figure 6: Average Time Weighted SMP 2011 (Clifford & Clancy, 2011).....	28
Figure 7: Direct Employment by Type of Company	30
Figure 8: The Single Electricity Market Explained (Clifford & Clancy, 2011).....	32
Figure 9: Existing and planned wind farms in Ireland (EirGrid, 2011b)	34
Figure 10: Curtailment losses at 5% of overall wind output.....	36
Figure 11: Intermittency of wind vs. base load requirement	37
Figure 12: The Storage of Wind Energy in the Gas Network (Source: DENA, 2012).....	40
Figure 13: Basic Layout of the Power-to-Gas Concept (Sterner, 2009)	41
Figure 14: Power-to-Gas efficiency - Sankey diagram	43
Figure 15: SNG Production Costs	44
Figure 16: Power-to-Gas Process Diagram.....	45
Figure 17: Location Map Power-to-Gas / Gas Network (Source: BGN)	50
Figure 18: Energy Density Comparison of available Storage Technologies (Götz et al. 2011)	51
Figure 19: Comparison of different Energy Storage Technologies (stoRE-project, 2011).....	52
Figure 20: Driving Range Variation per Fuel Type.....	53
Figure 21: Wind Speed Simulation with Monte-Carlo Method.....	55
Figure 22: Markov Random Walk Wind Speed Simulation.....	55
Figure 23: Critical excess electricity production for increasing wind penetrations).....	57
Figure 24: Power Curve E-101.....	59
Figure 25: Single Location Baseload Generation	61
Figure 26: Accumulated Energy available from Storage	61
Figure 27: Power Curve at Ideal Baseload Level.....	62
Figure 28: Mid-merit Plant Energy Balance	63
Figure 29: Mid-merit Plant Power Output Curve	64

Figure 30: Breakdown of Delivered Gas Price	66
Figure 31: CEEP-Level with Increasing Wind Penetration.....	69
Figure 32: Emission Reduction per CEEP-Level	70
Figure 33: CO ₂ -Reduction from Mandatory Storage Ranges	72
Figure 34: CO ₂ Emissions vs. Percentage of Wind Penetration.....	73

LIST OF TABLES

Table 1: REFIT Reference Price per Category (DCENR, 2012)	26
Table 2: Job Opportunities in Irish Onshore Wind Farming	30
Table 3: Irish Offshore Projects under Development (Source: reNews, 2012)	31
Table 4: Vehicle Fuel Comparison	53
Table 5: Sample Transition Matrix	56
Table 6: Power output and Cp values for the Enercon E-101 3MW	59
Table 7: Technical Specifications E-101	60
Table 8: Simulation Parameters Employed	60
Table 9: Carbon Intensity of Different Fuels	68
Table 10: CEEP-Level at Increasing Wind Penetration	69

GLOSSARY OF ABBREVIATIONS

CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CEEP	Critical Excess Energy Production
CER	Commission for Energy Regulation
CH ₄	Methane
CNG	Compressed Natural Gas
CO ₂	Carbon Dioxide
DC	Direct Current
DCENR	Department of Communications, Energy and Natural Resources
DSO	Distribution System Operator
EU	European Union
GB	Great Britain
GHGs	Greenhouse gases
HFCSS	Hydrogen Fuel Cell Storage System
IWEA	Irish Wind Energy Association
kWh	Kilowatt-hour
mcm	Million cubic meter
mscm	Million standard cubic meter
MEC	Maximum Export Capacity
MWh	Megawatt-hour
NI	Northern Ireland
NIAUR	Northern Ireland Authority for Utility Regulation
OCGT	Open Cycle Gas Turbine
P2G	Power-to-Gas
PHES	Pumped Hydro Energy Storage
PSO	Public Service Obligation
RAs	Regulating Authorities
RES-E	Electricity produced from renewable energy sources

ROI	Republic of Ireland
SEM	Single Electricity Market
SNG	Synthetic Natural Gas
SOEC	Solid Oxide Electrolyser Cell
SOFC	Solid Oxide Fuel Cell
SONI	System Operator for Northern Ireland
TER	Total Electricity Requirement
TSO	Transmission System Operator
TWh	Terawatt-hour
WEC	Wind Energy Converter

1 INTRODUCTION

1.1 Background

Ireland's dependency on energy imports was rated at 89.9% in 2008 (Eurostat, 2011). While Ireland's energy production relies merely on gas, 92.1% of the required volumes had to be imported. Increased market pressures and environmental impacts resulting from conventional power production have led to a joint approach on energy and environmental policies among the European Union (EU) member states. In 2007, the EU agreed the 20-20-20 targets: 20% reduction in greenhouse gas emissions, saving 20% of energy consumption by improving energy efficiency and 20% of energy consumption from renewable sources by 2020. In order to meet these targets Ireland has to review its electricity market mechanism. Besides a high import dependency Ireland's specific constraints include high proportions of intermittent wind penetration, limited interconnection with neighbouring markets, a weak electricity grid and limited financial strength for investments in major infrastructure projects. This thesis examines the concept of Power-to-Gas energy storage and its effects on reducing emissions and increasing energy security for Ireland. It analyses the opportunity and associated benefits of producing synthetic methane from wind power in order to increase wind power viability and reducing Ireland's import dependency.

1.2 Motivation

Electricity from wind power generation is inconsistent due to the stochastic nature of wind. The larger the share of wind power in the overall system the greater the challenges to compensate for the fluctuations of wind power. Excess electricity is produced in times of high winds and low demand and wind power output is curbed. The amplified integration of renewable sources leads to increased curtailment of 'free' surplus energy, despite the fact that valuable and limited resources are exhausted at peak times due to lack of storage abilities. Expectations in smart grid application and storage technologies to overcome these constraints are high. Previous research in the area of energy storage for Ireland comprised of pumped hydroelectric energy storage (Connolly, 2010; Connolly et al., 2012) and Power-to-Gas technologies focusing on the production of hydrogen (González et al., 2003; Carton & Olabi, 2010).

The previously researched technologies are deficient in utilising existing assets when identifying concrete and practical solutions for the Irish electricity market. The deployment of existing infrastructure components such as the gas network and its storage capacities could alleviate Ireland's fuel dependency and encounter the challenges created by the transformation process towards a low carbon economy. Special consideration is given towards the cost aspect of infrastructure supporting the RES-E target and its development beyond, as these costs are usually carried by the consumer/taxpayer.

1.3 Hypothesis

The utilisation of excess wind power to generate synthetic natural gas (SNG) would make a positive contribution towards the strategic goals of Irish Energy Policy. Power-to-Gas could deliver the following benefits:

- Enhance the integration of renewable energy into the national grid
- Ensure wind power meets base load requirements
- Improve the exploitation of Ireland's free, natural resources (renewables)
- Increase energy security for Ireland
- Contribute to reduced import dependency
- Reduce Ireland's carbon emissions
- Reduce the exploitation of fossil resources
- Lead the transformation towards 2020 and beyond at most advantageous costs with least environmental impacts

1.4 Aim & Objectives

The aim of the thesis is to identify the instruments and measures required to enable power-to-gas technology to replace Ireland's most greenhouse gas emitting power plant by maximising the utilisation of Ireland's renewable energy sources. Hence, the suggested concept will assist meeting national targets for 2020 and beyond without limiting Ireland's competitiveness, rather enhancing the ability to forecast energy cost by ensuring security of supply.

The objectives set under the aim contain the identification of the process requirements for the transformation from electricity to gas, the storage potential of energy by the system, the technological implications and the benefits achievable for Ireland.

1.5 Approach & Methodology

The research approach includes the initial assessment of the Irish power system in the context of Irish Energy Policy. With the identification of four applicable sites for wind power generation and suitable access links to the gas network a model is used to simulate the probability distribution of electric output. The information derived from the model is used to design a power system for Ireland based on electricity generation primarily from wind power and gas. The subsequent review of the findings will evaluate the Power-to-Gas concept in an environmental and economical perspective.

1.6 Scope & Demarcation

The thesis assesses the Power-to-Gas concept as an energy storage technology for Ireland. Since the introduction of the single electricity market (SEM) in 2007, Northern Ireland and the Republic of Ireland are consisting of an All-Ireland-Electricity-Market, in this thesis referred to as Ireland. Due to its isolation from mainland Europe and limited interconnectivity, Ireland has a high need of being self-sufficient in terms of energy generation and storage. Its sparse population and enormous wind resources imply that the Island of Ireland could become autonomous from harvesting and utilising their natural resources efficiently. With wind power contributing the largest share of RES-E in Ireland this thesis focuses on wind power alone. Nevertheless, the concept of Power-to-Gas energy storage is equally applicable to electricity generated by other intermittent technologies such as tidal, wave and solar power.

The explanations in this thesis are triggered by the findings from Power-to-Gas research currently underway by the Center for Solar Energy and Hydrogen Research in Baden-Württemberg (ZSW), in partnership with SolarFuel GmbH and the Fraunhofer Institute for Wind Energy and Wind Energy System Technology (IWES) in Germany.

2 ENERGY SECURITY & CLIMATE CHANGE

2.1 Introduction

Recent changes in political policies towards sustainability and environmental issues have encouraged development and investment levels in novel technologies within the fields of energy, water and the environment. Publications such as *'Defusing the global warming time bomb'* (Hansen, 2004), *'The end of cheap oil'* (Campbell and Laherrère, 1998) and *'The population explosion'* (Ehrlich & Ehrlich, 1990) are taking a systematic view on concerns that pave the way towards the megatrends of the 21st century. Climate change, energy security and population pressure are forming a central concern in the world of globalisation.

In the 1990s two ground-breaking events transformed the way of environmental and economic development: The Rio Declaration of 1992, recognizing the integral and interdependent role of nature for human welfare, and the Kyoto Agreement in 1997, when 37 industrialised countries and the European Union signed the Kyoto protocol. The commitment to a reduction in carbon dioxide (CO₂) emission levels contained the inherent need to revise energy use and the production of electricity.

In March 2007, the European Union (EU) decided on an integrated approach on climate and energy policy. In an attempt to tackle climate change whilst simultaneously increasing energy security, the European Countries committed to transform themselves into a highly energy-efficient, low carbon economy. The resultant directives and 2020 targets have a common denominator. Energy and environmental policies are based on the concept of *sustainable development*.

2.2 Sustainable Development

The Brundtland Report (1987) defined sustainable development as a process that *'meets the needs of the present without compromising the ability of future generations to meet their own needs'*.

The Energy White Paper (2007), containing the energy policy framework 2007 – 2020 *'Delivering a Sustainable Energy Future for Ireland'* outlines a wide range of strategies, targets and actions to promote the sustainability of energy use and supply. Efforts towards sustainability include the diversification of fuel mixes, both for power generation and transport, energy efficiency measures and aspects to ensure security of supply. The increased deployment of natural resources such as wind, wave and biomass for energy generation is regarded as a vital part in the transition from fossil fuels to renewable sources. However, the contemporary use of land, forests and marine environments has to ensure that land use change and the development of alternative technologies are not detrimental. In recent years the employment of some novel technologies caused unintended and adverse effects, e.g. the rapid increase in the demand for biofuels shifted the production of food crops towards the production of energy crops therewith stimulating food prices (Rosegrant, 2008).

Further challenges arise from the large scale deployment of new technologies. Research and development in novel technologies cannot neglect the need for sustainable material ingredients. Expensive and rare raw materials are useless for large scale application. Hence, modern solutions to global concerns only become viable when they can be spawned in a sustainable way and counteract resource depletion.

Unintended consequences resulting from land use change and the formation of monocultures for the production of biofuels can be averted and changes in socio-economic or environmental context must be controlled through good policy making, continuous monitoring and where necessary subsequent adjustments. Power-to-Gas technology can mitigate some of the adverse effects and simultaneously enhance the usability of renewable energy sources.

2.2.1 Energy Use in Ireland

While each member state of the EU committed working towards the joint 2020 targets - 20% reduction in greenhouse gases, 20% increase of renewable energy sources in overall energy use and 20% energy savings through energy efficiency (European Commission, 2009)

- it is the responsibility of each individual country to define national targets and implement 16

EU directives into national law. The domestic target set by the Irish Government in the National Renewable Energy Action Plan (NREAP, 2009) is striving for 40% electricity to be produced by renewable sources (RES-E) by 2020. 37% thereof are expected to come from wind energy. Under the EU Directive 2009/28/EC, Ireland is legally obliged that by 2020 at least 16% of all energy consumed originates from renewable sources. Further sub-targets include that at least 10% of transport fuels and 12% of heat demand must come from renewable sources.

The increased deployment of wind power is also aiming to address the projected increase in energy demand while simultaneously meeting the imperative to reduce greenhouse gases. The non-synchronous supply from wind generation is to date offset by the installation of back up capacity in form of gas turbine plants (EirGrid, 2011b). In order to improve the overall capacity value of wind power large scale energy storage technologies are required.

In 2011 the total electricity use in Ireland accounted for 35.33TWh (ROI 26.04TWh, NI 9.02TWh) whereof 16.75% (5.92TWh) was produced by renewable sources (Eirgrid, 2011c & SONI, 2012). The share of each fuel type in electricity generation is shown in Figure 1.

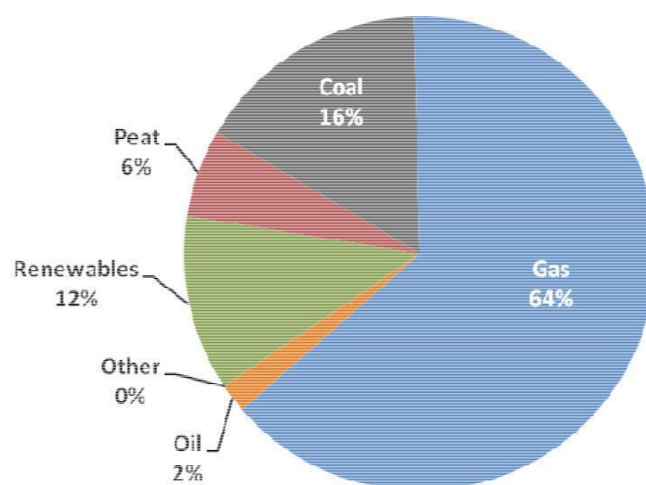


Figure 1: All-Island Fuel-Mix 2010 (Source: CER, 2011)

In Northern Ireland (NI) 510 MW of conventional plant will be decommissioned from Ballylumford by 2016, while in the Republic of Ireland (ROI) the oil based generation units at Tarbert and Great Island are due to close over the next ten years, leading to a further reduction in capacity of 802MW (EirGrid, 2011b). The shortfall of power capacity will be mitigated by five new gas powered stations that are according to EirGrid (2011b) expected to go online before 2020 adding a generation capacity of 808 MW. Further decentralised generation is expected from an increase in combined heat and power (CHP) applications. In 2010 CHP generation in Ireland contributed only 6.8% to the gross electricity generation and hence supplied only marginal over half of the EU average of 11.4%. CHP or cogeneration is a technology able to gain maximum efficiencies of power plants by producing heat and power in the same plant. The technology, generally consisting of a gas turbine with heat recovery, can achieve efficiencies of up to 60% (Siemens, 2012). When there is a demand for heat output, efficiencies of over 75% can be achieved. Statistics published by the EEA (2006) state that average energy efficiency of thermal electricity and heat production in the EU-27 stands at 47%. With the installation of five new, modern OCGT and CCGT, further improvements of energy efficiencies in electricity generation are expected.

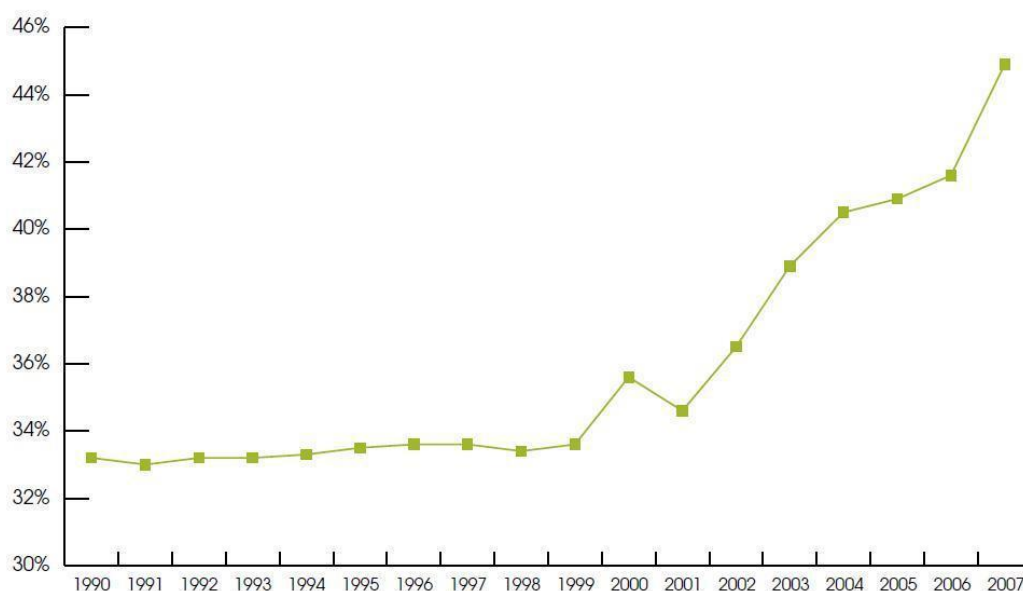


Figure 2: Energy Efficiency in Electricity Generation (DCENR, 2009)

Business as usual projections indicate that more than 70% of base load electricity would be generated from natural gas by 2020 (DCMNR, 2007). In 2010 national gas demand for ROI

was 5700mcm. Domestic production accounted for 400mcm, only 7% of overall demand (IEA, 2010). Indigenous natural gas production has fallen fivefold since 1995 and approximately 93% of the ROI Gas demand was supplied by Great Britain (GB) through the Moffat entry point in 2009/2010. Figure 3 depicts the historical indigenous (IND) natural gas production in ROI. NI has no natural gas resource of its own and is 100% dependent on imports.

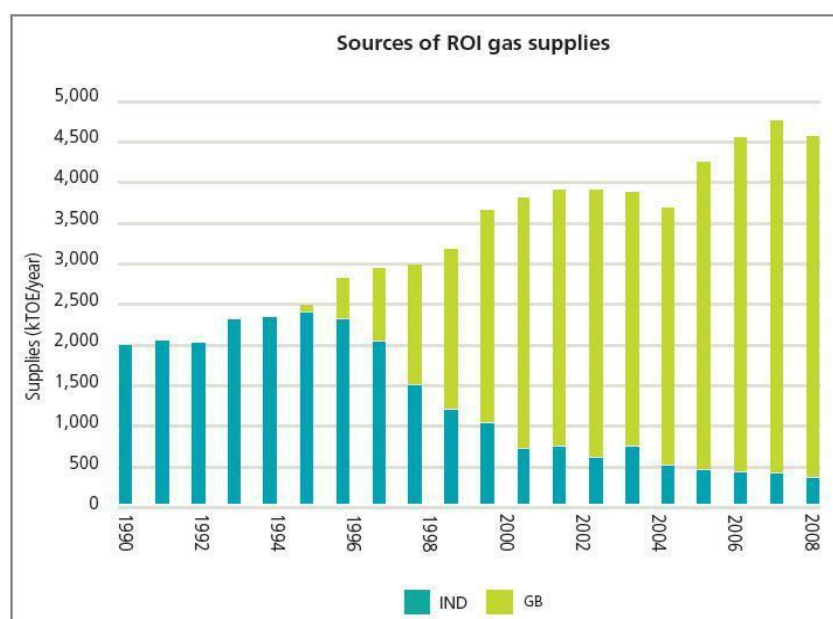


Figure 3: Historical annual gas supplies ROI (Gaslink, 2011)

The increasing import dependency, rising energy prices and augmented interconnection of life-style and energy consumption causes unrivalled pressures on global markets. Energy security has become one of the main drivers in the transformation of power generation.

2.3 Drivers of Energy Management

The nuclear power plant disaster in Fukushima Daiichi, Japan on March 11th 2011, has enlivened the ongoing public debate on energy supply and energy security. Germany's commitment to shut down all of its 20 nuclear power reactors by 2022 is setting the pace for the implementation of a new energy era. Although Ireland does not have any nuclear power stations, the transformation of its power system is required to meet European targets, Kyoto commitments and internal market pressures. The cost of energy is connected

to economic prosperity. Hence the stability of energy supplies and energy cost is important to attract and retain businesses. Furthermore a low level in energy prices is enhancing competitiveness on global markets. Energy management has therefore become an industry of its own. The urgent need for adequate energy management is shown in the fact that only 31 % of all primary fuel inputs for electricity generation resulted in useful final electricity consumption (SEAI, 2011). This implies not only that the nearly €6 billion of annual energy costs exported from the domestic economy are poorly utilized it also highlights the wasteful handling of finite natural resources. As a consequence the Irish Government set the following energy efficiency targets:

- delivering 20% energy efficiency savings by 2020
- a target of 33% for the public sector (DCENR, 2009)

2.3.1 Energy Security

Ireland's energy import dependency in 2009 was 88% and in 2007 fossil fuels accounted for 96% of all energy use in Ireland. While over 60% of the electricity generated in 2010 relied on natural gas (SEAI, 2011a), indigenous gas production since 1990 has decreased by 78%.

