Incentives to Decentralise:

Community Energy in Ireland's Electricity Sector

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handed in by

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"*All models are wrong, but some are useful.*"

George E. Box

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Abstract

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The energy transition from fossil-fuel resources to renewables is a vital aspect of climate change mitigation. It is anticipated that increased penetration of renewable energy resources will be accompanied by a change in the structure of the energy sector. The electricity industry is expected to become more decentralised, with distributed generation from technologies like wind turbines and solar photovoltaic panels. These changes have a climate, economic and social dimension. Incentives for small-scale generators to enter the electricity market are crucial, while it is important that the industry remains competitive. This thesis focuses on the climate, economic and social implications of incentive policies in the Irish electricity sector.

A model is adapted from the industrial organisation literature on electricity wholesale markets to represent the Irish electricity industry. The stylised model's general structure is constructed and theoretically analysed through the lens of four different scenarios: the sector status-quo, the introduction of community energy, the market remuneration for community electricity generation, and the cessation of support schemes for renewable electricity. A numerical illustration of the model is then offers insights into the economic implications of incentivising community energy development in Ireland. The implications of these scenarios are then discussed in terms of decarbonisation, market power, and the distributional benefits of the energy transition.

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List of Abbreviations

AEA	**A**nnual **E**mission **A**llocation
AER	**A**lternative **E**nergy **R**equirement
BM	**B**alancing **M**arket
CfD	**C**ontract **f**or **D**ifference
CAP	**C**limate **A**ction **P**lan
CM	**C**apacity **M**arket
CRU	**C**ommission for **R**egulation of **U**tilities
DERs	**D**istributed **E**nergy **R**esources
DSO	**D**istribution **S**ystem **O**perator
ESD	**E**ffort **S**haring **D**ecision
ESB	**E**lectricity **S**upply **B**oard
EU ETS	**E**uropean **U**nion **E**missions **T**rading **S**cheme
IEA	**I**nternational **E**nergy **A**gency
IPCC	**I**ntergovernmental **P**anel on **C**limate **C**hange
I-SEM	**I**ntegrated - **S**ingle **E**lectricity **M**arket
IEM	**I**nternal **E**nergy **M**arket
MW	**M**ega**w**att
MWh	**M**ega**w**att **h**our
NDCs	**N**ationally **D**etermined **C**ontributions
OPEC	**O**rganisation of Arab **P**etroleum **E**xporting **C**ompanies
OREDP	**O**ffshore **R**enewable **E**nergy **D**evelopment **P**lan
PPA	**P**ower **P**urchase **A**greement
PSO	**P**ublic **S**ervice **O**bligation
PV	**P**hoto**v**voltaic
RES	**R**enewable **E**nergy **S**ources
RES-E	**R**enewable **E**nergy **S**ources **E**lectricity
RESS	**R**enewable **E**lectricity **S**upport **S**cheme
SEAI	**S**ustainable **E**nergy **A**uthority of **I**reland
SONI	**S**ystem **O**perator for **N**orthern **I**reland
TSO	**T**ransmission **S**ystem **O**perator

Dedicated to Simon, my guiding light…

Chapter 1

Introduction

1.1 The Energy Transition

The world is entering a critical decade in our efforts to tackle climate change. Successive assessment reports by the Intergovernmental Panel on Climate Change (IPCC) have communicated the consistent conclusions from the scientific community: anthropogenic climate change is indisputable and constitutes an unprecedented threat to human civilisation. The recommendations are equally clear from the IPCC special report on 1.5 degrees warming compared to pre-industrial temperatures (IPCC, 2018). To avoid dangerous warming beyond this level, it is imperative to rapidly reduce global emissions of greenhouse gases over the 2020–2030 period and decisively set the world on the path to a zero-carbon global economy. In this context, there is an urgent need to identify and overcome the challenges related to reducing greenhouse gas emissions.

Greenhouse gas emissions — carbon dioxide, methane, nitrous oxide and other fluorinated gases — have a diverse range of sources, including electricity generation, transport, industry and agriculture. In 2013, the entire global energy sector (electricity and heat production, transport, and manufacturing and construction) accounted for 72% of all emissions (Center for Climate and Energy Solutions, 2020). According to the IPCC's 2014 fifth assessment report on climate change, 25% percent of global greenhouse gas emissions in 2010 were specifically due to electricity and heat production (IPCC, 2014) (see Figure 1.1). Across the EU in 2018, the production and use of energy caused 75% of the Member States greenhouse gas emissions (European Commission, 2018). Evidently, the global energy sector is responsible for vast greenhouse gas emissions. To effectively stabilise the climate, it is then vital that the global energy sector transforms from a fossil-fuels-based system to a net-zero emissions system. This is referred to as the energy transition[1].