Energy security is an important factor to social welfare and economic development. Securing future energy needs requires a reduced dependency on fuel imports and a reduction of finite sources such as fossil fuels in the overall energy mix. Hence, strategic measures include the diversification of energy sources and an increase in the application of renewables. Besides securing a stable and reliable supply chain, energy security also requires the adequate generation, transmission and distribution of domestic power production.

The introduction of the Large Combustion Plant Directive (2001/80/EC) and the Industrial Emissions Directive (2010/75/EU) mean that generating units must adhere to strict emission limits. Older, inefficient and highly pollutant plants have either to be retrofitted or shut down. Yet, the increasing influx of renewable and intermittent power generation poses substantial challenges for the transmission system operator (TSO) and distribution system operator (DSO) in terms of operation and management of the electrical system.

Interconnection between Ireland and Great Britain can help in meeting adequacy levels and in balancing system load requirements at high costs. However, as long as renewable energy is intermittent in nature and cannot be stored the electricity system has to rely on conventional plant. According to EirGrid (2011b), sufficient base load power is available to meet Ireland's supply and demand balance for electricity for the period up to 2021 but the growing employment of non-synchronous renewable generators requires the renewal of the existing transmission system to accommodate changed electricity flow patterns. In order to enhance the utilisation of RES-E the storage of excess electricity produced at times of high electricity output but low consumer demand is necessary.

2.3.2 Kyoto Protocol

In 1997 the European Union and 37 industrialised countries signed the Kyoto Protocol. The Kyoto Agreement was setting binding targets to reduce GHG emissions by an average of 5 to 8% against 1990 levels in the five year period from 2008 to 2012. In order to achieve this reduction a range of options including measures such as energy efficiency, energy conservation and the employment of renewable energy (RE) sources has been identified.

Since, the international community consisting of 195 countries collectively ratified the United Nations Framework Convention on Climate Change (UNFCCC). While all parties agree on the ultimate aim of preventing 'dangerous' human interference with the climate system, there is dissent among the parties to what extend various measures are required. A subsequent agreement to the Kyoto Protocol is expected by 2015.

2.3.3 Legislative Framework & Policy

In an attempt to address climate change whilst increasing energy security, the European Union decided on an integrated approach on climate and energy policy. In 2009 the EU launched its Europe 2020 strategy including its flagship initiative "Resource Efficient Europe". The joint targets set by the member states are by far exceeding the targets set in the Kyoto Protocol. At its forefront is the development and improvement of the energy infrastructure beyond national boundaries in order to create a properly functioning energy market that enables the integration of renewable energy sources, increases energy

efficiency, enhances security of supply and allows for the adoption and integration of new and intelligent technologies.

Leading documents for the development of legislation and policy making are the Europe 2020 Strategy for smart, sustainable and inclusive growth (COM 2020, 2010), the Energy Infrastructure Priorities for 2020 and Beyond (COM 677, 2010) and the Energy Roadmap 2050 (COM 885/2, 2011).

2.3.3.1 EU Directives

The central draft of legislation for energy policy and associated activities is the EU Directive 2009/28/EC. The directive includes a comprehensive number of actions and defines international guidelines from where national legislation is drafted. The extensive document outlines the requirements for national action plans and energy efficiency specifications. It further covers the strategic goals for the integration of renewable generation and the objectives towards meeting the 2020 targets and developments beyond. The 2009/28/EC Directive is repealing the Directives 2001/77/EC *on the promotion of electricity produced from renewable energy sources in the internal electricity market* and 2003/30/EC *on the promotion of the use of biofuels or other renewable fuels for transport*. Relevant pieces of Irish legislation resulting from the 2009/28/EC Directive are first and foremost S.I. No. 147 (DCENR, 2011) on renewable energy and its integration according to the European Directive. Furthermore a number of strategies have been drafted outlining the national targets for Ireland.

2.3.2.2 National Strategy

Recent national strategies include the NEEAP 'The National Energy Efficiency Action Plan 2009 – 2020' (DCENR, 2009), and the NREAP 'The National Renewable Energy Action Plan' (DCENR, 2010). The national strategies outline how the joint targets set at European level are being met in relation to national abilities and constraints. Ireland is hereby experiencing additional pressures due to the aftermath of the financial crises. Hence the state is constricted from paying subsidies and investing in new infrastructure projects due to a number of other financial commitments. On the other hand the transformation of energy

services and efficiency improvements offer a chance of creating new employment opportunities, retrieve growth in GDP and to reduce the transfer of billions of Euros out of the domestic market into foreign economies.

The Power-to-Gas energy storage technology examined in this thesis features such a chance which is not only in line with national strategies it also offers a solution to reduce network constraints and curtailment and improve security of supply. The following chapter discusses the role of wind energy and the unrivalled possibilities of its utilisation.

3 INTEGRATED ASSESSMENT – THE ROLE OF WIND ENERGY

3.1 Wind Energy and Sustainability

Wind energy has been identified as a key element in reaching the EU policy objectives to achieve a sustainable energy future. Its application contributes to tackle climate change, ensuring energy security and enhancing competitiveness. Ireland has an abundance of strong wind, particularly at the west coast. In terms of wind resources Figure 4 clearly shows that Ireland has among the best wind resources in the EU.

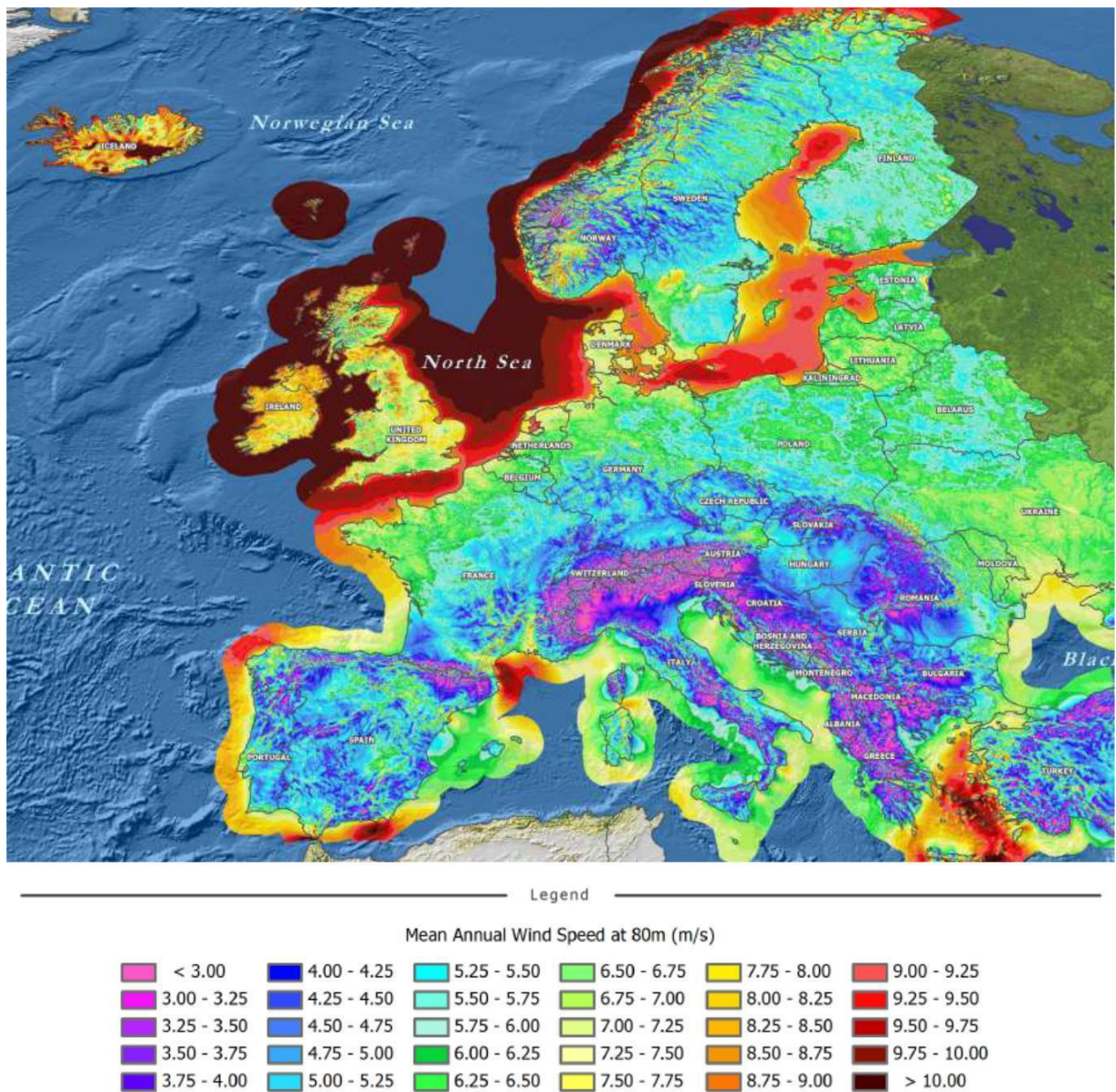


Figure 4: European Wind Resource, May 2011 (AWS Truepower)

When wind energy is combined with energy storage it can present a viable alternative offering increased output stability and a capacity level far greater than the 25 - 45% typically associated with wind generation (Denholm et al., 2005). When managed accordingly wind energy systems can provide a stable and reliable base load similar to conventional power stations including a reduction of negative by-products such as the greenhouse gas CO₂ and without the release of harmful sulphur dioxides and nitrogen oxides.

In times of high electricity output but low demand the electricity network is challenged by a critical excess energy production (CEEP). When CEEP occurs in the energy system wind farm output is curtailed¹ and wind farms are shut down. The available energy output is lost. In times of high electricity demand but low RES-E output, back-up power from conventional plant is required. An increase in energy storage capabilities could mitigate the requirement for conventional back-up supply and increase the benefits of RES-E. A number of energy storage options such as PHEs and CAES have been examined in recent years.

3.2. Economic Impacts from the Promotion of Wind Energy

The change from a conventional fossil fuel based power system towards one carried by renewable sources is resulting in higher capital costs upfront. Hence the economic impacts from the promotion of wind energy have repeatedly been disputed.

A report by SEAI, reviewing and analysing economic and enterprise benefits, states: *'In a market comparison with fossil fuels, several forms of RE have been shown to be competitive – even before the added benefits of security of supply, environmental improvements and RE employment are factored in'* (SEAI, 2012). With increasing fuel costs for conventional power production the economic benefits of wind generation will materialise in the short to medium term. The total cost of Irish electricity generation is based on three variables: the wholesale cost of electricity, the PSO cost of wind and the dispatch constraint costs. In the following section the impact from wind power support mechanisms on the wholesale electricity price is examined. A detailed explanation of the Irish electricity market is given in chapter 3.3 *The Irish Supply System*.

¹ For definition on curtailment, see page 35

3.2.1 The Cost of Financial Support Schemes

In the Republic of Ireland, investment into renewable electricity generation is supported by the Renewable Energy Feed-In Tariff (REFIT). The scheme guarantees investors a minimum payment for RES-E over a period of 15 years and hence has to be seen as a subsidy. The cost of the scheme is passed on to the electricity consumer in form of a Public Service Obligation (PSO) Levy which is added as an additional cost item in the electricity bill. The PSO levy is composed from all costs accumulated under the national policy objectives of security of energy supply, the use of indigenous fuels (i.e. peat) and the use of renewable energy sources in electricity generation (CER, 2012).

Evidence indicating that wind power generation increases electricity prices for consumers has to be put in context. Wind energy converters (WECs) do not consume fuel and hence can bid the lowest price within the Single Electricity Market (SEM). In line with policy targets wind power generation is supported by two payment mechanisms: the introductory Alternative Energy Requirement (AER) scheme and the current Renewable Energy Feed in Tariff (REFIT). Both schemes pay a reference price per kWh output determined by the mechanism. The REFIT Scheme covering 4,000MW of renewable generation capacity (DCENR, 2012) is not paid where the market price is equal or greater than the sum of the REFIT reference price. In times where the market price is below the REFIT reference price the scheme is paying the difference between the guaranteed tariff and the system marginal price. In June 2012 the scheme catered for 1,379MW (CER, 2012) and estimated costs of the scheme amount to €35.8 million². Table 1 illustrates agreed reference prices per MWh for each technology category covered by the REFIT 2 Scheme.

Category	REFIT reference price MWh
Onshore wind (above 5MW)	€66.35
Onshore wind (equal to or less than 5MW)	€68.68
Hydro (equal to or less than 5MW)	€83.81
Biomass Landfill Gas	€81.49

Table 1: REFIT Reference Price per Category (DCENR, 2012)

²PSO Levy Period: 1st of October 2011 to the 30th of September 2012

With a benchmark price set at €64.61/MWh for the period 2012/2013, suppliers of electricity from wind will receive a subsidised payment of €0.00174/kWh at times where the market price is below the REFIT reference price plus 15% of the REFIT reference price to cover the cost of managing the variable production of wind energy. After 15 years the subsidised payment will end.

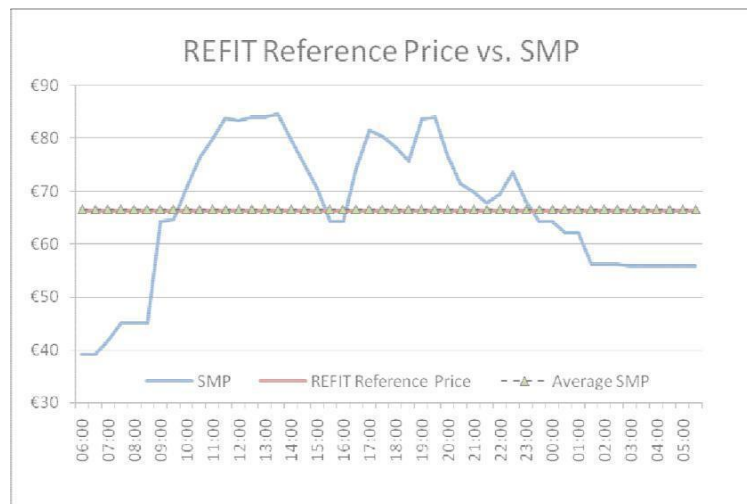


Figure 5: REFIT Reference Price vs. SMP (13/07/2012)

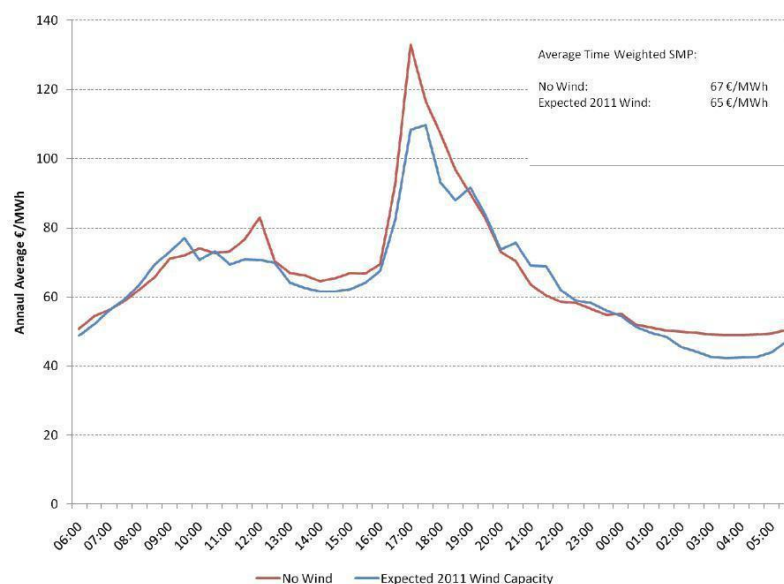
Electricity demand in Ireland is generally lower during the summer resulting in lower electricity cost. Figure 5 compares the system marginal price (SMP) on the 13/07/2012 as per SEMO (2012) with the REFIT reference price. The average SMP is €0.25 higher than the guaranteed reference price. Only when the SMP falls below the REFIT reference price the payment guarantee mechanism is paying. During the winter months when electricity demand is high the SMP goes up. The REFIT scheme is effectively only a payment guarantee that secures investors a return if a shortfall of revenues from normal market activity should emerge.

In contrast Devitt and Valeri (2011) investigated the effects of wind energy on the overall electricity price. They found that when fuel prices are high wind generation has a hedging effect on electricity prices. However, due to the presence of fixed payments by the REFIT scheme the cost of renewables is elevated artificially and cost are unnecessary high when fuel prices are low. The result of the wind power support mechanism is effectively a reduction in the variability of the System Marginal Price (SMP). The SMP is the energy

component of the total cost of producing electricity (see Figure 8: The Single Electricity Market Explained).

A study by Clifford & Clancy (2011) modelling the impact of wind generation on wholesale electricity cost indicates that the impact of wind generation in 2011 reduces overall wholesale electricity cost by on average €2/MWh (see Figure 6). However, the study concludes that the total reduction of €74 million is almost completely offset by the costs of the PSO associated with wind generation as well as increased constraint costs.

Figure 6: Average Time Weighted SMP 2011 (Clifford & Clancy, 2011)



A negative cost-benefit ratio is emerging first when wind power output has to be curtailed. Research by Connolly et al. (2010) *modelling the existing Irish energy-system to identify future energy costs and the maximum wind penetration feasible* defined the optimum wind penetration level in economical terms. The study based on data from 2007 found that lowest system costs are achieved at a wind penetration level of 31.6%. For Ireland's power system this would correspond to about 8.23TWh / 3,030MW (2011) and 8.74TWh / 3,271MW (2020) of wind energy in ROI. According to the study additional wind capacity installations will be counterproductive in economical terms unless the CEEP can be exported or stored profitably.

The technical advancement of WECs and a reduction in production costs has shown that electricity generation from wind now can compete with conventional power production. The new generation of WECs is taller and more effective in utilising the forces of wind. The concept of repowering³ is availing of this benefit. The average unit cost of one kWh_{el} of wind power in 2005 stood at 0.062Eur/kWh, for 2020 a price of 0.045Eur/kWh and in 2030 of 0.036Eur/kWh is predicted (EEA, 2009). Subsequent cost reductions in the sector are expected in line with falling price levels in recent years.

Another reason for the improved viability of wind power is that conventional generation equipment has to pay increasingly for its own environmental costs.

3.2.2 Employment Opportunities

Great economic benefits are lying in the job creation opportunities arising from the development of wind power. While construction related job creation is factored with 1.2 jobs per annual MW installed, 0.33 long term Jobs are created in operations and maintenance per MW of cumulative capacity installed (EWEA, 2009)⁴. With a target of 6100 MW of wind capacity installed the sector would secure 540 construction jobs (based on 3,777MW remaining to be installed over 7 years) and employ further 1,250 people in operation, maintenance and repairs over a 20-25 year life span of wind farms. This figure does not take into account the job creation opportunities arising from development, consultancies, R&D or utility services. Much higher employment effects are attributed to offshore wind generation which has been stagnant in Ireland since the installation of the first offshore wind park in Europe, the Arklow Banks.

Table 2 below lists the job opportunities available from onshore wind generation when implementing the 40% RES-E target for Ireland. While the work intensive manufacturing processes associated with wind power generation are unlikely to materialise without relevant long-term commitments from government, the development, construction, O&M and other services are very likely to turn out in Irish jobs with great benefit for regional

³ Repowering, a term describing the replacement of old wind turbines with modern ones, follows the concept of reducing the number of turbines by half while duplicating the engine power. As a result generating output on the same area can be tripled.

⁴ applicable to onshore activities

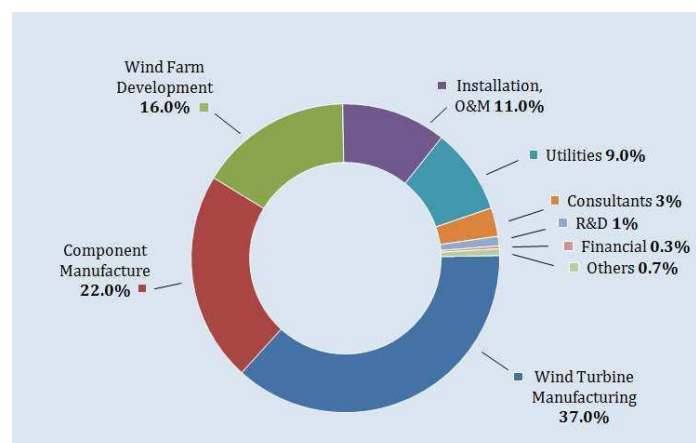
development. From the compilation based on the Wind at Work Report by EWEA (2009) 9,095 job opportunities could be created assuming that 6100MW of wind power capacity will be realised (excluding employment in the manufacturing sector). There were 1500 people employed in the wind industry in Ireland in 2007. Figure 7 illustrates how employment opportunities are distributed in the wind industry.