A critical goal of the energy transition is to substitute electricity generation from fossil-fuel resources with generation from renewable, zero-carbon resources and use this renewable electricity[2] for fuel production and transport. The transport sector can be decarbonised through electric vehicles and the use of fuels like hydrogen that can be produced by electrolysis (a process which requires only water and electricity). The building sector can be decarbonised by using technologies such as heat pumps (Sugiyama, 2012). There are other sectors which are more difficult to decarbonise, such as aviation and production of materials like steel and concrete. However, carbon capture and storage (CCS) can help to reduce emissions from these challenging areas (Davis et al., 2018). Considering that most decarbonisation involves electrification

[1] *Low-carbon transition* and *zero-carbon transition* are more general terms that can describe changes outside of energy sector, however, they are often used interchangeably.

[2] Renewable electricity will be used throughout this thesis as a term for electricity generated from renewable energy sources (RES-E).

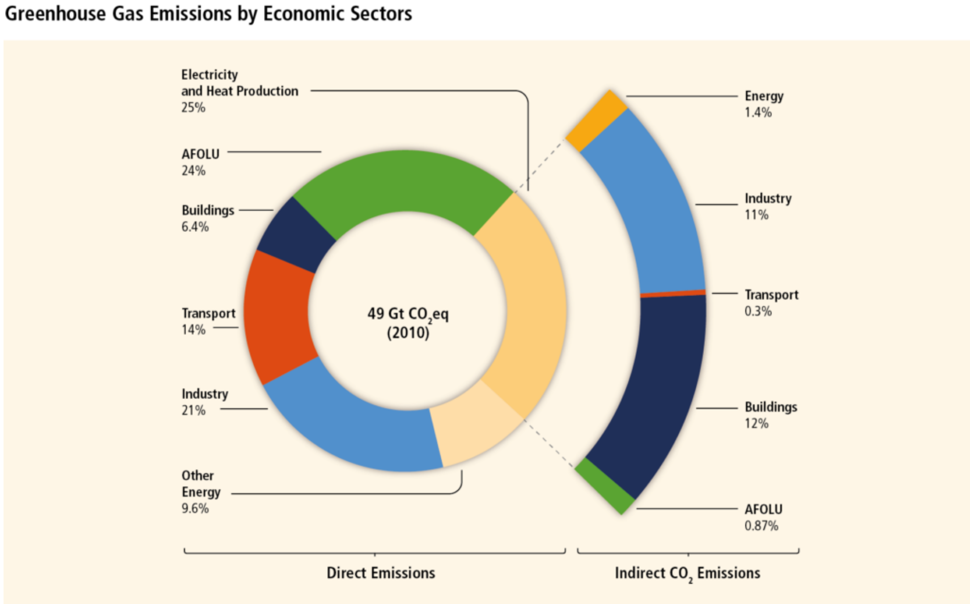


FIGURE 1.1: Greenhouse Gas Emissions by Economic Sector in 2010 (IPCC, 2014)

of previously fossil-fuel dependent processes, it is evident that significant reductions in global emissions are fundamentally dependent on widespread electricity generation from renewable energy sources.

There are competing visions about decarbonisation in the energy transition. Some argue that renewable energy technologies should remain centralised in the hands of efficient and effective strategic energy firms, while others believe decentralisation is critical to reduce the market power of the economic actors who created an unsustainable and undemocratic energy system (Lilliestam and Hanger, 2016). In a sense, this describes a tension between the *SuperGrid* and *SmartGrid* conceptions of the future of electricity systems. The former envisions continental-scale grids supplying electricity to consumers from far-away solar and wind installations, while the latter focuses on intelligent use of resources to manage demand on the distribution side of the network. The combination of these ideas about the structure of the electricity system is a *SuperSmartGrid* (Battaglini et al., 2009). Despite the differing visions about the nature of the process, it is widely accepted that the electricity system will become more decentralised during the energy transition.

Decentralisation will include the increased use of Distributed Energy Resources (DERs). DERs include distributed generation technologies, meaning electricity generation on a more local level on the distribution side of the electricity grid [3]. DERs also include energy storage technologies. Distributed wind turbine and solar photovoltaic (PV) installations are expected to displace some of the generation from centralised fossil-fuel power stations. These small-scale distributed electricity generation technologies can be utilised not only by large energy firms, but also on a community level and even by individual energy citizens. Energy citizens actively participate in the management of their own energy demand and supply.

The introduction of these technologies to the existing energy system raises many questions. What effect will they have on electricity markets? What are the benefits,

[3]Electricity grids are generally composed of a transmission grid, which carries high voltage electricity from power stations to heavy industry or transformers, and a distribution grid, which carries the transformed low-voltage electricity to consumers.

barriers and challenges related to their use? Who will reap the benefits? How best can their adoption be incentivised? The answers to these questions remain unresolved in many cases, and so, decentralisation in electricity generation remains a challenge in most countries. To facilitate electricity system decentralisation, technical obstacles must be overcome, economic issues must be clarified, and political acceptance across many different societal groups must be achieved. This thesis investigates the questions introduced here, with a focus on the economic issues of market power and incentive policies. The policies used to incentivise[4] distributed renewable electricity generation play an important and complex role in shaping the path taken during the energy transition.