Table 2: Job Opportunities in Irish Onshore Wind Farming

	Share of Direct Employment	Direct Employment
Wind Turbine Manufacturing	37.0%	8,207
Component Manufacture	22.0%	4,880
Wind Farm Development	16.0%	3,549
Installation, Operation & Maintenance	11.0%	2,440
Utilities	9.0%	1,996
Consultants	3.0%	665
R&D	1.0%	222
Financial	0.3%	67
Others	0.7%	155
Total	100.0%	22,182

* Share of Direct Employment from EWEA, 2009; Direct Employment Figures based on 6100MW

Figure 7: Direct Employment by Type of Company



With one of the best wind resources in Europe, Ireland could not only become self-sufficient in its energy supply, Ireland could also become a major exporter of wind energy. Beside the opportunity to create thousands of regional jobs this would also secure long term revenues from electricity sales. The potential economic value of electricity generated by wind could reach almost €15 billion by 2050 according to an estimate by SEAI (2011c).

Another economic benefit of locally sourced power is the reduced flow of revenues from fuel imports into foreign markets. The more wind farms in Irish ownership the more revenue will stay within the economy. Figures for wind farm ownership in Ireland have been sought from IWEA but no such information was available at the time of writing.

3.2.3 Attracting Foreign Direct Investment

Current projects in Irish offshore wind development reach a capacity of 3,414MW (see Table 3). By August 2012 the Irish Government did not offer any financial supports or incentives towards the development of offshore wind energy. However, discussions with the British Government are underway exploring scenarios of enhanced transmission lines and the export of Irish wind power to the UK market. The long term commitment of Irish legislative bodies is required to support such ventures and attract foreign investments into the offshore wind industry in Ireland. Consequently investments in manufacturing facilities, harbour development and infrastructure would become viable. SEAI (2012) claims that sustainable energy could support at least 30,000 Irish jobs by 2020.

Table 3: Irish Offshore Projects under Development (Source: reNews, 2012)

Developer	Project Name	Project Size	Status	Location
Treasury Holdings & Fred Olsen	Codling Bank	1,100MW	holding licence but no grid offer	Coast off Co. Wicklow
Treasury Holdings & Fred Olsen	Codling Bank Ext.	1,000MW	holding licence but no grid offer	Coast off Co. Wicklow
SSE Reneables	Arklow Wind Farm	520MW	holding licence but no grid offer	Coast off Co. Wicklow
Saorgus	Dublin Array	364MW	holding grid but no planning approval	Coast off Co. Dublin
FST*	Na Sceirde	100MW	holding grid but no planning approval	Coast off Co. Galway
Oriel	Oriel Windfarm	330MW	holding grid but no planning approval	Coast off Co. Louth
Total:		3,414MW		

*Fuinneamh Sceirde Teoranta

3.3 The Irish Supply System

The Irish supply system operates as a Single Electricity Market on the island of Ireland. Since 2007 system operators EirGrid and System Operator Northern Ireland (SONI) are acting under the Single Electricity Market Operator (SEMO). Figure 8 taken from a joint publication from EirGrid and SEAI summarises how the Single Electricity Market is operating.

Single Electricity Market (SEM) and the Public Service Obligation (PSO)

The rules of the all-Island Single Electricity Market (SEM) are detailed in the trading and settlement code. Under the code, electricity generators offer electricity into a central pool from where electricity suppliers purchase electricity to cover their consumer's demand for each half hour throughout the day. Price making generators bid into the pool a price for their production that is equal to the short term cost of producing that energy. The SEM pool price is set by the most expensive generator required to meet supplier demand in a half hour trading period. All generators who produce electricity in a trading period receive the SEM pool price for that period, which for most generators is greater than their short term cost of producing electricity. This System Marginal Price (SMP) is the energy component of the total cost of producing electricity. Other market payments are made to generators, to ensure that the system has adequate generation capacity into the future. These payments are called capacity payments. The capacity price and the market SMP price represent the average long term cost of producing electricity in the SEM.

The SEM market software produces a least cost schedule of generation for all the units on the system with the assumption that there is no network or operational constraints. In order to maintain a safe and secure power system, the Transmission System Operator (TSO) may have to deviate from the generation schedule created by the SEM. This creates additional costs to the system, called Dispatch Balancing Costs, commonly known as constraints costs.

Policy supports have been introduced by Government to encourage the development of renewable energy in order to capture some of the wider benefits associated with renewable energy – such as a reduction in the reliance of Ireland on imported fossil fuels. These supports are also required to comply with targets specified in EU legislation. Wind power generation is supported by two policy mechanisms that are paid through the PSO levy on all electricity consumers: the legacy Alternative Energy Requirement (AER) scheme and the current Renewable

Energy Feed in Tariff (REFIT). Under these schemes an electricity supplier buys the output of a wind farm at a fixed rate determined or influenced by the policy mechanism. The supplier then sells the electricity into the SEM pool. If the aggregate revenue a supplier receives from each trading period throughout the year is less than the policy tariff then the difference is paid through the PSO. Under REFIT, suppliers also receive a balancing payment – 15% of the large wind category tariff – to cover the cost of managing the short term variable production of wind energy.

As wind generators do not consume fuel they have no short term costs and hence can bid a zero price to the SEM. As price takers in the SEM, they receive the SMP set by the most expensive generator for their output in that half hour trading period. By displacing higher cost fossil fuel generation, wind generation tends to reduce the total cost of producing electricity and hence the SMP.

Figure 8: The Single Electricity Market Explained (Clifford & Clancy, 2011)

Although Irish legislation demands the priority dispatch of generating units using energy from renewable sources (DCENR, 2011) the limited grid capacities especially in remote areas constitute a limitation of the available power supply. Wind generators with a firm access offer registered as a Price Taker are compensated for what they could generate when shut down during a period of times of transmission constraints or curtailment of wind-only reasons (CER, 2008). A Price Taker is defined as any type of plant that is given priority in meeting demand in the unconstrained schedule but does not set the price (CER & NIAUR, 2008).

3.3.1 Integration of Wind Energy in Energy Supply Systems

Ireland's wind energy sector has grown continuously since 1997 and the 2030MW of wind power installed by the end of 2011 generated approximately 15% of the overall electricity demand. With 270MW of wind power installed in 2011, annual wind power installations have to increase in order to meet the approximately 5100MW (ROI 3800MW, NI 1300MW) of total wind power capacity required by the 40% RES-E target (EirGrid, 2011). The projects currently in the development and planning process amount to 1875MW of electrical capacity, whereof 1367MW of wind capacity are signed by a connection agreement with EirGrid and 508MW of wind power capacity have received planning approval in Northern Ireland (EirGrid, 2011b).

Figure 9 illustrates where existing wind farms and wind farms in planning stage⁵ are located. A major challenge in the deployment of wind power is the electricity generation in remote areas as shown in the map below. Wind power is generally generated in coastal, mountainous and rural areas away from the major demand centres. This separation of resource and demand entails the need for the extension and upgrade of the existing transmission and distribution network. In line with RES-E targets set for 2020 and beyond EirGrids GRID25 Implementation Programme states that in respect to future grid requirements approximately further 1,150 km of new power circuits have to be build. This

⁵Planned Wind Farms refers to wind farms that have signed a connection agreement within ROI or have received planning approval in NI

represents an increase of approximately 20%. In addition 2,300 km of the existing transmission lines will require to be upgraded (EirGrid, 2012).



Figure 9: Existing and planned wind farms in Ireland (EirGrid, 2011b)

3.3.2 Curtailment and Network Constraints

The rising number of wind farms connected to the single electricity market (SEM) results in the unavoidable consequence of curtailment. According to the regulating authorities (RAs) curtailment of wind generation occurs when there is excess wind generation available to meet system demand (CER & NIAUR, 2012). ‘Curtailment’ is hereby defined as a system operation issue and is not linked to network capacity. Where there is not sufficient capacity on the network to take the electrical output from wind generation, then the event is classified as a ‘constraint’. The TSOs on the island are both heavily investing in reducing limitations in the system and increasing the secure level of system performance as both curtailment and constraints are resulting in an economic loss to customers when electricity which would otherwise be exported to customers is turned down.

The treatment of curtailment in so called tie-break situations⁶ affects the remuneration of generating units and hence impacts on its economic viability. Wind energy converters (WEC) without a firm access offer and a sufficient maximum export capacity (MEC) might not be able to secure investment for development. This in turn might jeopardise the achievement of 40% RES-E by 2020. The public consultation process in connection with scheduling and dispatch (tie-break situations) has been ongoing for a number of years. A decision on the treatment of curtailment in tie-break situations is due to be released by the RAs in due course. The utilisation of a base load hybrid system (as outlined in section 3.4 Base load energy systems) aims to compromise CEEP by storing the excess electricity. Up to date wind farm owners are compensated when curtailed.

Under the priority dispatch regulation⁷ wind farm owners receive the average value of the estimated output when curtailed although no electricity is generated. Simultaneously, conventional power plants that are run to maintain system stability are being compensated for their operating costs. In consequence, the same unit of electricity delivered to the consumer is paid twice thereby causing an avoidable cost.

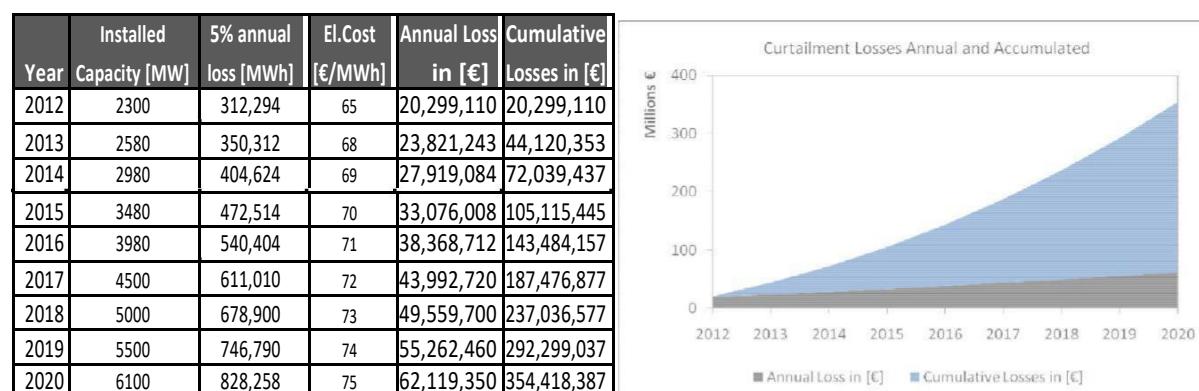
⁶Tie-break Situation: a situations where a number of available generation units have to be curtailed

⁷S.I. No. 147

In order to alleviate the loss of RES-E EirGrid and SONI established a programme of work entitled ‘*Delivering a Secure, Sustainable Electricity System*’ (DS3). The programme is aiming to increase the secure level of non-synchronous penetration of wind power to 75%. According to the TSOs own estimates the level of wind curtailment in 2020 can be kept at about 5% (CER & NIAUR, 2012). Above government commitments of 40% RES-E the GRID 25 report by EirGrid (2011) and subsequent publications estimate that a total of 6100MW of total wind generation will be installed by 2020.

Assuming a conservative capacity factor of 31%, a 5% loss of the total RES-E output would account for 828GWh in electrical energy being lost⁸. Assuming the average cost of electricity in 2020 will be at €75.00/MWh⁹ the financial loss in 2020 alone will amount to €62million. Cumulative losses in the eight years from 2012 to 2020 will have reached more than €350 million. Figure 10 below illustrates cumulative and annual losses from curtailment at 5%.

Figure 10: Curtailment losses at 5% of overall wind output



The level of curtailment is based on 5%; Installed Capacity is estimated; Electricity costs allow for annual adjustments starting at €65/MWh in 2012, ending at €75/MWh in 2020.

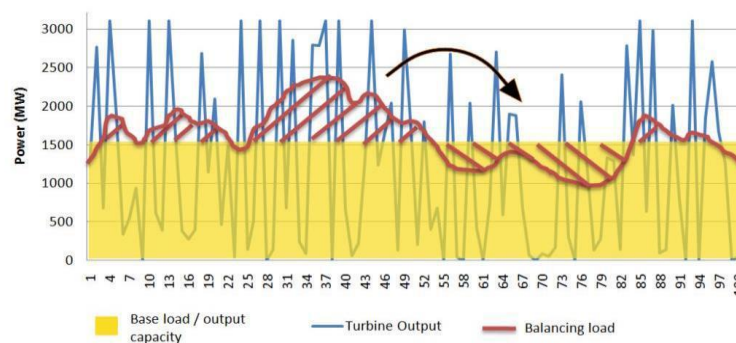
⁸ Calculations shown in appendix

⁹ Price estimation based on an increase in natural gas prices, carbon tax and PSO costs

3.4 Base load Energy Systems

The optimal integration of wind energy into the Irish power system requires a reduction of the variable output of wind farms. This can be achieved by two mechanisms. The first mechanism will reduce the peak electrical output by virtually ‘de-rating’ the maximum output towards a more frequent and therewith stable output capacity. The second mechanism will buffer the excess energy resulting from the de-rating process to provide a standing reserve if electricity output from wind is below the designed output capacity (Figure 11).

Figure 11: Intermittency of wind vs. base load requirement



Ideally the system is maintaining a continuous output capacity and therefore can be treated as a base load system. Black and Strbac (2005) argue that the cost of maintaining system security dominates all other costs while approximately 30% of all power production must come from base load systems in order to provide a stable electricity system (Connolly et al., 2012). Power plants with baseload characteristics maintain grid stability and enable system operators to balance between demand and supply. The integration of wind energy into baseload systems requires the strategic positioning of wind farms combined with the option of energy storage. Both aspects are explained in the following sections.

3.4.1 Base load Provision by Dispersion of Wind Farms

The dispersion of wind farms results in a major benefit to the electricity system. A very large wind farm with several 100MW of capacity connected to the transmission system at a single access point will have a more significant impact on the energy balance than the same total output dispersed over a number of small wind farms throughout the country. In addition, wind conditions usually vary throughout different sites and a reduction in wind output on

one site would only affect the rated output at that location and not of the whole wind capacity installed, i.e. if the same capacity would be located on one site the impact on the power system would be considerably greater and the contribution from wind energy in the overall energy mix considerably reduced.

A study into the impacts of increased levels of wind penetration on the Irish electricity system by Garrad Hassan (2002) states: *'[...] the combined output of the wind farms which were widely dispersed across the country would rarely fall to zero, so reliance could be placed on the availability of some proportion of their combined rated capacity'*. In order to maintain a base load system the dispersion of WECs will enhance the capacity factor of the wind in the overall base load mix consisting of WEC output and energy storage.

3.4.2 Base load Provision from Hybrid Systems

A Hybrid System combining wind generation and power generation from gas turbines is able to provide a constant base load similar to conventional power plants. Traditionally the concept utilises wind turbines and conventional power production in separate systems. These could be diesel engines, gas turbines or other thermal plant with short response time. A hybrid system whether run on gas or wind will be able to provide a constant load to the network. Since the growth of RES-E results in critical excess electricity production (CEEP) energy intensive storage technologies with low efficiencies become viable in that their 'operating costs' are carried by the CEEP. A hybrid system then does not need a conventional fuel supply. Instead of curtailing WECs the CEEP is used to convert electricity through electrolysis and methanation into synthetic natural gas (SNG). The process interconnects the power and gas network, improves the value of wind energy and offers unprecedented opportunities for the sustainable management of energy.

The transformation process of electricity into SNG represents the storage of electrical energy as chemical energy in gaseous form. The stored energy content can be converted back into electrical energy when needed. Research in Power-to-Gas technology has been ongoing in the USA, Denmark and Germany. A breakthrough has been made since the development of the first 25kW unit by a consortium consisting of the SolarFuel GmbH, the Center for Solar Energy and Hydrogen Research in Baden-Württemberg (ZSW) and the

Fraunhofer Institute for Wind Energy and Wind Energy System Technology (IWES) in Germany. Currently an up-scaling of the 25kW-alpha-model is underway. The new system sized at 250kW is planned to produce SNG by summer 2012.

In parallel, the AUDI AG is developing the first industrial Power-to-Gas system in order to fuel 1,500 AUDI A3 TCNG cars. The 6.3MW unit producing 1,000t of SNG per annum is expected to become operational by 2013. The system is powered by four 3.6MW offshore wind turbines with an expected power output of 53,000MWh/year (Mangold, 2012). Chapter four will describe the concept of Power-to-Gas, examine the conversion technology and evaluate the conversion efficiencies and costs. In chapter five a hybrid power plant design for Ireland is developed and the benefits achievable for Ireland are critically reviewed.

4 WIND GAS – ENERGY STORAGE IN THE GAS NETWORK

4.1 Concept of Wind Gas / Synthetic Natural Gas (SNG) from Wind

The Power-to-Gas technology is based on the transformation of electricity into chemical energy storage. The increasing employment of wind power in the overall electricity system requires the balancing of fluctuating power production. At times of high wind penetration but low electricity demand critical excess electricity is produced. In order to protect the network from instabilities wind energy converters are restricted from energy production, a process called ‘curtailment’. Power-to-Gas technology aims to utilise this critical excess energy production (CEEP) and converts excess electricity into synthetic natural gas (SNG). The process currently transformed in two steps requires water for electrolysis and carbon dioxide for the methanation of hydrogen. The final products are methane, oxygen and water. Subsequently the natural gas substitute can be fed into the existing gas network where it can be stored and withdrawn when needed.

The comparability of SNG and natural gas allows its complete substitution (Sterner, 2009). Consequently, locally produced SNG can be offset against imported gas. An important aspect in terms of practicability and economic value is the utilisation of an existing piece of infrastructure. The existing gas network with more than 13,000 kilometres of network acts hereby as an energy storage facility. Furthermore any environmental impacts associated with the construction of pumped hydro electrical storage systems (PHES) are avoided.

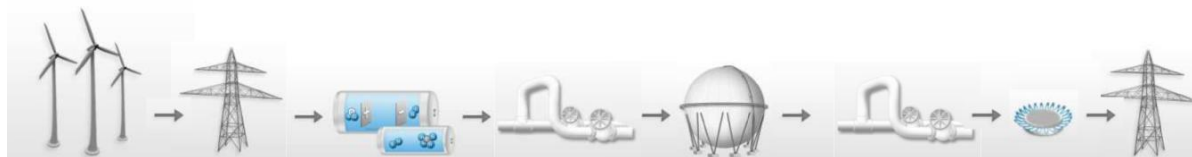


Figure 12: The Storage of Wind Energy in the Gas Network (Source: DENA, 2012)

Past research focused on the storage of energy in form of hydrogen (González et al., 2003; Carton & Olabi, 2010). In comparison to hydrogen Jensen and Morgensen (2004) state that CH₄ contains three times more energy than H₂ per unit volume, therefore CH₄ has a higher value both in terms of heating value but also in terms of cost of storage.

4.1.1 Conversion Technology

The Power-to-Gas process requires electricity, water and carbon dioxide as input. The process yields oxygen, water and methane as output. In a first step water is broken down in to its molecules in order to produce hydrogen. The two techniques commonly used are the traditional alkaline electrolysis used in industrial processes and the proton exchange membrane (PEM) electrolysis favoured for its high purity and on-site application. In the first step water (H₂O) is dissociated into the molecules hydrogen (H₂) and oxygen (O₂). The by-product of oxygen is released from the process. In a subsequent process hydrogen is transformed into methane through a chemical reaction with carbon dioxide (CO₂). The process known as Sabatier reaction or methanation results in the end products of methane (CH₄) and water (H₂O).

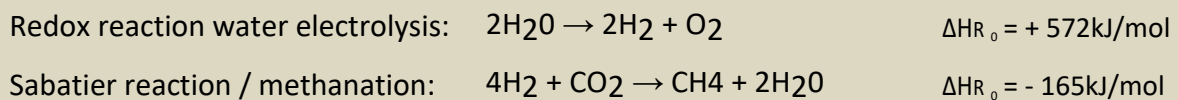
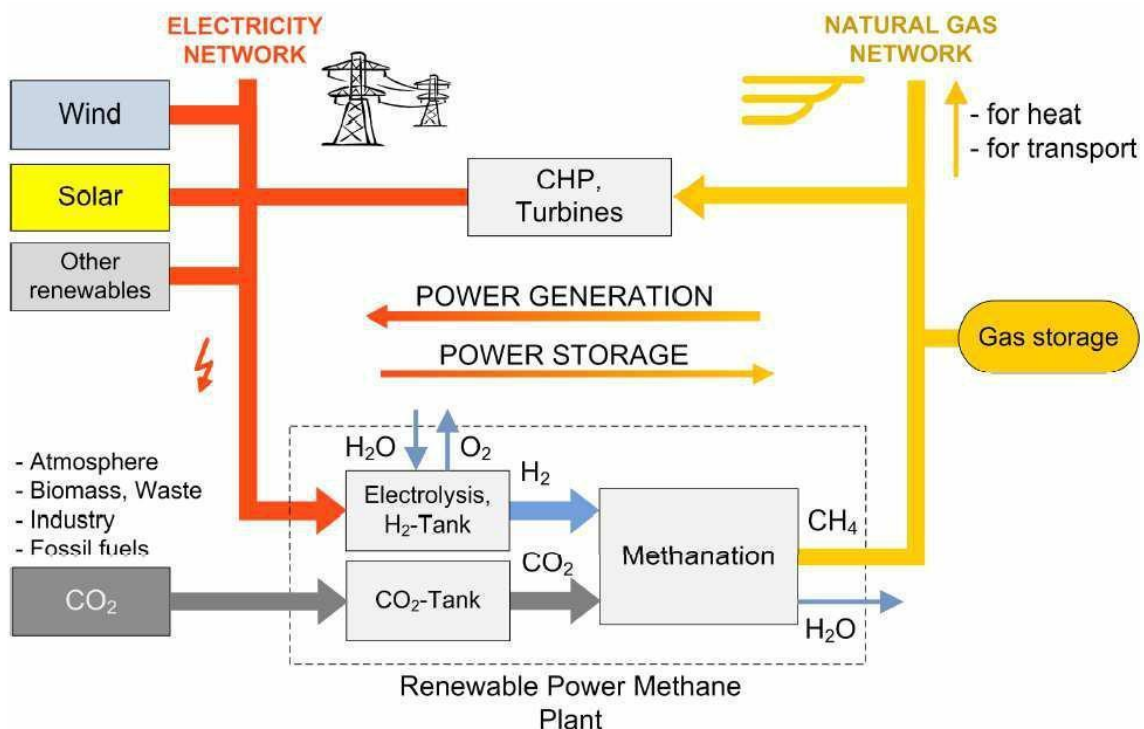


Figure 13: Basic Layout of the Power-to-Gas Concept (Sterner, 2009)



The energy requirement per cubic meter SNG is approximately 18kWh_{el}, whereby 15kWh_{el} of the energy input are associated with the electrolysis process and 3kWh_{el} for CO₂ absorption.

The CO₂ required for the process can be taken from renewable/ conventional power production, industrial processes or from the atmosphere. Efficiencies vary between 49% and 77% depending on the process arrangement. The SNG produced has identical characteristics as the natural gas imported through UK pipelines. SNG can therefore replace natural methane. The energy 'stored' in the gas is described as energy value per unit volume and is about 39MJ/m³ or 10.8kWh per cubic meter.

When SNG is used for re-electrification it can be utilized in fuel cells or combustion engines. The CO₂ released from the processes corresponds to the amount of CO₂ captured during the Sabatier process. As a consequence it could be argued that SNG is a CO₂ neutral fuel.

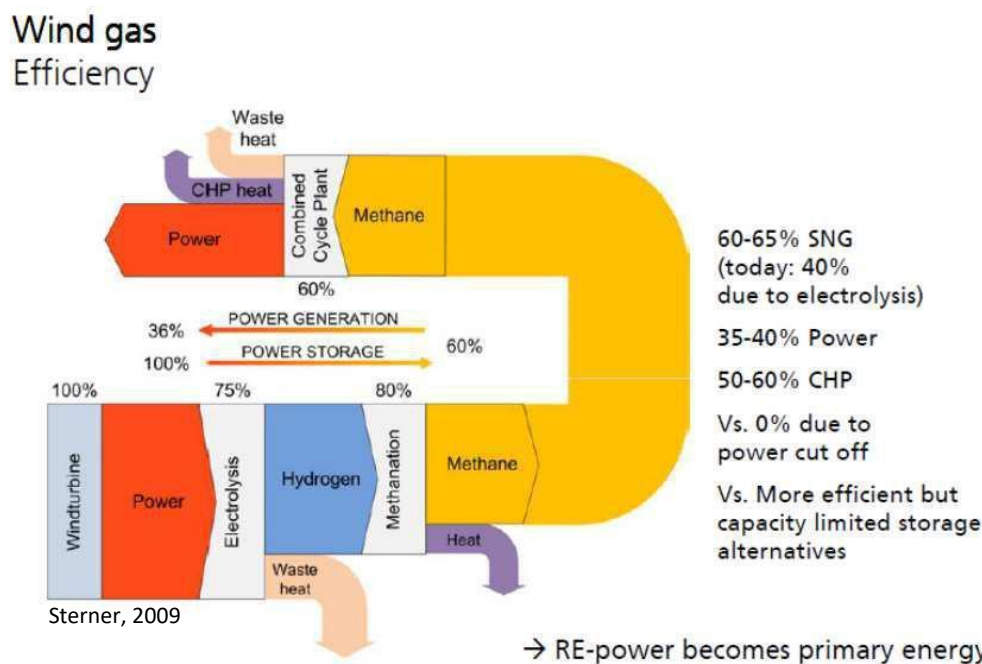
4.1.2 Conversion Efficiency & Costs

Inefficient conversion technologies have so far impeded the viability of Power-to-Gas technology. Research by Jensen and Morgensen (2004) states that reversible Solid Oxide Cells (SOC) can be used both as Solid Oxide Fuel Cells (SOFC) and as Solid Oxide Electrolyser Cells (SOEC) and hence become a cost effective way to solve conversion problems. SOC technology is still in research and development stage but current market demand for highly efficient fuel cell technology contributes to increased expenditure in material development and a decrease in component costs.

High efficiencies can be achieved with a concentrated CO₂ stream and the utilisation of process heat. Up to 60% of the CEEP can be stored in the gas network after the conversion process to SNG. Based on a high efficiency gas turbine or fuel cell technology with conversion efficiencies of up to 60% the round trip efficiency from power-to-gas-to-power is 36% (Jentsch et al. 2011). However, with regard to the utilisation of excess electricity that otherwise would be lost the efficiency ratio is playing a subordinated role. The curtailed wind power output in 2011 was 123.5GWh. Even with a round trip efficiency of only 35%

the energy available would correspond to 27 times the max. storage capacity of Turlough Hill, Irelands only large scale PHES.

Figure 14: Power-to-Gas efficiency - Sankey diagram



The Sankey diagram taken from Sterner (2009) illustrates the losses acquired during the transformation processes. Sterner also investigated the cost of such a system. Key figures applicable to this thesis are outlined below.

A Balance of Plant (BoP) system in the magnitude of 20-200MWeI scale costs approximately €1,000/kW_{eI} according to Sterner (2009). Unit costs for industrial SOFC are estimated at €765/kW_{eI} (Thijssen, 2009). The relation between cost and system size are linear as PEMs/SOCs are build in modular stack units. The methanation technology remains the same, independent of the scale of the final unit. Variable cost items include the key ingredients of electricity, water and CO₂. The value of wind power during high wind but low demand will be very low. Future costs are estimated between 0 and 3 EUR-cents per kWh_{eI}. For this exercise 1.5 cents/ kWh_{eI} are equally allocated for the wind farm owner and the network operator for operation and maintenance. Required water volumes will be collected by a rainwater harvesting system. Associated costs are included in the fixed cost item. Although

both the collection of CO₂ and its transport might generate additional costs, it is assumed that these costs are carried by the source and hence the cost is zero. In fact carbon sequestration might rather earn revenue than causing costs for the system owner.

The cost of SNG is calculated through the following equation:

$$C_{CH_4} = \left(\frac{C_{CeI} \times CRF + (O\&M + C_{CEEP} \times CEEP_{kWh})}{CH_4} \right)$$

Where

C_{CH_4} : Cost of SNG in c€/kWh

C_{CeI} : Capital Cost of the Power-to-Gas facility

CRF : Capital Recovery Factor

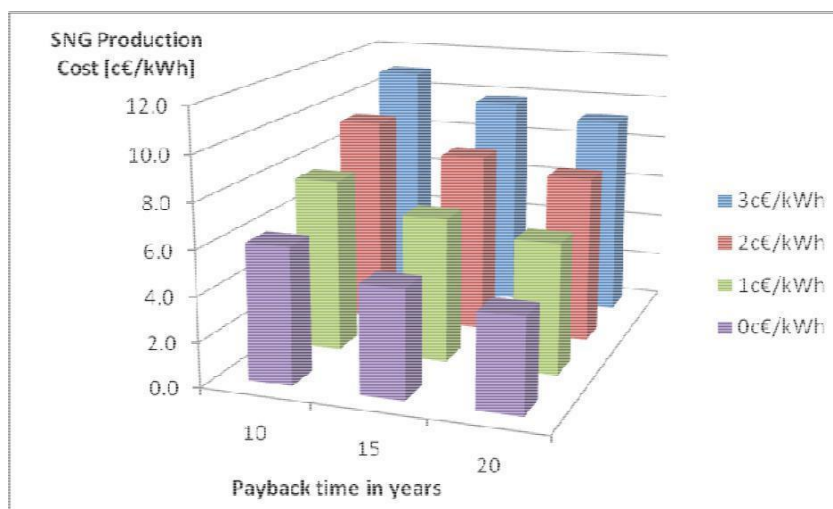
$O\&M$: Operation and maintenance costs

C_{CEEP} : Cost of CEEP Electricity

$CEEP_{kWh}$: Annual surplus electricity utilised

CH_4 : Annual SNG production

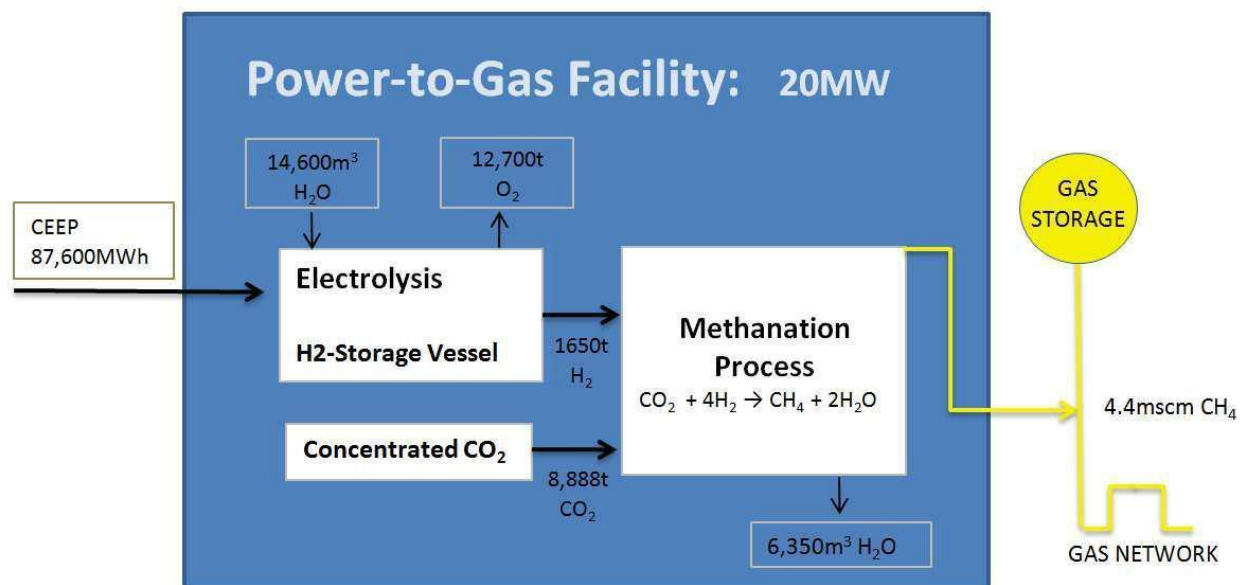
Figure 15: SNG Production Costs



The cost analysis shows that SNG can be produced at costs between 4 and 11 cents per kWh dependent on the remuneration of system operators and turbine owners and the investment period. Given a payment of 3cents per kWh CEEP and an investment over ten

years (interest rate: 5%) the cost of SNG is 11 cents per kWh. Capital cost for a Power-to-Gas facility is €1,000 per kW, the capital recovery factor for 10 years is 0.1295, O&M 3% of capital cost. A 20MW unit using up to 5% of the annual output of two selected wind farms (Mount Callan Wind Farm, Co. Clare & Arklow Bank Extension, Co. Wicklow)¹⁰ will generate 47,500MWh or 4.4mscm of SNG per annum. The 4 to 5% of the total output corresponds to the amount of curtailment expected for such a development. Costs fall considerably if the CEEP is available free of charge. The cost per kWh SNG then stands at 6.06 cents/kWh¹¹. At 1st of April 2012 fuel costs for natural gas in Ireland including carbon tax of €0.00277 per kWh were 5.72 cents/kWh and 7.19cents/kWh for commercial and domestic use respectively (SEAI, 2012b). Domestic production costs of SNG put in context could offer a viable alternative to imported natural gas from fossil fuel reserves.

Figure 16: Power-to-Gas Process Diagram



A 20MW facility will require up to 40m³ of water per day. During the methanation process 17.4m³/day of water will be released again. The net demand is therefore 22.6m³/day. With relatively regular intervals of precipitation, a collection tank sized to cover periods of

¹⁰ Both Developments have full planning permission and are waiting for grid connection. Mount Callan Wind Farm: 93MW; Arklow Bank Ext.: 520MW; Combined estimated annual output: 1,876,392MWh

¹¹ Detailed cost calculations in the appendix

drought up to 2 weeks should be sufficient. In the case of insufficient water collection mains-water has to be used. With 80mm average rainfall per month (Met Eireann, 2012) a rainwater harvesting system with a collection area of 395m² will ensure sufficient water is collected and stored. If all the water would be drawn from the local supply network annual cost of approximately €10,500 would arise.¹² In the context of the overall annual costs the rates payable for water are negligible.

Costing rates for the feed-in of SNG into the gas network for storage are not available in Ireland yet as no such mechanism exist by now. Approximate costs are therefore orientated on feed-in cost for bio-methane in Germany and estimated as 0.15cent/kWh. Without availing of any incentive payments or subsidies the price of SNG today is approximately twice that of current fossil reserves. However the price gap among SNG and natural gas will shrink with an increase in carbon taxes. As a carbon neutral, sustainable and domestically produced fuel SNG is likely to qualify for subsidy payments as known from biogas or landfill gas schemes.

Prevailing feed-in tariffs for electricity from landfill gas stand at €81.49MWh and are high in comparison to other renewables such wind¹³. These short term subsidies are clearly set to build industry capacity thereby contributing in meeting Ireland's 2020 targets. At the time of writing the injection of SNG into the Irish natural gas network was not regulated. The Regulating Authorities in ROI and NI (RAs) and Bord Gais Networks are currently working towards the development of a code for the injection of gas into the grid. Similarly there is no tariff structure for grid injection in place although the development of such a structure is underway (Coveney, 2011). Coveney's report suggests that a flat rate of €0.12€/kWh is paid for the electricity component of biogas. In comparison: In Germany €0.1818 per kWh for CHP plants using grid bio-methane is paid.

¹²Based on water charges in County Clare for 2011 and 2012 of €1.24/m³ (Clare County Council, 2012)

¹³ Onshore wind above 5MW: €66.35; Onshore wind equal or less than 5MW: €68.68

Oswald (2012) argues that at current price levels of €80/MWh Power-to-Gas technology is not economically viable. However, financial incentives and a consistent framework would encourage the deployment of such technology and in the medium term a fall in price levels can be expected. The benefits of Power-to-Gas in the balancing of the electricity system must also be recognised. The technology could also reduce the costs associated with the upgrade of the electricity grid as such or minimise the extensive costs of interconnections with the United Kingdom.

Wind farm developments halted by the outstanding decision on *treatment of curtailment in tie-break situations*¹⁴ (CER, 2012) could see their projects gaining momentum again as financial returns from hybrid systems consisting of wind farms and Power-to-Gas facilities would result in a viable option for all market operators. A combination of wind farms, Power-to-Gas facilities and OCGTs could perform as a virtual power station and provide besides a superior environmental performance increased value to the system by providing a stable and continuous electricity output. A recently published consultation paper by the RAs envisages favouring such hybrid plants over a reference thermal plant whereby the criteria for qualification of hybrid plants for priority dispatch are not transcribed in regulation yet.

The additional value added by such virtual power stations (hybrid systems) allows system operators to respond to changes in demand and supply through the increased ability of load balancing. Linked as a virtual power plant with smart grid applications the technology can help balancing the electricity system above a base load agreement by both allowing wind and gas turbines running simultaneously during peak hours or improving load management by accommodating surplus electricity for SNG conversion when local wind output is below its design capacity but supply is greater than demand.

¹⁴The decision due involves ambiguity about curtailment approaches for the next generation of wind projects. The decision foregoes an extensive consultation process by the CER & NIAUR in regard to the treatment of new wind farm connections under the grandfathering and pro-rata approach. 'Grandfathering' involves effectively a last-on, first-off approach while a 'pro-rata' approach would see the burden shared equally among the generators. A third option of risk sharing involves the consideration whether some of it (the risk) is shared by consumers. (Further information are available in the Consultation Paper SEM-12-028 at www.allislandproject.org)

4.2 Localisation and Operation

The first Power-to-Gas trial plant installed in Stuttgart, Germany utilized CO₂ absorbed from the surrounding air. To maximise the process efficiency in the methanation process a concentrated CO₂ stream is required. Biomass plants can help meeting that objective as 30 to 50% of raw biogas produced by anaerobic digestion (AD) consists of CO₂. Other sources of concentrated CO₂ streams are landfills, breweries, the chemical process industry and the concrete industry. The close proximity of a concentrated CO₂ source is regarded as vital to operate Power-to-Gas facilities economically.

A Power-to-Gas facility requires access to both the electricity and the gas network. Four locations have been chosen where the application of Power-to-Gas facilities is thought to offer greatest benefits in both balancing power output and storing excess energy generated from wind energy converters. The locations are shown in Figure 17. All four locations are chosen on the assumption that wind farms that have received planning permissions to date are offered a grid connection and that the 37% RES-E target from wind is met by 2020.

1. Coolkeeragh, Co. Derry: Coolkeeragh is located north of Derry along the NI-ROI border. Both border Counties (Donegal and Derry) observe an above average penetration of wind power in the overall electricity mix due to favourable wind conditions combined with a sparse population density. In April 2012 Donegal had the highest wind penetration of all counties on the Island with 284MW of wind capacity installed. By April this year the installed wind capacity in County Derry was 85MW. In the coming years additional capacities are expected as several wind farms have received planning permission. The connection of the NI gas network to Coolkeeragh and the high gas storage potential in the area (800mscm) make Coolkeeragh to one of the most favoured Power-to-Gas locations within the island.

2. Arklow, Co. Wicklow: The Arklow Banks Wind Farm was the first offshore wind farm in Europe. A 520MW extension of the existing farm has received planning permission. The combined rating of 550MW of wind power joining the electricity grid at a relatively narrow stretch of grid infrastructure poses major challenges in balancing fluctuations in electricity

supply. The installation of a Power-to-Gas facility could absorb surplus electricity and 48

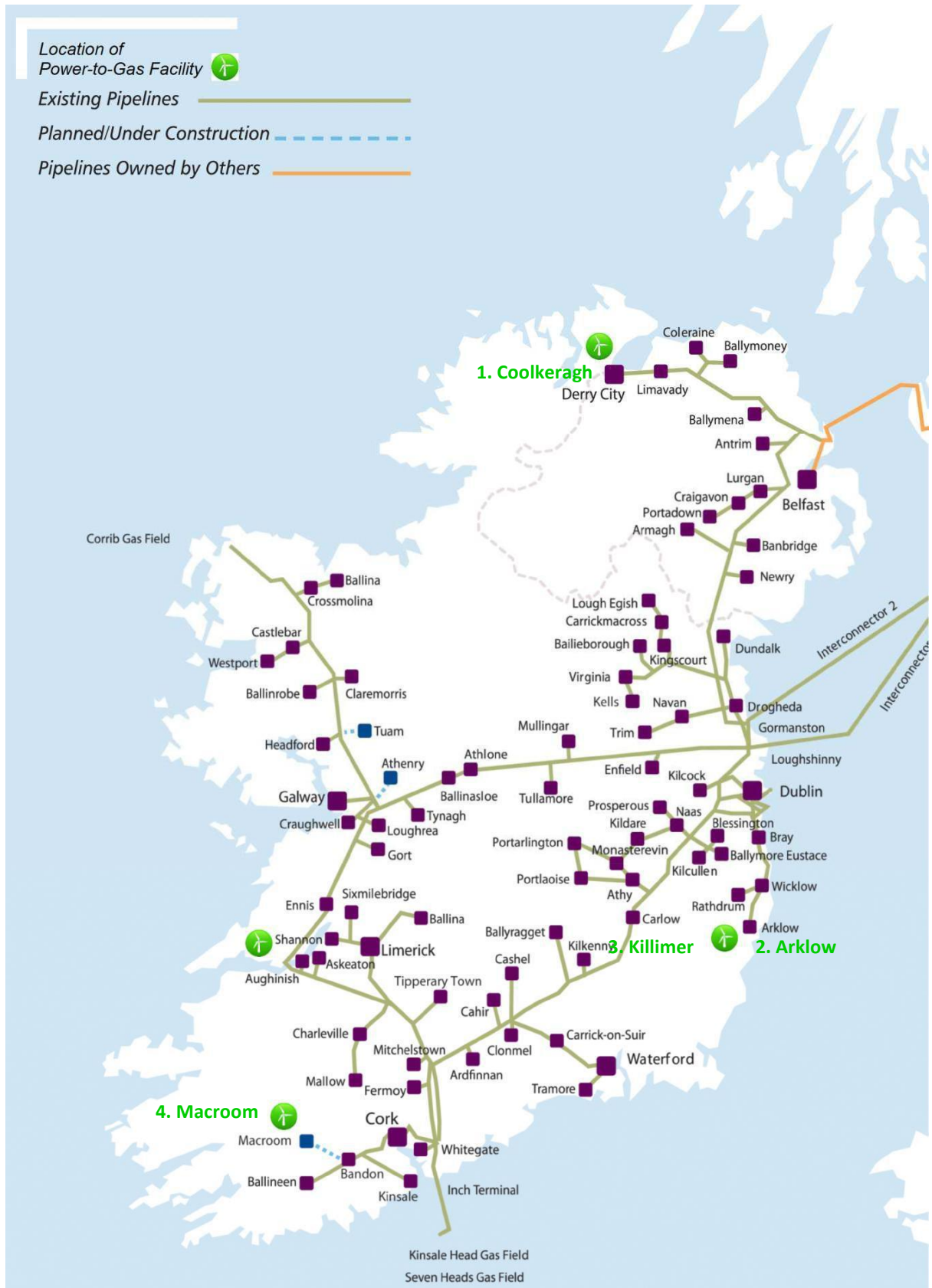
combined with modern turbine or fuel cell technology, maintain the flow of electricity in times of reduced wind generation. Arklow is connected to the gas network and the interconnection of the gas and electricity grid will improve energy flows towards Ireland's primary demand centre, Dublin.