The energy transition can be analysed at many different scales, from global to national to local. Without effective national energy transitions, the global goals that are necessary to avoid catastrophic climate change will not be achieved. Each nation crafts its own energy and climate policies. Much of the rest of this thesis will be focused on the national energy transition in the Republic of Ireland. Consideration will also be given to the role of local communities, as the process of energy system decentralisation is expected to engage communities and alter their relationship with energy (Dütschke and Wesche, 2018). However, before addressing community energy in Ireland, the energy transition at the European scale must be discussed.

1.1.1 Europe's Energy Transition

The region of the world with the most ambitious and detailed plans for the energy transition is the European Union (EU). Its energy industry has already undergone a different type of transition, moving from state-owned monopolies operating the electricity and gas infrastructure, to an unbundled, competitive, liberalised energy market. It has also led the way on climate and energy policies in many respects, for example, in 2005 the EU implemented the first large emissions trading scheme in the world, the European Union Emissions Trading Scheme (EU ETS), which covers emissions from over 11,000 energy-intensive installations.

The EU's climate and energy targets for the critical decade up to 2030 are strong, with the net-zero carbon vision for 2050 a necessary but formidable goal. The 2020 Climate and Energy Package encompasses a set of binding laws which outline the so-called 20-20-20 targets. These are targets for 2020 to cut EU-wide greenhouse gas emissions by 20% relative to 1990 levels, use renewables for 20% of aggregate EU energy, and achieve a 20% collective improvement in energy efficiency. The Effort Sharing Decision (European Union, 2009a) covers the national binding annual emissions reduction targets for 2020 and the Renewable Energy Directive (European Union, 2009b) details the binding national targets for renewable energy for 2020. On an EU-wide level, these targets are on track to be met, with emissions reduced by 23% in 2018 compared to 1990 levels, while energy from renewable sources was 18.9% of gross final energy consumption in the same year (European Commission, 2020b).

The 2030 goals are described in the 2030 Climate and Energy Framework (European Commission, 2014), with the following key targets: at least 40% reduction in greenhouse gas emissions compared to 1990 levels, at least 32% share for renewable energy, and at least 32% improvement in energy efficiency. The latter targets were revised upwards from 27% in 2018. The Effort Sharing Regulation sets the binding emissions reduction targets for the EU Member States up to 2030, while the EU ETS covered sectors will need to reduce their emissions by 43% compared to 1990 levels

[4] Incentive policies are often also referred to as support policies. The former term will be used throughout this thesis to describe policies which encourage a certain type of electricity generation.

(European Union, 2018). National governments were required to adopt national energy and climate plans and submit them to the European Commission by the end of 2019. The European Commission claims that if the targets for climate, energy and mobility laid out in the Union law are implemented, emission reductions will exceed the 40% target and reach 45% compared to 1990. However, the commission also notes that Member States must accelerate their implementation to achieve these goals (*Climate strategies & targets*).

The European Green Deal is the overarching strategy of the European Union's goals to become the world's first carbon-neutral continent by 2050 (European Commission, 2019b). It is described as the "roadmap for making the European economy sustainable". Regarding energy, the key principles are to prioritise energy efficiency and develop the electricity sector to be based on primarily renewable sources, create a secure and affordable energy supply in the EU, and fully integrate, interconnect and digitalise the EU energy market. Other goals of the Clean Energy proposals in the Green Deal (European Commission, 2019a) include interconnecting energy systems and integrating renewable energy sources into the grid, empowering consumers and tackling energy poverty. The European Green Deal even includes an explicit hydrogen fuel strategy (European Commission, 2020c). These issues relate directly to the themes discussed in this thesis of distributed generation and its effect of electricity markets and the role of community energy.

Carbon-neutral means net zero greenhouse gas emissions, allowing for emissions in some sectors that must be balanced by greenhouse gas drawdown from other sectors. These ambitions are described in detail in the strategic vision by the European Commission on a clean planet for all (European Commission, 2018). The European Climate Law proposes to write into law the goals set out in the European Green Deal and create systems to monitor the progress towards these ambitious targets. The legislative proposal is, as of July 2020, under consideration by a range of European bodies.