3. Killimer, Co. Clare: Located at the west coast of Ireland, Co. Clare has one of the best wind resources within the Country. Clare's wind energy strategy is part of the local development plan. The document envisages a working target of harnessing 550MW of wind energy by 2020 (Clare County Council, 2011). With a relatively sparse population the county could become self sufficient from wind by storing its surplus wind energy. Due to the presence of Ireland's biggest power station, Moneypoint, Killimer has a strong grid infrastructure with power lines serving local, regional and national demand. With the installation of the second interconnector crossing the Irish Sea the Clare power hub will even connect to Britain. The prevailing conditions allow a Power-to-Gas facility located at the foot of Ireland's strongest ring circuit to provide excellent balancing characteristics by gathering CEEP produced both locally, in the midlands or elsewhere.

4. Macroom, Co. Cork: With 283MW of wind power installed County Cork has the second highest wind capacity within the all-island market. North-West of Macroom further 42MW are currently under construction. Its beneficial location with high wind sites in the South-West of Ireland and close proximity to the demand centre Cork City mean that its large wind penetration can be utilised efficiently. According to the GRID25 strategy by EirGrid (2008) 1610MW of wind capacity are expected to be installed by 2025. A Power-to-Gas facility in Macroom will allow for the storage of surplus electricity generated in times of low demand. The SNG produced can be fed into the local network where it can be used directly by Ireland's largest gas powered stations Whitegate (445MW) and Aghada (963MW) or it can be stored in the Kinsale gas field, the first and only offshore gas storage facility in Ireland. To date the power station in Aghada is the only generating plant which currently serves all three market segments of baseload, mid-merit and peak demand (ESB, 2012).

The chosen locations for Power-to-Gas facilities in the all island electricity market are shown in the gas pipeline map in Figure 17 kindly provided by Bord Gáis Networks.

Figure 17: Location Map Power-to-Gas / Gas Network (Source: BGN)



4.2.1 Characteristics of Synthetic Natural Gas

While energy storage systems can be limited by insufficient storage the utilisation of the national gas network reduces such constraints due to its enormous capacity, a continuous demand and its interconnection with Great Britain. When comparing latter option with PHES, CAES or battery storage systems, insufficient storage capacity results inevitable in the ‘spillage’ of energy (Denholm et al., 2005). The fact that Power-to-Gas energy storage in form of SNG is not limited to a confined storage vessel results in increased economical and environmental performances of Power-to-Gas storage systems over constrained systems. SNG fed into the network can offset import requirements arising under constant market demand or be stored in the network and its long term storage facilities. Besides the increased availability of storage volume, energy storage in form of SNG is a mature and proven technology that has some superior performance characteristics. In terms of stored energy per volume SNG has the highest energy density as shown in Figure 18 below.

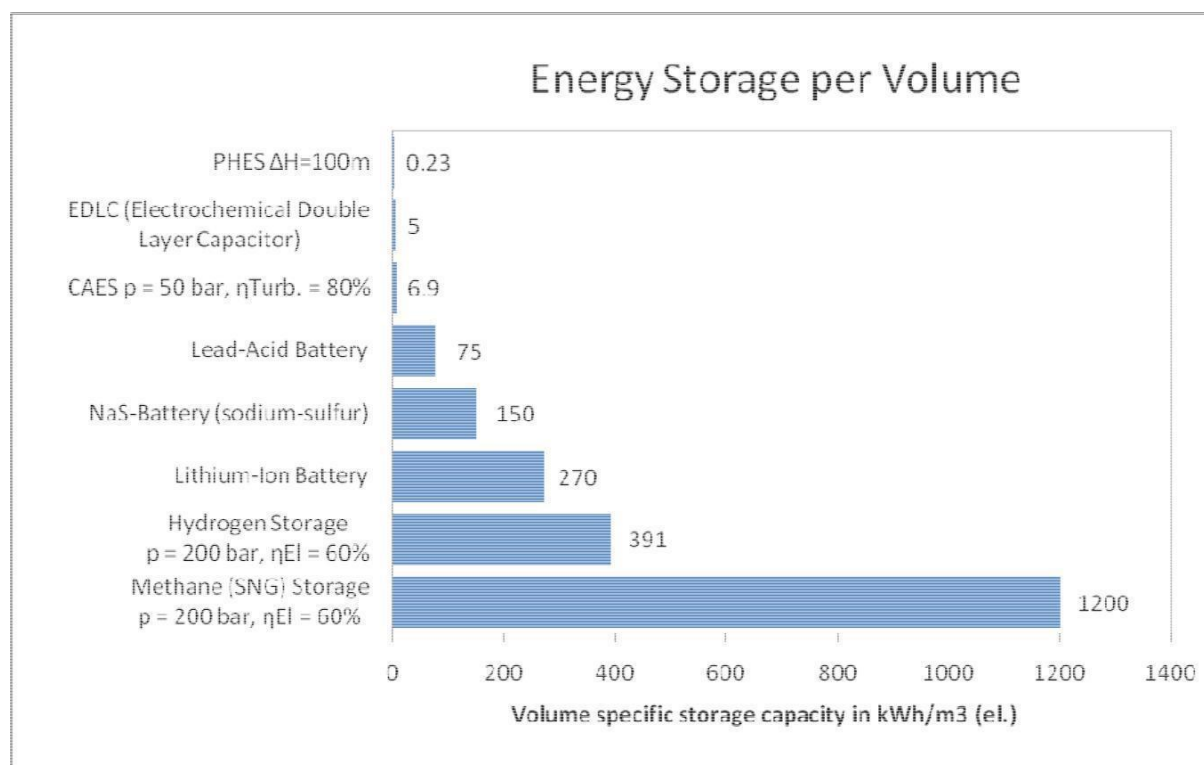


Figure 18: Energy Density Comparison of available Storage Technologies (Source: Götz et al. 2011)

SNG can be used as a substitute to natural gas and therefore offers the same benefits as the most environmentally benign fossil fuel. The storage of SNG is to date the only large scale long term storage option available in Ireland. With the existing storage facility in Kinsale

(230mscm) and two further storage facilities under development (Islandmagee Gas Storage – 500mscm and North East Gas Storage – 300mscm), Ireland's energy storage capacity would total to approximately 10.8TWh (18% of annual gas demand). This compares to the 1.59GWh available from Ireland's only PHEs, Turlough Hill.

Amongst the generally accepted storage technologies Power-to-Gas storage allows the widest spectrum of discharge times and power ratings dependent on the energy conversion technology utilised. Figure 19 taken from the summarizing report of the European Research Project 'stoRE' is a comparison of discharge times and power ratings of different electricity storage technologies. The Figure has been modified in that the Power-to-Gas area shown by the dotted red line was initially assigned to a Hydrogen Fuel Cell Storage System (HFCSS). Since CH₄ has a greater energy density than H₂ and equally can be used in fuel cells or combustion engines the HFCSS description has been replaced with a Power-to-Gas label.

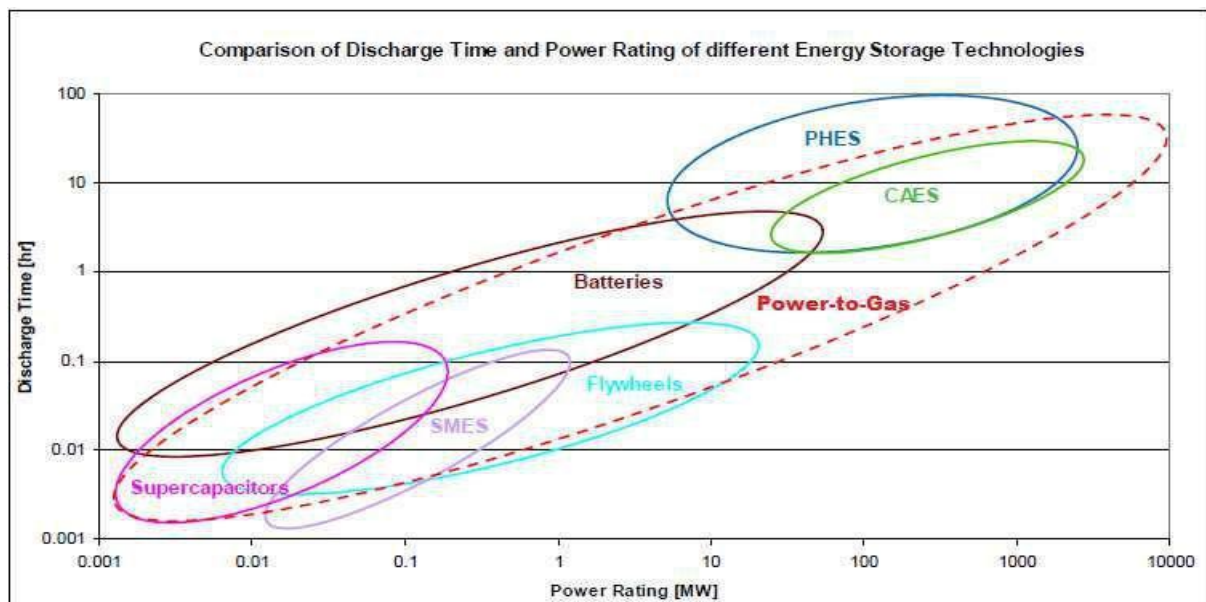


Figure 19: Comparison of different Energy Storage Technologies (stoRE-project, 2011; modified by Author)

Beside its superior storage characteristics the gas network likewise supersedes the energy transport capacities compared with other options. Specht et al. (2009) argues that high voltage direct current (DC) transmission is restricted to outputs < 7GW, gas pipelines can reach up to 70GW. The wide spectrum of usability of gas in the domestic, industrial and transport sectors is further enhancing its status as a universal deployable energy storage medium.

Multiple applications for SNG include its usability in domestic, commercial and industrial heat and power generation, transport applications and other industrial processes. SNG used as transport fuel is identical to Compressed Natural Gas (CNG). The utilisation of CNG in transport is growing and worldwide an estimated 11 million Natural Gas Vehicles (NGVs) are currently in operation (Callanan, 2010).

According to an Oireachtas Report on biogas energy evaluating Swedish practices in biogas utilisation in transport, bio-methane is priced at €1.29/Nm³ (Coveney, 2011). Comparing its energy content with gasoline the equivalent price would be €1.02/Nm³. At a production cost of €0.11/kWh a cubic meter of SNG will cost €1.19. Besides fuel savings of up to 40% NGVs are quieter and their CO₂ emissions are about 20% less than from those vehicles driving on traditional fuels. Assuming an average motorist in Ireland drives 16,000km per year than the annual fuel cost savings will be €621. Annual savings will increase over time with conventional fuel prices on the rise and SNG costs expected to fall. Due to the expected classification as carbon neutral and its mature technology SNG driven vehicles offer a viable alternative to electric vehicles.

Table 4: Vehicle Fuel Comparison

Fuel Type	Fuel Cost [€/l]	Calorific Value [MJ/unit]	Cost per Unit [€/kWh]	Annual driven distance [km]	CO ₂ -emission [g CO ₂ /kWh]	Annual Cost [€]*	Emissions/year [t CO ₂ /kWh]	Cost Savings [%]	Emission Savings [%]
Petrol	1.60	44MJ/kg	0.18	16,000	251.9	1,600	2.24	0.0%	4.7%
Diesel	1.50	42MJ/kg	0.15	16,000	263.9	1,335	2.35	16.5%	0.0%
SNG (CNG)	0.12	39MJ/m ³	0.11	16,000	205.6	979	1.83	39.0%	22.0%

*Average vehicle output: 1.8km/kWh (Annual energy requirement: 8,900kWh)

Figure 20: Driving Range per Fuel Type

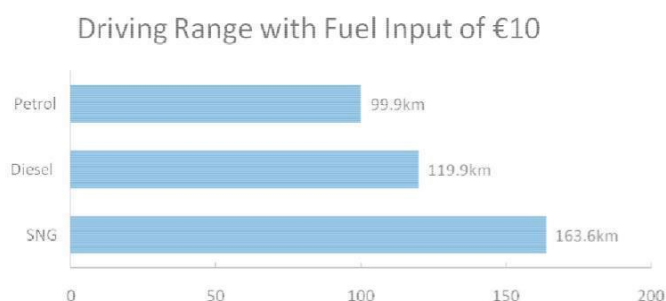


Figure 20 illustrates the superior performance of SNG above conventional fuelled vehicles. With a fuel value of €10 NGVs have an average driving range of 163km compared with a driving range of 100km for Petrol and 120km for Diesel cars.

5 HYBRID POWER PLANT DESIGN FOR IRELAND

In this chapter a model is used to simulate wind energy output at different locations in Ireland based on average wind speeds as published in the SEAI Wind Atlas (SEAI, 2012c) and the Weibull factor associated with each region as per research undertaken by (Frank & Landberg, 1997). The simulation presents the wind energy output available for Power-to-Gas energy storage. By running different scenarios of wind farms in a single and combined set-up the performance of virtual power plants for both baseload and mid-merit power contracts is simulated. By comparing the all-island energy system today with and without Power-to-Gas technology and the energy system as expected in 2020 the benefits for the all-island market in economical and environmental terms will be examined.

5.1 Basic Design Parameters

The design criteria applied to simulate wind energy output are modelled in an MS-DOS application programmed in FORTRAN by O'Mahony (2012). The model uses the Markov Method for simulating Non-Gaussian wind speed time series as prepared by McNerney and Veers (1985) for Sandia National Laboratories. The application generates wind time series with any distribution of hourly averages, exponentially decaying autocorrelation and a Gaussian realisation of the turbulence. The method which is based on the Markov random walk produces a realisation of hourly averages in a defined space of wind speeds between 0 and 25. The process is Markovian in that each succeeding wind speed is defined only by its preceding value and not that of earlier wind speeds.

As shown in the sample transition matrix in Table 5 a tapered scheme is employed to produce a smooth transition between adjacent time values. The diagonal probability matrix ensures to uncouple each hourly average based on the two defined parameters: a) the desired probability density and b) autocorrelation of the preceding wind speed value. The sum of all probabilities in each row is equal to 1. Each run simulates the annual electricity output of 8760 hours.

The model has been chosen as a preferred option over other programmes as its probability distribution is orientated on the preceding wind velocity and is not assigning wind speeds in

a random fashion as known from i.e. the Monte Carlo method. The program is regarded as superior in that it mirrors more likely wind speed variations in line with observations from nature. In particular this means that higher wind speeds are generally building-up and changes in wind velocities are gradually and not completely random from i.e. 2m/s to 22m/s and then back to 5m/s. In a more realistic scenario wind speeds will climb from 2m/s to 8m/s and from 8 m/s to 16m/s and so on. A comparison of the Monte-Carlo Method and the Markov Random Walk is shown in Figure 21 and Figure 22 respectively.

Figure 21: Wind Speed Simulation with Monte-Carlo Method

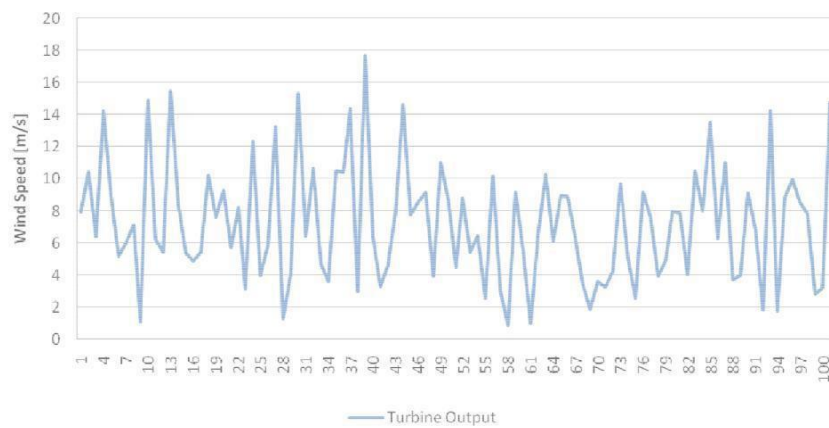
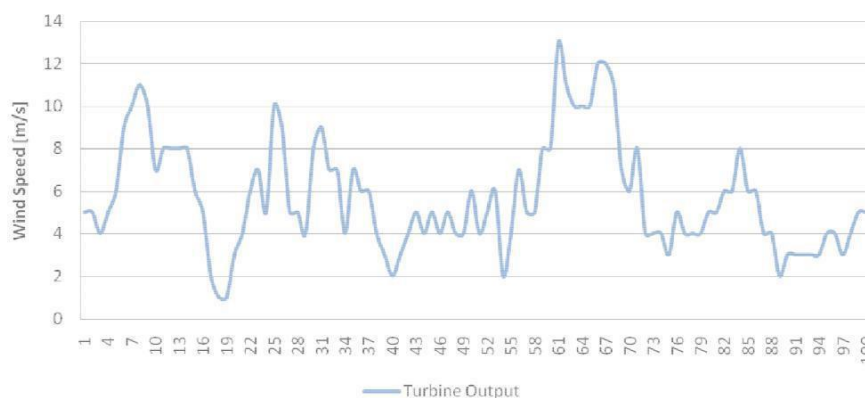


Figure 22: Markov Random Walk Wind Speed Simulation



A weakness of the model described above is that it does not accommodate for varying monthly wind speeds usually experienced over the duration of a year. Generally wind speeds in Ireland are higher during winter month than during the summer month (Met Éireann, 2012b). However, the mean average wind speeds simulated by the model 55

correspond to the mean average wind speeds measured over a year as illustrated in the SEAI Wind Atlas (SEAI, 2012c). The results are therefore regarded as sufficiently reliable for the purpose of this study.

Table 5: Sample Transition Matrix

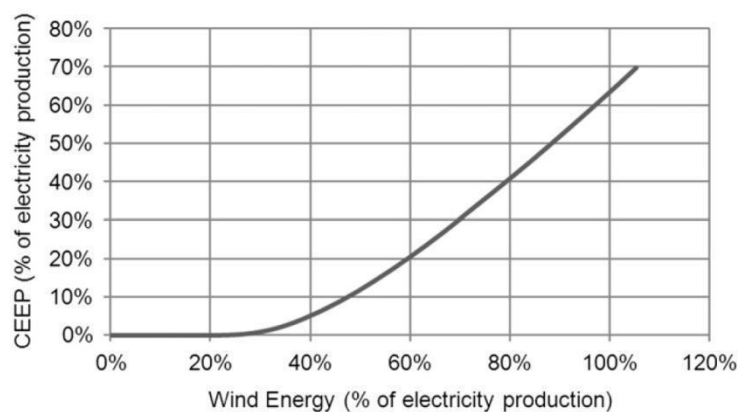
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25				
1	0.33	0.26	0.17	0.10	0.07	0.03	0.02	0.01	0.01																				
2	0.14	0.33	0.22	0.13	0.08	0.05	0.03	0.01	0.01																				
3	0.06	0.16	0.32	0.19	0.12	0.07	0.04	0.02	0.01	0.01																			
4	0.03	0.08	0.16	0.31	0.18	0.11	0.06	0.03	0.02	0.01	0.01																		
5	0.02	0.04	0.09	0.17	0.31	0.18	0.10	0.05	0.02	0.01	0.01																		
6	0.01	0.02	0.05	0.09	0.17	0.30	0.17	0.09	0.05	0.03	0.01	0.01																	
7	0.01	0.01	0.03	0.05	0.09	0.17	0.28	0.17	0.09	0.05	0.03	0.01	0.01																
8		0.01	0.02	0.03	0.05	0.11	0.17	0.29	0.16	0.08	0.04	0.02	0.01	0.01															
9			0.01	0.02	0.03	0.06	0.10	0.17	0.30	0.15	0.08	0.04	0.02	0.01	0.01														
10				0.01	0.02	0.03	0.06	0.10	0.18	0.29	0.16	0.08	0.04	0.02	0.01														
11					0.01	0.02	0.04	0.06	0.10	0.18	0.29	0.15	0.07	0.04	0.02	0.01													
12						0.01	0.01	0.02	0.04	0.07	0.11	0.18	0.29	0.14	0.07	0.03	0.02	0.01											
13							0.01	0.01	0.02	0.04	0.07	0.11	0.18	0.30	0.14	0.07	0.03	0.01	0.01										
14								0.01	0.01	0.02	0.03	0.04	0.07	0.11	0.18	0.29	0.13	0.06	0.03	0.01	0.01								
15									0.01	0.10	0.02	0.03	0.04	0.05	0.09	0.15	0.26	0.13	0.06	0.04	0.01	0.01							
16										0.01	0.01	0.02	0.03	0.05	0.08	0.12	0.17	0.27	0.13	0.06	0.03	0.01	0.01						
17											0.01	0.01	0.02	0.03	0.05	0.08	0.12	0.18	0.25	0.13	0.06	0.03	0.02	0.01					
18												0.01	0.01	0.02	0.04	0.06	0.07	0.12	0.17	0.26	0.11	0.07	0.04	0.01					
19													0.01	0.01	0.02	0.04	0.06	0.08	0.12	0.18	0.26	0.12	0.05	0.03	0.01				
20														0.01	0.01	0.02	0.03	0.04	0.06	0.08	0.12	0.18	0.25	0.11	0.06	0.02	0.01		
21															0.01	0.01	0.02	0.03	0.04	0.06	0.09	0.13	0.18	0.24	0.11	0.05	0.02	0.01	
22																0.01	0.01	0.03	0.05	0.09	0.11	0.17	0.28	0.15	0.06	0.02	0.01		
23																	0.01	0.01	0.02	0.02	0.05	0.07	0.11	0.18	0.29	0.14	0.07	0.03	
24																		0.01	0.01	0.01	0.02	0.03	0.06	0.10	0.13	0.19	0.22	0.14	0.08
25																			0.01	0.01	0.03	0.04	0.06	0.09	0.11	0.15	0.24	0.15	0.11

5.1.1 Analysis of Wind Power Storage Requirements

The critical evaluation of wind power storage requirements is based on previous research outputs, actual data received from EirGrid and estimates published by key market participants in line with the RES-E target of 40% by 2020. According to figures provided by EirGrid (2012b) 2.2% of the total aggregated wind production in 2011 was curtailed. These figures correspond with research by Connolly et al. (2010) modelling the Irish energy-system in order to identify optimum wind penetrations for the existing energy-system. Figure 23 illustrates the critical excess electricity production (CEEP) expected from an increased wind energy penetration on the overall energy-system as modelled by Connolly et al. (2010). With a targeted 40% RES-E from intermittent sources the CEEP produced by 2020 is about 5%. A 2020 generation portfolio analysis jointly published by EirGrid and SONI (2011) states expect curtailment losses between 5% and 22% depending on a number of factors such as interconnection, storage ability and network constraints. The minimum amount of

curtailment identified for 2020 is 5%. For this reason the potential of the overall aggregated wind production available for storage is set at 5%.

Figure 23: Critical excess electricity production for increasing wind penetrations (Connolly et al. 2010)



5.1.2 Analysis of Balancing Load Requirements

The intermittent nature of wind as well as the uncorrelated relation between wind power output and customer demand poses unconventional challenges for system operators. Load management techniques include energy storage, load shifting and load balancing whereby CEEP is stored, exported or curtailed. Export costs of electricity generated in Ireland require cost intensive and limited interconnections. In addition, intermittent power supply results in restricted security of supply and thus prevents cost security. Electricity prices at times of high influx but low demand are generally low and will barely cover the cost of expensive high voltage sub-sea cables to France or the United Kingdom. The construction of the 500MW East-West Interconnector connecting north Dublin to Britain is estimated to cost €600million. A Power-to-Gas plant of comparable size will cost in the order of €500million.

The ability to store excess energy close to the supply centres prevents network constraints and frees accumulated energy reserves at times of high demand. Besides a reduction in cost of fuel and infrastructure, energy storage reevaluates the unit price of energy. Long-term storage solutions such as Power-to-Gas allow the harvesting of critical excess energy generated during the summer month in order to meet peak demand during winter months.

At a CEEP-level of 2.2% the total amount of energy available for storage corresponds to approximately 130GWh¹⁵. In 2020 wind power output will account for 37% of all electricity demand. Demand figures published by the network operators SONI and EirGrid forecast a total electricity requirement (TER) of between 40,000 and 43,000GWh per annum (EirGrid & SONI, 2011b). With an expected curtailment level of 5% the demand for electricity storage will amount to 740GWh.

In the following section different scenarios of wind farms connected to Power-to-Gas energy storage are examined. Several inquiries to organisations dealing with wind farm data have been made. As many wind farm operators treat their wind farm output as commercially sensitive no real time data for Irish wind farms was accessible. Instead the Markov Model was used to simulate wind farm output and storage abilities.

5.1.3 Power-to-Gas Hybrid Plant Simulations

A hybrid plant describes a power plant generating a constant output based on different sources of fuel or energy input. In this context a hybrid plant describes the combined output from wind turbines coupled with Power-to-Gas energy storage¹⁶.

5.1.3.1 Baseload Plant Simulation

In the first simulation a baseload power plant approach consisting of a Power-to-Gas facility and a single wind turbine was chosen. The turbine chosen is the E101, a 3MW turbine from Enercon. The turbine has a low cut-in wind speed of only 2m/s and operates up to wind speeds of 34m/s using the Enercon storm control function. As a result the turbine is able to achieve one of the highest capacity factors on the market. Its power curve showing the electricity output (marked by the blue line) and the power coefficient (illustrating turbine efficiency at various wind speeds) is depicted below.

¹⁵Based on 5.91TWh annual electricity demand supplied from renewables; CEEP in 2011: 2.2% (EirGrid, 2011c)

¹⁶Re-electrification of SNG is either through conventional gas fired power stations (virtual power plant) or large scale fuel cells.

Figure 24: Power Curve E-101

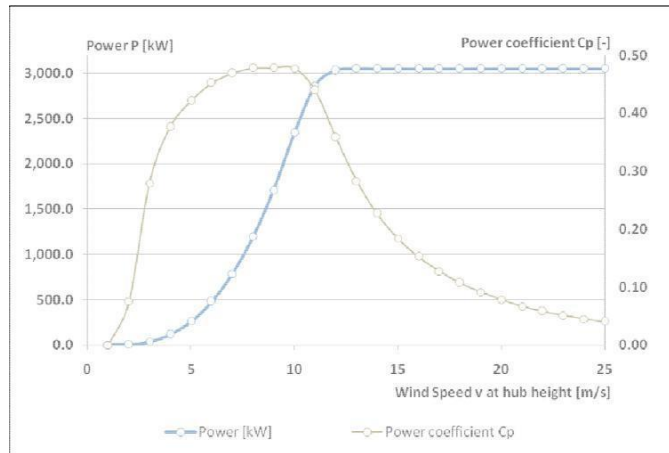


Table 6: Power output and Cp values for the Enercon E-101 3MW

Wind [m/s]	Power [kW]	Power coefficient Cp
1	0.0	0.000
2	3.0	0.076
3	37.0	0.279
4	118.0	0.376
5	258.0	0.421
6	479.0	0.452
7	790.0	0.469
8	1,200.0	0.478
9	1,710.0	0.478
10	2,340.0	0.477
11	2,867.0	0.439
12	3,034.0	0.358
13	3,050.0	0.283
14	3,050.0	0.227
15	3,050.0	0.184
16	3,050.0	0.152
17	3,050.0	0.127
18	3,050.0	0.107
19	3,050.0	0.091
20	3,050.0	0.078
21	3,050.0	0.067
22	3,050.0	0.058
23	3,050.0	0.051
24	3,050.0	0.045
25	3,050.0	0.040

Table 7: Technical Specifications E-101

Turbine Model	Rated Power [MW]	Cut-in speed [m/s]	Rated speed [m/s]	Cut-off speed [m/s]	Rotor Diameter [m]	Swept area [m ²]	Hub height [m]
E-101	3	2	13	28-34	101	8,012	99 / 135

The turbine data combined with local wind condition factors for Co. Clare have been fed into the model (Shape factor: 1.88; Scale factor: 7.83). An overview of all parameters required by the model is shown in Table 8 :

Table 8: Simulation Parameters Employed

Parameter	Symbol	Unit
Shape Factor	k	n/a
Scale Factor	c	m/s
Air Density	ρ	kg/m ³
Radius of Wind Turbine	r	m
Coefficient of Wind Turbine	Cp	-
Cut-in Speed	v_{in}	m/s
Cut-out Speed	v_{out}	m/s
Number of Samples	ns	No
Number of Turbines	nt	No
Stored Energy	.	kWh
Storage Level	.	kW
Base Load	.	kW
Wind Farm Output	.	kW

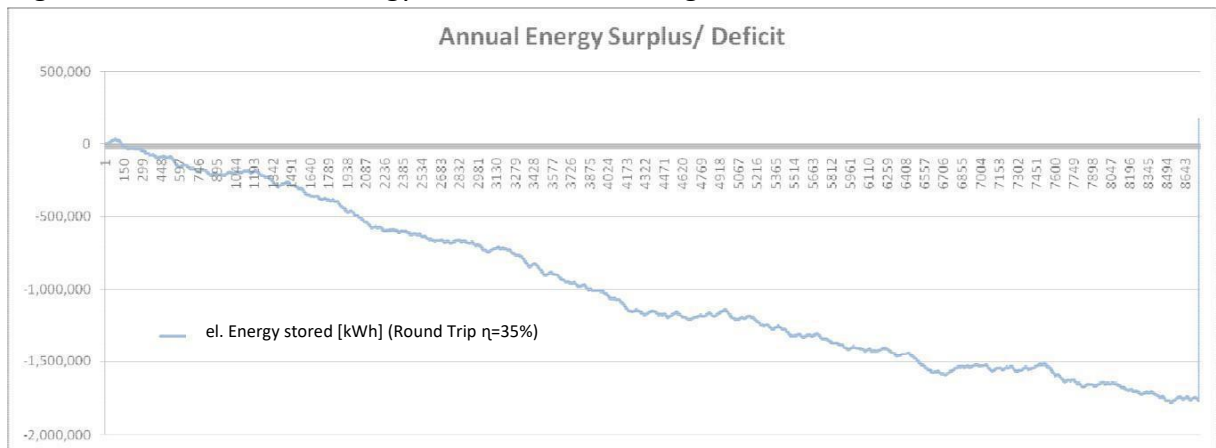
Figure 25 depicts the outputs available in a baseload set-up for a single turbine. Initially a baseload level of 1.6 MW had been defined. The baseload level in turn defines the CEEP and hence the energy fed into storage. The area coloured in blue is the energy produced by the wind turbine and directly supplied to the electricity grid. When the output is higher than the defined baseload level (red area) the CEEP is supplied to the Power-to-Gas facility where the energy is stored in form of SNG. With a roundtrip efficiency of about 35% only a 3rd of the CEEP produced can be accounted for as stored electrical energy (shown by the green dotted line). The accumulated and stored energy required for complementing a shortage in wind energy is shown by the green area.

Figure 25: Single Location Baseload Generation



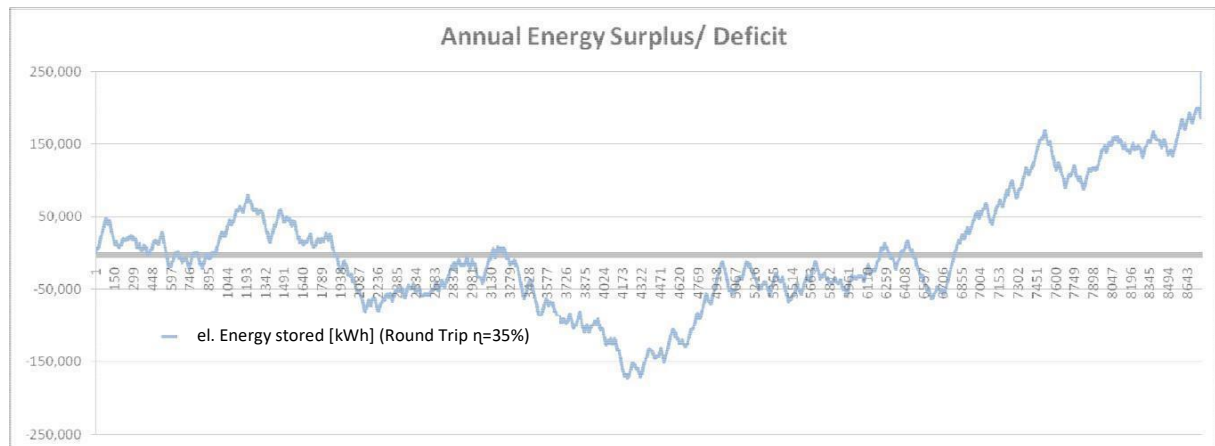
When illustrating the accumulated energy available for re-electrification (based on a roundtrip efficiency of 35%) the baseload level of 1.6MW is found to be positioned too high. The analysis of the accumulated energy fed to/ or drawn from storage shows that an energy-deficit is evolving (Figure 26).

Figure 26: Accumulated Energy available from Storage



Several simulations have been run with baseload levels ranging from 1.8MW to a 1.0MW.

A break even, i.e. sufficient energy is stored to maintain the baseload while feeding maximum electricity into the grid, is achieved at a level of 1.05MW (Figure 27).

Figure 27: Power Curve at Ideal Baseload Level

The simplified baseload arrangement with a single turbine clearly shows a significantly reduced but therefore constant power supply. The annual electricity output with a 95% capacity factor is 8,322MWh. A single turbine operating at an average capacity factor of 30.6% (as per joint Generation Capacity Statement 2012-2020, EirGrid & SONI, 2011b) would result in an annual usable electricity output of 7640MWh¹⁷. The result states that although the MEC of the virtual power plant is de-rated to only a third of the turbines maximum power rating, the joint load provision is exceeding the annual performance of a single turbine operating at full output capacity.

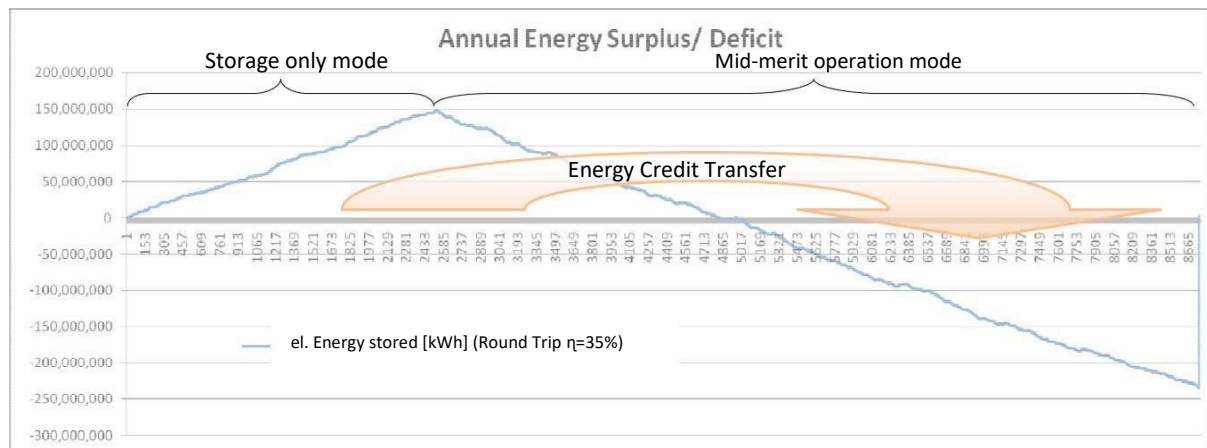
5.1.3.2 Mid-merit Plant Simulation

In a second approach the hybrid system is designed to provide only sufficient load capacity in order to qualify for a mid-merit plant. This approach has the following two benefits: a) market prices paid for mid-merit plants are higher than those paid for baseload plants and b) the level of de-rating the direct system output can be increased. As a result the enhanced output capacity and unit prices payable offer greater returns. According to the SEM Committees' proposal a mid-merit plant is defined as a plant that runs between 910 – 6221 hours per year (CER & NIAUR, 2012b). A mid-merit plant must generate its contracted quantity in the trading periods between 07:00 and 23:00 on Business Days and up to 80% of the contracted quantity on non-business days.

¹⁷ 8760h x 3MW x 30.6% = 8042MWh - 5% CEPP = 7640MWh

For the mid-merit plant design the first 2,539 hours of system output are completely supplied to storage (Figure 28). The hybrid plant then signs a mid-merit supply contract for the supply of up to 6,221 hours per year. The ‘frontloading’ of energy storage in the gas network allows the accumulation of an ‘energy credit’.

Figure 28: Mid-merit Plant Energy Balance

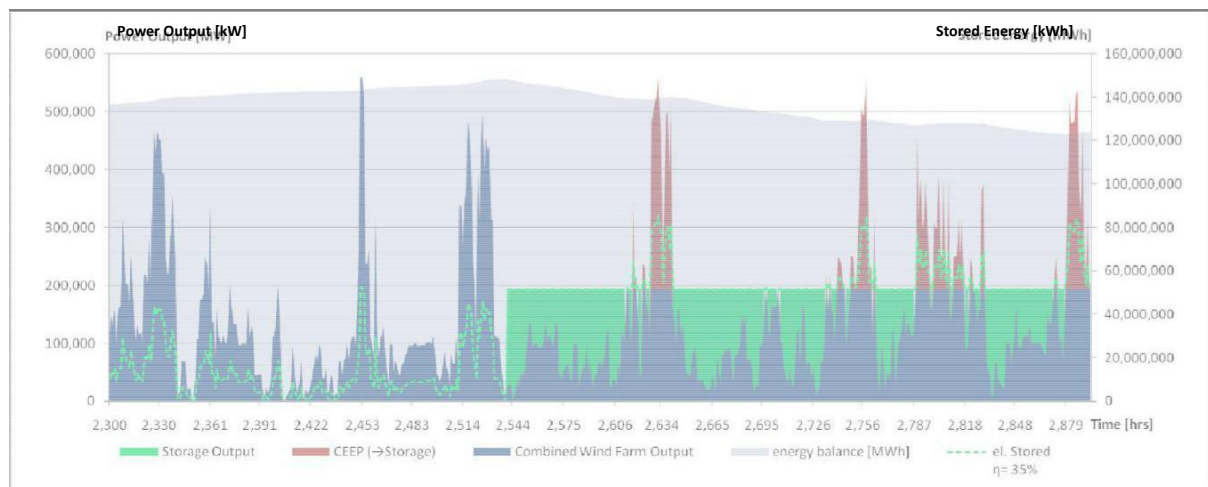


The frontloaded energy is stored in the gas network and will be withdrawn at times where electricity output from wind is insufficient. This allows the hybrid plant to operate environmentally benign as long as the energy withdrawn from the gas network is covered by the ‘energy credit’ previously accumulated.

The set-up for the mid-merit simulation combines two wind farms and two Power-to-Gas facilities each located in close proximity to a wind farm. The first wind farm located in County Clare consists of 31x3MW onshore turbines. The second wind farm positioned on the East coast is located offshore and consists of 70x7.5MW Turbines (Arklow Banks Extension). The dispersion of both wind farms shall improve the joint capacity of the virtual power plant. Connected through a ring circuit of high voltage power lines optimal load balancing between the wind farms and Power-to-Gas stations is possible. The combined wind farms produce a total annual output of between 1.4 and 2GWh. The ideal MEC, established by the simulation of a mid-merit plant scenario is 193,000kW. At this level the energy balance at the end of the contracted 6,221 hours is still positive. However, in order to avail of priority dispatch electricity suppliers of hybrid plants must only pass the *de-minimis* threshold of 10% RES-E.

Figure 29 illustrates the power output from the combined wind farms in the hours 2300 to 2895. The energy output from storage is marked in green and commences after 2539 hours of operation in the storage only mode. Only then sufficient energy has been accumulated to operate the hybrid plant at 193,000kW output for the remainder of the year. The accumulated energy in storage is shown by the blue area chart (right axis). Wind farm output and output from storage are shown on the axis to the left.

Figure 29: Mid-merit Plant Power Output Curve



Should both wind farms operate independently and without energy storage a high level of curtailment is expected. In a hybrid set-up and classified as a mid-merit plant the virtual power plant is able to compete with conventional and fossil fuel driven power plants.

5.1.4 Load Balancing Requirements in 2011 & 2020

In this section the Power-to-Gas concept is applied as a load balancing solution for the All-Island Electricity Market. The load balancing solution utilises surplus energy/CEEP which is lost due to the curtailment of wind turbines in times where electricity supply exceeds the demand. The Power-to-Gas technology employed at four locations as suggested in Figure 17 on page 50 is hereby serving as the load balancing tool. The CEEP is converted into SNG and stored in the gas network. This process increases the economic efficiency of wind power plants and reduces Ireland dependency on fossil fuels. The utilisation of carbon neutral SNG in power production is also reducing the carbon intensity of Irish power generation and subsequently reduces its costs.

In 2011 about 130GWh of electricity were lost due to curtailment. The transformation of electricity into SNG has at current standard of knowledge a process efficiency of about 60%. This means effectively that 7.2mcm of SNG could have been produced from CEEP¹⁸. It is assumed that in 2020 the minimum amount of CEEP increases to 5%. The amount of CEEP then corresponds to 740GWh: a SNG production potential of 41mcm of natural gas substitute. Based on the maximum scenario of 22% curtailment, the carbon neutral process could replace up to 300mcm of natural gas¹⁹. The figure corresponds to 5% of Ireland's annual gas consumption in 2010.

5.2 Evaluation of Economic Benefits

The evaluation of economic benefits derived from environmentally benign technologies is difficult in such that resultant costs of social welfare, severe weather events and consequences from climate change are not measureable in monetary terms especially associated to carbon emissions. For that reason the expected economic benefits evaluated in this section have been limited to measureable impacts on pricing and not on social welfare costs.

5.2.1 Impact on Fuel Prices

Electricity generated from SNG which originates from Power-to-Gas technology should be exempt from carbon tax as it basically represents a carbon neutral fuel. Hence, a reduced unit price of SNG should give those power plants using the substitute gas a competitive advantage over other gas turbines running on conventional gas. The European carbon prices will average at €7.88/t in the second half of 2012 (Reuters, 2012). The ongoing downward trend of carbon prices is expected to result in regulators withholding permit sales from next year. Forecasts indicate that carbon prices could more than triple by next year. The sustainable energy authority of Ireland expects the cost of carbon to increase to about 33€/tCO₂ by 2020 (SEAI, 2011d). Electricity generation from carbon neutral SNG would therefore result in considerable lower generation costs. Hence the Power-to-Gas technology

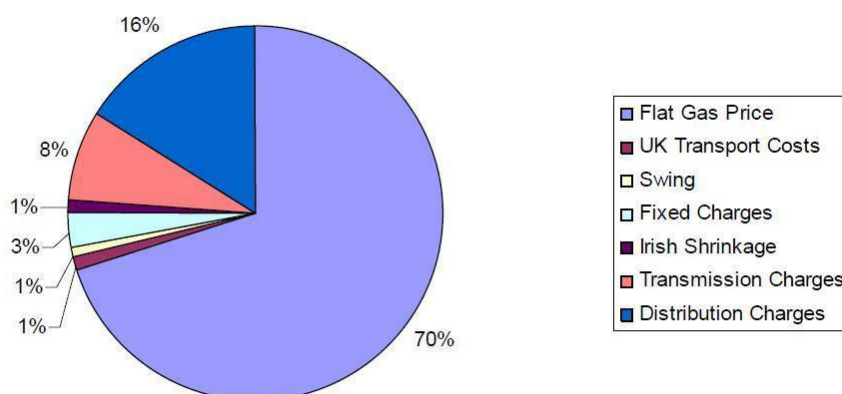
¹⁸Based on 1m³ SNG = 10.8kWh

¹⁹ Equals 3,256GWh stored energy

could contribute to an overall reduction in energy prices. Associated benefits include improved competitiveness for businesses and enterprises located in Ireland.

In addition, 25% of the overall gas price in Ireland is associated with the cost for UK transport, transmission and domestic distribution charges (Figure 30 by Gallagher, 2009). Locally produced SNG can offset the transport and transmission charges and reduce distribution costs. As a result regionally supplied SNG offers a viable alternative to conventional natural gas.

Figure 30: Breakdown of Delivered Gas Price



When SNG is utilised in the transport sector unit prices are 16% and 39% lower than those for diesel and petrol respectively. Fuel costs per kWh are 11 €cent for SNG, 15€cent for diesel and 18€cent for petrol.

5.2.2 Impact on Plant Competitiveness

When analysing various power systems for their competitive operating costs, maintenance related outages are an important consideration in the overall economic assessment. The 365-day rolling availability rate of power plants in the Irish electricity supply system in 2011 was 83.8% (EirGrid, 2011d). Conventional gas systems have a capacity factor²⁰ of about 90%.

²⁰Capacity Factor is defined as the average plant output divided by the maximum possible output over a period of time, generally a year (Denholm et al, 2005)

Power-to-Gas hybrid systems are able to operate with an improved capacity factor because some of the maintenance on the gas side can be performed while the wind turbines are generating the required output energy. This advantage means that Power-to-Gas systems contracted as a hybrid system have a lower cost of energy (COE) and hence a competitive advantage against other generating plants.

Power-to-Gas hybrid systems will yield additional gains if the current feed-in tariff for electricity from landfill or biogas would be extended to SNG. When the system proves eligible to current substitution levels under the REFIT-scheme it could yield returns in the order of 2 to 3 times above a wind only generation system. However, a power plant generating electricity from SNG will attain a preferred dispatch status against its competitors. Under EU regulations electricity generation from domestic fuels is treated outside the bidding process for supply contracts and is dealt with through the PSO-mechanism.

5.2.3 Commercial Viability Analysis

In chapter 4 the production costs of SNG have been established. A wind farm owner taking up the Power-to-Gas storage of CEEP is able to produce SNG at the cost of €0.073/kWh. (Assuming a unit cost of 1.5€cent/kWh is paid to the system operator). A unit of natural gas as per 1st of April 2012 costs €0.0572/kWh including a carbon tax of €0.0027 (SEAI, 2012b). The production of SNG becomes viable when the cost of natural gas reaches the production cost of SNG. With carbon tax and fuel prices on the increase the point of breakeven is likely to be reached before 2020. Percentage changes in gas prices since 1st April 2011 are up +32%. Carbon tax is up from €0.0027 to €0.0037/kWh (SEAI, 2012d). The production of SNG becomes viable at a gas price of €0.0668/kWh and a carbon tax of €30/t (€0.0062/kWh). Compared with domestic rates for natural gas (€0.0719/kWh, SEAI, 2012e) the production of SNG is commercially viable already today.

5.3 Evaluation of Environmental Benefits

The All-Island-Grid Study (DCENR, 2008) examined different emission levels from Irish power production based on changes to the All-Ireland energy system. In Scenario 5 the impact of 6000MW of RES-E on the system performance was analysed. The study claims that an annual reduction of 21.8Mton CO₂ emissions could be achieved. The replacement of Moneypoint, Ireland's only coal fired power station with gas-fired boilers would result in overall emission savings of about 10.8Mton CO₂. In the event that the entire capacity is replaced with SNG originating from RES-E, the CO₂ emissions could be completely omitted as SNG can be regarded as carbon neutral. The carbon intensity of different fuels is listed below.

Table 9: Carbon Intensity of Different Fuels

Fuel	Emission Factors g CO₂/kWh
Gas/ Diesel Oil	263.9
LPG	229.3
Coal	340.6
Milled Peat	420.0
Sod Peat	374.4
Peat Briquettes	355.9
Natural Gas	205.6
SNG	0.0
Electricity (2010)	519.0

The evaluation of additional environmental benefits available from Power-to-Gas technology is based on two approaches. In the first assessment any CEEP generated by an increased level of wind penetration is considered as supplied to SNG storage. Each unit of electricity stored is treated as a replacement unit for conventional power production. The environmental benefit of each unit available from storage is a reduction in carbon emissions in the order of 519g CO₂/kWh (SEAI, 2011b). The second assessment postulates that a fixed percentage share of electricity generated by renewable intermittent power providers is to be supplied to storage for system balancing purposes.

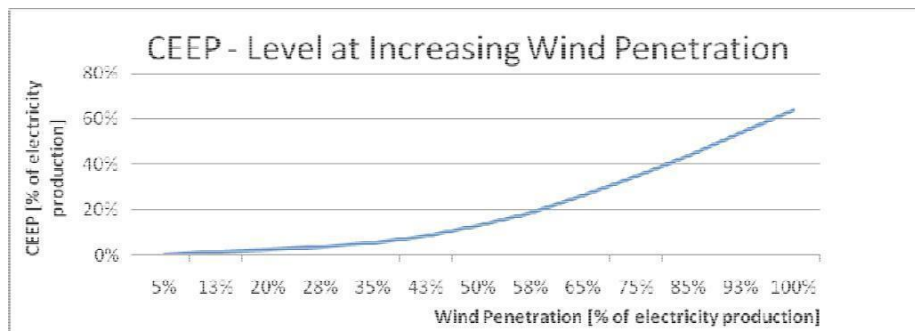
5.3.1 CEEP Based Assessment

The CEEP based assessment identifies the reduction potential of carbon emissions from Power-to-Gas technology utilising CEEP only. Estimated wind curtailment levels/ CEEP levels based on the EnergyPLAN simulation of the Irish energy system by Connolly et al. (2010) are listed in Table 10. Following assumptions have been made: A total electricity requirement (TER) of 40,000TWh, as predicted for 2020 by EirGrid and SONI has been used for the assessment. The wind power installed per TWh is calculated based on a wind power capacity factor of 30.6%. The wind penetration level refers to the TER. CEEP values are established by correlation with results published by Connolly et al. (2010). No consideration is given to any carbon reduction measures undertaken by plant owners and system operators or other forms of energy storage and associated benefits.

Table 10: CEEP-Level at Increasing Wind Penetration

Wind Energy [TWh]	Wind Power Installed [MW]	Wind Penetration [%]	CEEP [TWh/year]	CEEP [%]
2	746.11	5.00%	0.00	0%
5	1,865.28	12.50%	0.06	1%
8	2,984.45	20.00%	0.18	2%
11	4,103.62	27.50%	0.40	4%
14	5,222.79	35.00%	0.70	5%
17	6,341.96	42.50%	1.40	8%
20	7,461.13	50.00%	2.60	13%
23	8,580.30	57.50%	4.28	19%
26	9,699.47	65.00%	6.76	26%
30	11,191.69	75.00%	10.50	35%
34	12,683.92	85.00%	14.96	44%
37	13,803.09	92.50%	19.98	54%
40	14,922.26	100.00%	25.60	64%

Figure 31: CEEP-Level with Increasing Wind Penetration



The data provided in Table 10 states the level of CEEP based on a theoretical increase of wind power to 100% of Ireland's TER. The increase of CEEP is not a linear function. As shown in Figure 31, with an increase of wind penetration levels in the electricity market the CEEP is amplified. At a capacity level of 14,922MW (100% penetration) of wind power, the curtailment level is reaching up to 64%.

However, wind penetration levels will only increase as long as the turbine owner receives compensation for the units of electricity produced. Otherwise the economic viability of the project is not given and projects are halted. The current mechanism of a fixed payment allowance irrespective of occurrences of curtailment is unsustainable. Power-to-Gas technology is so far the only technology which enables the continuous growth of the Irish wind industry as it effectively increases the economic viability of a wind turbine while simultaneously allowing an increased penetration of non-synchronous power plants in the overall energy system.

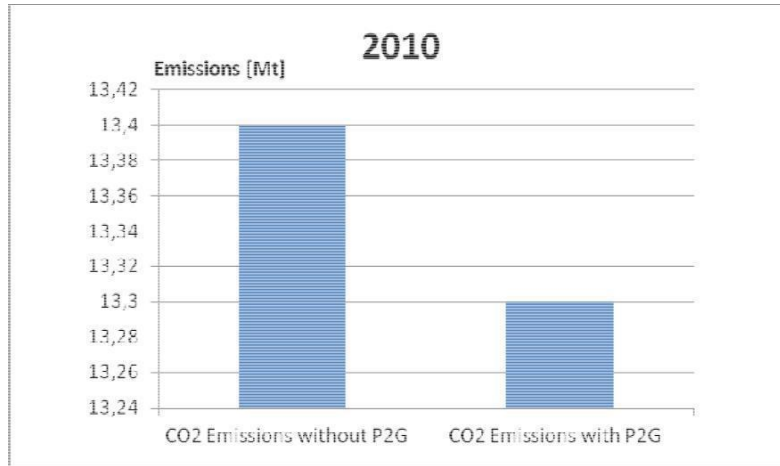
Maximum carbon emissions aimed for under the Irish 2020-targets are 0.393g CO₂/kWh. With 40% of the overall electricity demand supplied by RES-E (treated as carbon free) the annual system emissions without Power-to-Gas technology are 10.1million tonnes of CO₂. Each kWh CEEP converted into SNG and re-electrified will offset at least 205.6g CO₂/kWh.

Figure 32: Emission Reduction of P2G-technology²¹

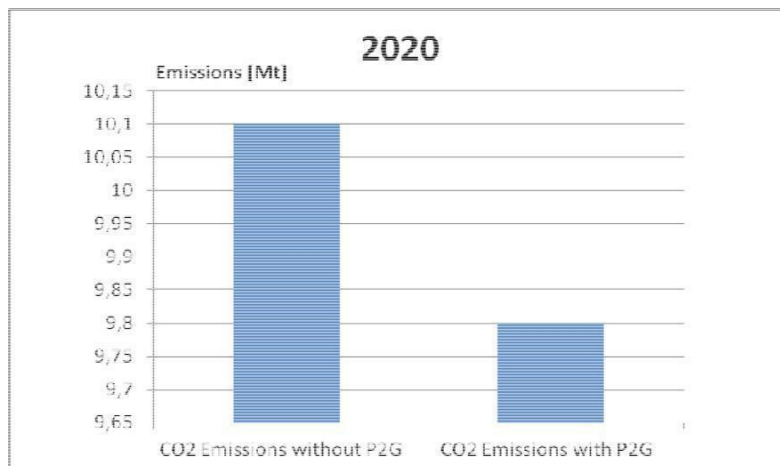
Year	Emissions CO ₂ [Mt]	CEEP [GWh]	CO ₂ Emission [t/GWh]	CO ₂ Savings [t/GWh]	CO ₂ with P2G technology [Mt]
2010	13,4	130	519	67470	13,3
2020	10,1	740	393	290820	9,8

²¹System emissions as per EPA (2010); CEEP as per p.58; CO₂ emission factor as per 2020 target: 26.2% less CO₂ than 2008: 533g/kWh (SEAI, 2011b)

CO2 Emission Savings at 2.2% CEEP (2010)



CO2 Emission Savings at 5.0% CEEP (2020)



5.3.2 Mandatory Storage Requirement for Intermittent Supply Sources

The second assessment of environmental benefits is based on a fixed percentage share of electricity supplied to storage. This share could be defined as a mandatory range to be supplied by all non-synchronous power providers for balancing purposes. Illustrated below are CO₂ reduction quantities in tonnes at percentage shares of 5%, 10%, 25% and 50% (Figures based on 2020 scenario).

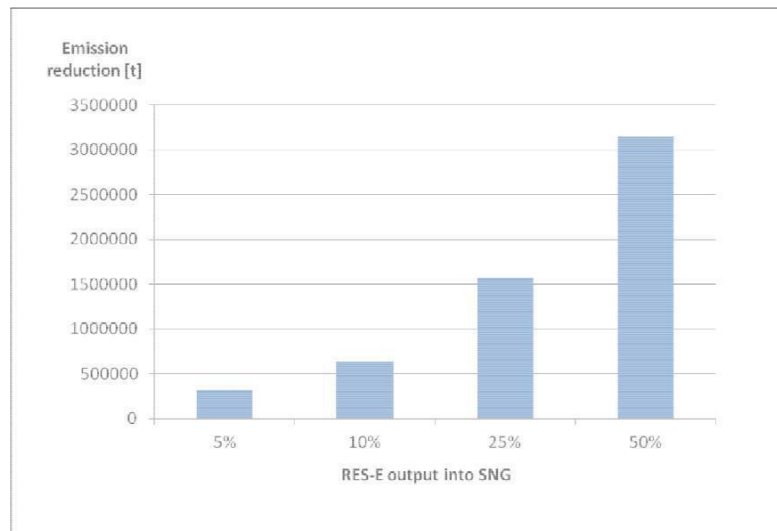
Figure 33: CO₂-Reduction from Mandatory Storage of RES-E

Figure 34 depicts the CO₂ emissions of the Irish energy system according to the wind penetration level. A mandatory storage quota can:

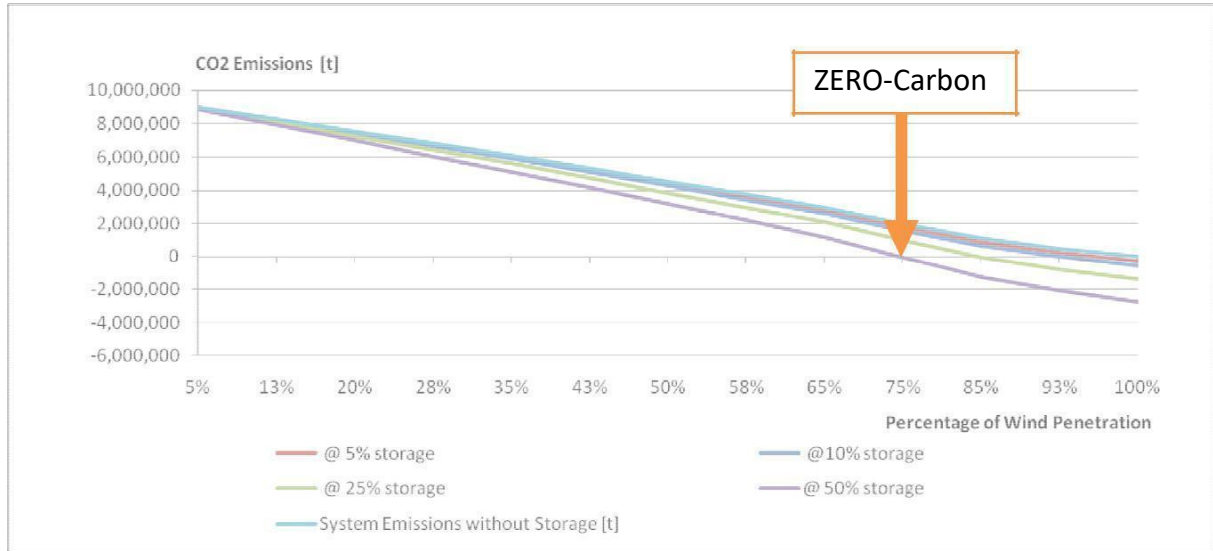
- improve security of supply,
- reduce costs associated with balancing of system loads,
- reduce import dependencies and
- reduce overall system related carbon emissions

Mandatory storage requirements might be avoided when Power-to-Gas technology becomes an established technology utilised to maximise revenues from erratic renewable sources. As CEEP levels will raise with the increased employment of wind power, storage technologies will become more economically viable. The avoidance of curtailment will be an elemental part in the future utilisation of renewables. The associated benefits are not only measurable in increased revenues for plant owners. Each unit of energy stored (originating from a renewable source) replaces a unit of conventional power production. In measurable terms this implies an emission reduction of between 205g to 519g CO₂/kWh.

Energy storage does also reduce the required wind penetration level in order to achieve a carbon neutral energy system. Figure 34 illustrates that an installed wind capacity of 11,000MW (75% wind penetration) with a mandatory storage range of 50% can result in a

carbon free energy system for Ireland. Given that the CEEP level at 11,000MW is at 35% about 15% of additional output send to storage will result in a self sufficient power system for Ireland.

Figure 34: CO2 Emissions vs. Percentage of Wind Penetration



6 DISCUSSION AND CONCLUSION

Despite the process technology and fields of application have been well known for many years, Power-to-Gas applications never became a viable technology. A changed agenda on electricity generation has triggered an enormous growth market of renewable power generation from natural resources such wind, wave and solar. The ability to harvest 'free' energy has reached a level where renewable power output exceeds market demand. This relatively novel situation allows the energy intensive storage of surplus energy basically free of charge. Although the roundtrip conversion of Power-to-Gas-to-Power obliterates almost $2/3^{\text{rd}}$ of its input value, the fact that the input is provided numerous and free of charge turns out as a viable invention. The practical implementation of Power-to-Gas technology is still in its infancy. This thesis aims to highlight the benefits and possibilities contained in the concept with focus on the Irish market situation. A summary of the main findings is presented in this last section.

6.1 Discussion of Main Findings

An evaluation of the Irish electricity system unfolds the urgent need of energy storage in order to enhance the usability of renewable energy sources. Despite its relative unspectacular presents hitherto Power-to-Gas energy storage offers many superior characteristics to other, as yet employed storage technologies. In comparison to PHES, CAES, battery storage and flywheel technology SNG represents the most energy dense storage medium for short and long term storage. SNG is usable in an existing infrastructure, with an established industry and a proven track record on its long term performance characteristics. The use of Power-to-Gas energy storage significantly enhances the ultimate penetration level of wind energy connected to the all-island network. The combined system allows for wind penetration levels of 70%+ compared to an otherwise upper limit of about 40% determined by the wind's low capacity factor.

In addition, SNG can be used in numerous applications for cooking, heating, power generation, transport and other industrial processes. Integrated in a transformed energy system Power-to-Gas energy storage can enhance the viability of renewable power generators and convert unwanted carbon emissions resulting from anaerobic digestion into

a useful element. The technology can be seen as a catalyser to merge various technologies currently operating independently to fulfil the same goal: the provision of energy.

The fact that the production process of SNG consumes an identical volume of CO₂ as being released when converted into electricity allows the suggestion to treat SNG as a carbon neutral fuel and hence a classification as environmentally benign. Besides its environmental supremacy over conventional fuels methane-fuelled vehicles emit lower amounts of harmful GHG than vehicles driven on diesel or petrol. Vehicles run on SNG/CNG are also more economical and quieter than those run on fossil derivatives.

6.1.1 Difficulties

1. The increasing number of renewable power plants, together with the simultaneous transformation of the all-island energy system results in the steady creation of new challenges. In order to address these challenges properly and fairly each issue has to pass through a time intensive consultation process. Contemporaneous to the writing of this thesis several consultation processes are ongoing which will bring clarification to issues touched throughout this text. The regulating authorities CER and NIAUR are jointly engaging in gathering public and industry views on regulatory decisions. However, the absence of regulatory frameworks and decision papers impeded the properly evaluation of economic benefits and the extent of a feasibility study. As a consequence some of the results presented herein are partially presented more general than originally anticipated.

2. The non-availability of actual wind farm performance data both of existing wind farms but also of the second generation wind turbines of above 100m hub-height (i.e. Siemens SWT-

6. 0-154) required the application of a mathematical model for the establishment of performance data. Unfortunately, mathematical simulations can only imitate performance data to a certain degree of accuracy. The output data received from the model employed are therefore theoretical values and have not been compared to real values. An adjustment of performance data might be necessary when accurate and reliable data sets become available.

6.2 Conclusions

The critical evaluation of the Power-to-Gas concept for Ireland has shown that the domestic production of SNG can make a positive contribution towards the strategic goals of Irish Energy Policy. Following benefits are associated with the introduction of such technology in Ireland:

- Enhanced integration of renewable energy generation through balancing characteristics
- Improved usability of Irelands' natural resources
- Reduced import dependency
- Reduced dependency on fossil fuel reserves
- Reduced carbon emissions
- Increased energy security for Ireland and improved competitiveness through lower costs of electricity.

In the long term SNG derived from RES-E can displace oil based products and natural gas from fossil sources.

In order to become a viable tool for Ireland Power-to-Gas energy storage requires the continuous development of renewable power generation in line with the 2020-targets as well as an urgent debate on how barriers to the integration of the technology can be overcome. Simultaneously research and development of process components has to continue with a joint initiative of industry and government to drive the production and storage of SNG to readiness for series-production.

7 FURTHER RESEARCH

The requirement for further research into fuel cell technology and other process components is obvious. Solid Oxide Cells enabling the reversible flow of electricity and gas in form of SOFC and SOEC-modes offer as yet the greatest potential to large scale applications without the need of conventional combustion engines/turbines.

Research into the possibilities of integrating Power-to-Gas technology into the Irish energy system require the anticipatory safeguarding of results from the ongoing consultation processes on curtailment issues, network access, feed-in mechanisms into the gas network and integration of hybrid plants. Further research opportunities about the integration of SNG into the gas network and the associated challenges are numerous.

Other areas suggested for further research include:

- Classification and treatment of carbon credits and carbon rates for Power-to-Gas energy storage
- An investigation into the feasibility to fuel Irelands' transport industry on CNG from renewable sources
- An investigation into the impacts of burden-sharing of load balancing cost by the originator, namely non-synchronous power plants

8 REFERENCES

Callanan, P. (2010) *Compressed Natural Gas transport fuel for your vehicles*, BGN [online], available at: http://www.bordgaisnetworks.ie/Global/Gas%20Industry/NGV/CNG_Info_Sheet.pdf [accessed: 01/08/2012]

Campbell C.J. & Laherrère J.H., (1998), The end of cheap oil, *Scientific American*, Vol.278 No. 3, pp. 78-83

CER (2008), *Fuel Mix Disclosure and CO2 Emissions 2008* [online], available at: <http://www.cer.ie/en/documents-by-year.aspx?year=2008> [accessed: 26/06/2012]

CER (2011), *Fuel Mix Disclosure and CO2 Emissions 2010* [online], available at: <http://www.cer.ie/en/documents-by-year.aspx?year=2011> [accessed: 26/06/2012]

CER (2012), *Public Service Obligation Levy 2012/2013 - Proposed Decision Paper*, The Commission for Energy Regulation: Dublin

CER & NIAUR (2008), *Wind Generation in the SEM, Policy for Large-Scale, Intermittent Non-Diverse Generation – Discussion Paper*, SEM/08/002 [online], available at: http://www.allislandproject.org/en/sem_publications.aspx?year=2008§ion=2 [accessed: 25/06/2012]

CER & NIAUR (2011), *Consultation Paper for the Treatment of Transmission Network Tariffs for Gas Storage Facilities*, CAG/11/05 [online], available at: http://www.allislandproject.org/en/project_office_cag_publications.aspx?year=2011§ion=1 [accessed: 13/07/2012]

CER & NIAUR (2012), *Treatment of Curtailment in Tie-Break Situations – Consultation Paper*, SEM-12-028 [online], available at: http://www.allislandproject.org/en/sem_publications.aspx?year=2012§ion=2 [accessed: 25/06/2012]

CER & NIAUR (2012b), *Criteria for Qualification of Hybrid Plant for Priority Dispatch in the SEM*, SEM-12-056 [online] available at: http://www.allislandproject.org/en/sem_publications.aspx?year=2012§ion=2 [accessed: 26/08/2012]

Clare County Council (2011), *Clare County Development Plan 2011-2017 - Wind Energy Strategy, Vol. 5* [online], available at: <http://www.clarecoco.ie/planning/publications/clare-county-development-plan-2011-2017-volume-5-clare-wind-energy-strategy-9109.pdf> [accessed: 27/07/2012]

Clifford, E. & Clancy, M. (2011), *Impact of Wind Generation on Wholesale Electricity Costs in 2011* [online], available at: http://www.seai.ie/Publications/Statistics_Publications/Energy_Modelling_Group [accessed: 04/07/2012]

Connolly, D., Lund, H., Mathiesen, B.V. & Leahy, M. (2010), Modelling the existing Irish energy-system to identify future energy costs and the maximum wind penetration feasible, *Energy*, Vol.35, pp. 2164-2173

Coveney, S. (2011), *Report on Biogas Energy in Ireland, Seventh Report of the Joint Committee on Climate Change and Energy Security*, Houses of the Oireachtas [online] available at: <http://www.oireachtas.ie/viewdoc.asp?DocID=-1&CatID=78&mypage=2&OrderAscending=0> [accessed: 10/07/2012]

DENA (2012), *Strategieplattform Power to Gas* [online], available at: <http://www.powertogas.info/> [accessed: 21/06/2012]

Devitt, C. and Valeri, L.M. (2011), *The Effect of REFIT on Irish Electricity Prices*, ESRI Working Paper No. 374

DCENR (2008), *All Island Grid Study*, Department of Communications, Energy and Natural Resources: Dublin

DCENR (2009), *Maximising Ireland's Energy Efficiency – The National Energy Efficiency Action Plan 2009-2020*, Department of Communications, Energy and Natural Resources: Dublin

DCENR (2011), *S.I. No. 147 European Communities (Renewable Energy) Regulations 2011*, Department of Communications, Energy and Natural Resources: Dublin

DCENR (2012), *Renewable Energy Feed in Tariff 2012* [online], available at: <http://www.dcenr.gov.ie/NR/rdonlyres/DF253F94-8366-4DE0-A2E6-DFA244E634DD/0/REFIT2TermsandConditionsMarch2012c.pdf> [accessed: 03/07/2012]

DCMNR (2007), *Government White Paper - Delivering a Sustainable Energy Future for Ireland*, Department of Communications, Marine and Natural Resources: Dublin

Denholm, P., Kulcinski, G.L., and Holloway, T. (2005), Emissions and Energy Efficiency Assessment of Baseload Wind Energy Systems, *Environmental Science and Technology*, Vol.39, pp. 1903-1911

EC (2001), Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants, *Official Journal of the European Communities* [online], available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2001:309:0001:0021:EN:PDF> [accessed: 25/05/2012]

EEA (2009), *Europe's onshore and offshore wind energy potential*, Technical Report, European Environment Agency: Copenhagen, DK

Ehrlich P.R. & Ehrlich A.H, (1990), *The Population Explosion*, Simon & Schuster: New York

EirGrid (2008), *GRID25 Strategy* [online] available at: <http://www.eirgrid.com/media/Grid%2025.pdf> [accessed: 31/07/2012]

EirGrid and SONI (2011a), *Ensuring a Secure, Reliable and Efficient Power System in a Changing Environment* [online], available at: http://www.eirgrid.com/media/Ensuring_a_Secure_Reliable_and_Efficient_Power_System_Report.pdf [accessed: 22/08/2012]

EirGrid & SONI (2011b), *All-Island Generation Capacity Statement 2012-2020*, EirGrid Plc: Dublin & SONI Ltd.: Belfast

EirGrid (2011a), *Annual Renewable Report 2011*, EirGrid Group: Dublin

EirGrid (2011c), *EirGrid Monthly Electricity Statistics Update – Jan to Dec 2011* [online], available at: <http://www.eirgrid.com/operations/systemperformancedata/electricitystatistics/> [accessed: 21/06/2012]

EirGrid (2011d), *EirGrid Monthly Availability Report – December 2011* [online], available at: <http://www.eirgrid.com/operations/systemperformancedata/availabilityreports/> [accessed: 05/07/2012]

EirGrid (2012a), *GRID25 Implementation Programme* [online], available at: <http://www.eirgrid.com/aboutus/latestnews/> [accessed: 05/07/2012]

EirGrid (2012b), Personal correspondence with Nezar Kamaluddin regarding the quarterly DS3 wind curtailment report [email from: 02/07/2012]

EPA (2010), Ireland's Greenhouse Gas Projections 2010 -2020 [online], available at: http://www.epa.ie/downloads/pubs/air/airemissions/EPA_GHG_Emission_Projections_2010.pdf [accessed: 30/08/2012]

ESB (2012), *Power Stations –Aghada* [online] available at: <http://www.esb.ie/main/about-esb/aghada.jsp> [accessed: 31/07/2012]

EU (2010), Directive 2010/75/EU of the European Parliament and the Council of the 24 November 2010 on industrial emissions (integrated pollution prevention and control), *Official Journal of the European Union* [online], available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:334:0017:0119:EN:PDF> [accessed: 25/05/2012]

European Commission (2009), *Leading Global Action to 2020 and Beyond*, Office for Official Publications: Luxembourg

European Environment Agency (2006), *EN19 Efficiency of conventional thermal electricity and heat production* [online], available at: <http://www.eea.europa.eu/data-and-maps/indicators/en19-efficiency-of-conventional-thermal-1/en19> [accessed: 16/04/2012]

EWEA (2009), *Wind at Work – Wind Energy and Job Creation in the EU* [online], available at: http://www.ewea.org/fileadmin/ewea_documents/documents/publications/Wind_at_work_FINAL.pdf [accessed: 26/06/2012]

Frank, H.P. & Landberg, L. (1997), *Modelling the Wind Climate of Ireland*, Risø National Laboratory: Roskilde, Denmark

Gallagher, C. (2009), *Energy Costs – Recent Trends and Future Prospects* [online], available at: http://www.engineersirelandcork.ie/downloads/BGE_ENERGY%20COSTS%203-2-09.pdf [accessed: 13/07/2012]

Gaslink (2011a), *Network Development Statement 2010/11 to 2019/2020*, Gas System Operator: Cork

Gaslink (2011b), *BGN Transmission Tariff for Gas Year 2011/2012* [online] available at:
http://www.gaslink.ie/files/Copy%20of%20library/20110908034456_BGN%20Transmission%20Tariff%20for%20Ga.pdf
[accessed: 13/07/2012]

Garrad Hassan and Partners (2002), *Study into the impacts of increased levels of wind penetration on the Irish electricity system* [online], available at: <http://www.cer.ie/en/renewables-reports-and-publications.aspx> [accessed: 27/06/2012]

Götz, M., Buchholz, D. and Bajohr, S. (2011), Speicherung elektrischer Energie aus regenerativen Quellen im Erdgasnetz, *energie | wasser-praxis*, Vol. 62 No.5 pp.72-76

Hansen, J., (2004), Defusing the global warming time bomb, *Scientific American*, Vol.290 No. 3, pp. 68-77

IEA (2011), *IEA – by Country, Gas Trade Flows in Europe*, Informations: Ireland [online] available at:
<http://www.iea.org/gtf/index.asp> [accessed: 12/06/2012]

Irish Government (2011), *S.I. No.147 of 2011*, European Communities (Renewable Energy) Regulations 2011, Stationary Office: Dublin

Irish Government (2011), *S.I. No.148 of 2011*, Sustainable Energy Act 2002 (Section 8(2)) (Conferral of Additional Functions – Renewable Energy) Order 2011, Stationary Office: Dublin

Jensen, S.H. & Morgensen, M. (2004), *Perspectives of high temperature electrolysis using SOEC*, Paper presented at the 19th World Energy Congress 2004, Sydney (AU)

Jentsch, M., Trost, T., Emele, L. & Sterner, M. (2011), Power-to-Gas als Langzeitspeicher, *Energy 2.0 No.5* [online], available at: www.energy20.net/PDF/E20611700 [accessed: 10/07/2012]

Mangold, R. (2012), *Das e-gas Projekt von Audi: Power-to-Gas im Verkehrssektor* [online], available at:
http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/BNNetzA/Sachgebiete/Energie/VortraegeVeranstaltungen/PowerToGas/PtG_221111_Mangold_%20pdf.pdf?__blob=publicationFile [accessed: 24/07/2012]

Met Éireann (2012a) *Rainfall in Ireland* [online] available at: <http://www.met.ie/climate-ireland/rainfall.asp> [accessed: 30/07/2012]

Met Éireann (2012b), *A Summary of Climate Averages for Ireland 1981 – 2010* [online] available at:
<http://www.met.ie/climate-ireland/SummaryClimAvgs.pdf> [accessed: 17/08/2012]

- NOW Ireland (2011), *Blueprint for the Development of Irish Offshore Wind* [online], available at: <http://www.nowireland.ie/uploads/docs/BLUEPRINT%20FOR%20THE%20DEVELOPMENT%20OF%20IRISH%20OFFSHORE%20WIND%20DATED%2030TH%20JANUARY%202011%20UPDATED%2014SEPTEMBER11%20MASTER%20%282%29.pdf> [accessed: 17/04/2012]
- O'Mahoney, D.C. (2012), Weibull and Wind Energy Output Simulation Model [programmed in line with requirements for this thesis], Department of Mechanical & Aeronautical Engineering: University of Limerick
- renews (2012), *Ireland Special Report 2012*, Renewables Limited: Winchester (UK)
- Reuters (2012), *Point Carbon News – EU ETS* [online], available at: <http://www.pointcarbon.com/news/1.1933897> [accessed: 04/07/2012]
- Rosegrant, M.W. (2008), *Biofuels and Grain Prices: Impacts and Policy Responses*, International Food Policy Research Institute: Washington (USA)
- SEAI (2009), *Energy Efficiency in Ireland, 2009 Report*, Sustainable Energy Authority of Ireland: Dublin
- SEAI (2011a), *Energy Security in Ireland, 2011 Report*, Sustainable Energy Authority of Ireland: Dublin
- SEAI (2011b), *Energy in Ireland, Key Statistics*, Sustainable Energy Authority of Ireland: Dublin
- SEAI (2011c), *Wind Energy Roadmap 2011-2050*, Sustainable Energy Authority of Ireland: Dublin
- SEAI (2011d), *Energy Forecasts for Ireland to 2020, 2011 Report*, Sustainable Energy Authority of Ireland: Dublin
- SEAI (2012a), *The Case for Sustainable Energy*, Sustainable Energy Authority of Ireland: Dublin
- SEAI (2012b) *Commercial / Industrial Fuels Comparison of Energy Costs* [online] available at: http://www.seai.ie/Publications/Statistics_Publications/Fuel_Cost_Comparison/Commercial_Fuel_Costs_Comparison_April_2012_pdf.pdf [accessed: 30/07/2012]
- SEAI (2012c) *Wind Atlas* [online] available at: <http://maps.seai.ie/wind/> [accessed: 18/08/2012]
- SEAI (2012d) *Commercial / Industrial Fuels Comparison of Energy Costs* [online] available at: http://www.seai.ie/Publications/Statistics_Publications/Fuel_Cost_Comparison/Commercial_Fuel_Costs_Comparison_July_2012_pdf.pdf [accessed: 31/08/2012]
- SEAI (2012e) *Domestic Fuels Comparison of Useful Energy Costs for Space Heating* [online] available at: http://www.seai.ie/Publications/Statistics_Publications/Fuel_Cost_Comparison/Domestic_Fuel_Costs_Comparison_July_2012_pdf.pdf [accessed: 31/08/2012]

SEMO (2012), *The Single Electricity Market Overview 13th July 2012* [online], available at: <http://www.sem-o.com/Pages/default.aspx> [accessed: 13/07/2012]

Siemens (2012), *Award for world's most efficient gas turbine power plant* [online], available at: <http://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2012/energy/fossil-power-generation/efp201202028.htm> [accessed: 16/04/2012]

SONI (2012), *Northern Ireland Electricity Statistics – 2011 Overall Summary* [online], available at: <http://www.soni.ltd.uk/upload/2011%20NI%20Electricity%20Statistics%20-%20Overall%202011%20Summary.pdf> [accessed: 21/06/2012]

Specht, M., Baumgart, F., Feigl, B., Frick, V., Stürmer, B. & Zuberbühler, U. (2009) *Storing bioenergy and renewable electricity in the natural gas grid* [online], available at: http://www.solar-fuel.net/fileadmin/user_upload/Publikationen/Wind2SNG_ZSW_IWES_SolarFuel_FVEE.pdf [accessed: 10/07/2012]

Sterner, M. (2009), *Bioenergy and renewable power methane in integrated 100% renewable energy systems*, PhD Thesis, University of Kassel

stoRE (2011), *D2.1 Report summarizing the current Status, Role and Cost of Energy Storage Technologies* [online], available at: <http://www.store-project.eu/> [accessed: 20/06/2012]

UN (1987), *Our Common Future: Report of the World Commission on Environment and Development*, A/42/427 (Brundtland Report), UN Department of Economic and Social Affairs [online], available at: http://www.un.org/esa/dsd/resources/res_publcorepubli.shtml [accessed: 17/05/2012]

UN (1992), *Rio Declaration on Environment and Development*, A/Conf. 151/26 (Vol. 1) Report of the United Nations Conference on Environment and Development, Rio de Janeiro: UN Department of Economic and Social Affairs [online], available at: <http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm> [accessed: 17/05/2012]

UN (1998), *Kyoto Protocol to the United Nations Framework Convention on Climate Change* [online], available at: <http://unfccc.int/resource/docs/convkp/kpeng.pdf> [accessed: 17/05/2012]

APPENDICES

Calculation: Total gas use in Ireland

230mscm = 4% (CER & NIAUR, 2011)

5750mscm = 100%

1030mscm = 18%

--

230mscm = 2,415.3GWh (CER & NIAUR, 2011)

1030mscm = 10,815GWh (10.8TWh)

--

Calculations from Page 34:

6100MW*0.31*8760h = 16,565,160MWh Annual

Output 5% = 16,565,160*0.05 = 828,258MWh =

828GWh 828,258MWh*€75.00/MWh = € 62,119,350 --

Wind output curtailed in 2011 (page 41):

Total capacity installed * AVG. Capacity Factor * 8760hours * %
curtailment 2030MW * 31.575% * 8760 * 2.2% = 123,528MWh =
123.5GWh --

$$C_{CH_4} = \left(\frac{CC_{el} \times CRF + (O\&M + C_{CEEP} \times CEEP_{kWh})}{CH_4} \right)$$

Where

C_{CH_4} : Cost of SNG in €/kWh

CC_{el} : Capital Cost of the Power-to-Gas facility

CRF : Capital Recovery Factor

$O\&M$: Operation and maintenance costs

C_{CEEP} : Cost of CEEP Electricity

$CEEP_{kWh}$: Annual surplus electricity utilised

CH_4 : Annual SNG production

For a 20,000kW facility following parameters are used:

C_{CH4} : Cost of SNG in €/kWh

CC_{el} : $20,000kW * €1,000 = €20,000,000$

CRF : 10years, $i=5\%$; $= 0.1295$

$$CRF = i (1+i)^n / (1+i)^n - 1$$

$O\&M$: 3% of $CC_{el} = €600,000$

C_{CEEP} : €0.03

$CEEP_{kWh}$: 5% of Total Wind Output Wind Farm Clare and Arklow (Total: 613MW installed;

estimated output: $613 * 8760 * 0.4 = 2,147,952MWh$; 5% $= 107,000MWh = 107,000,000kWh$

Assuming the facility is operating at a capacity factor of 50% a 20MW facility would consume 87,600,000kWh per year ($20,000kWh * 8760 * 0.5$)

CH_4 : 60% of $CEEP_{kWh} = 52,560,000kWh$

$$C_{CH_4} = \left(\frac{CC_{el} \times CRF + (O\&M + C_{CEEP} \times CEEP_{kWh})}{CH_4} \right)$$

$C_{CH_4} = (\€20,000,000 \times 0.1295 + (\€600,000 + \€0.03 \times 87,600,000kWh) / 52,560,000kWh)$

$C_{CH_4} = (\€2,590,000 + \€3,228,000 / 52,560,000kWh)$

$C_{CH_4} = \€0.11$

--

Water demand: $87,600MWh = 14,600m^3$ /year (Mangold, 2012: $27,600MWh = 4,600t$);

Water released from methanation process: $6,350m^3$ /year; Total requirement: $14,600 - 6,350 = 8,250m^3$; $8,250 / 365 = 22.6m^3$ /day; 14 days = $316m^3$

Rainwater harvesting system size: $316m^3 = \text{Avg. Monthly Rainfall Ireland is } 80mm$
(Met Eireann, 2012a) $= 0.8m^3/m^2$; $316 / 0.8 = 395m^2$