A paper by researchers at Bruegel (one of Europe's leading economic think tanks) and at several universities across Europe states the key priorities for the European Union's energy transition during the period of 2019–2024 (Tagliapietra et al., 2019). Firstly, decarbonise the transport sector, by reducing reliance on road transport through investment in public transport and by promoting clean vehicles with stricter emissions standards and gradual increases in fuel taxes. Secondly, prepare the electricity system for an increase in renewables by accelerating the convergence between decentralisation and digitalisation, through the use of smart distribution grids and the creation of a multi-level European electricity system. Thirdly, develop the EU's comparative advantage in low-carbon technologies such as renewables, in energy efficiency in buildings and in batteries. Fourthly, accelerate decarbonisation in industry by promoting the recycling of materials, and improve energy efficiency in buildings through efficiency standards and large scale retrofitting. The research in this thesis relates to the second priority: the preparation of electricity sectors for a large increase in decentralised renewables.

In the European context, the transition will be led in both a top-down and bottom-up fashion. The top-down aspect includes the numerous directives from the European Union, discussed above, which guide national policies. However, the implementation of those directives is at the discretion of national governments, which will devise their own policy approaches to accelerate the energy transition on a national and local level, thus taking a bottom-up approach (Eid et al., 2017). This is analogous to the way in which the energy transition is driven by a top-down force (climate change caused by greenhouse gas emissions) but will evolve in a bottom-up way (through the increasing use of distributed forms of renewable energy).

1.1.2 Ireland's Energy Transition

The Irish State has committed to a transformation of its energy system in the coming years, with an increased emphasis on renewable technology and the associated distributed aspects, and a reduction in dependence on fossil-fuels. Cherp et al. (2018) conceptualise national energy transitions as a co-evolution of three systems: the techno-economic, meaning energy flows and markets, the socio-technical, which focuses on technological change, and the political, involving energy policies. This thesis will include aspects of all three, by analysing the impacts of Irish energy policies on energy markets in the context of renewable technologies.

The transformation of the energy system in Ireland was first outlined in the Irish Government's 2015 White Paper on the guide to energy policy between 2015 and 2030 to help make the Irish transition to a low-carbon energy system (Department of Communications Climate Action and Environment, 2015). The White Paper emphasised the importance of active engagement of Ireland's citizens and communities in the energy transition, mapping out ambitions of market support for microgeneration and community energy schemes, while facilitating grid access for prosumers[5] of electricity. The White paper also states the three core objectives of Irish energy policy: sustainability, security of supply and competitiveness. The first and third of these objectives will be addressed in this thesis, by investigating the incentives for renewable electricity installations and assessing the effects of market power on the wholesale electricity market, respectively.

In 2019, the Irish Government published its landmark Climate Action Plan (CAP) (Department of Communications Climate Action and Environment, 2019). This document covers all the most up-to-date elements of the Irish governments' plans to tackle climate change and make the transition to a low-carbon economy, such as Carbon Budgets and government accountability to a Climate Action Committee, retrofitting of buildings for energy efficiency, and a massive uptake of electric vehicles. Specifically regarding the energy system, the CAP describes a vision of a hybrid energy system combining centralised electricity generation from legacy fossil-fuel plants and large-scale offshore and onshore wind farms with community energy schemes and micro-generation. The CAP commits to supporting microgeneration and creating opportunities for community participation. The target set out in the Climate Action Plan is to have 70% of Ireland's electricity generated from renewable sources by 2030 (Department of Communications Climate Action and Environment, 2019). This anticipated shift in electricity generation will constitute a fundamental reorganisation of the energy industry in Ireland.

The reorganisation of the electricity sector in Ireland is, as noted in the White Paper, significantly motivated by sustainability concerns, related to Ireland's climate and energy system targets. Ireland's Nationally Determined Contributions to the Paris Climate Agreement are regulated EU-wide targets. Like all EU countries, the power generation sector in Ireland is covered by the EU ETS, which exempts it from emissions-specific targets. Within the greater framework of Ireland's emission reductions commitments is the target to increase the share of electricity generated by renewable energy sources. EU-wide, the target is for 32% of gross energy production to come from renewable energy by 2030.

[5] A prosumer is an energy user who consumes, produces, stores and shares energy with other grid users (Espe et al., 2018).

The Effort Sharing Decision discussed in the previous section stipulates different reduction in non-ETS sector emissions by 2020 compared to 2005 levels, depending on national wealth. These are implemented through annual targets called annual emission allocations (AEAs). Ireland's target is to achieve a 20% reduction in non-ETS emissions by 2020. While the EU-wide target for final energy consumption from renewable energy sources (RES) for 2020 is 20%, Ireland's national target is 16%. The sub-target for electricity generation from renewable energy sources (RES-E) is 40%. The 2021–2030 period is governed by the EU's Effort Sharing Regulation, calling for a an effective target for Ireland of 30% emission reductions for non-ETS sectors by 2030 compared to 1990 levels. The Climate Action Plan states a commitment to achieving 70% RES-E by 2030.

However, according to projections by the Irish Environmental Protection Agency, Ireland will fall dramatically short of the 2020 non-ETS emissions reduction target of 20% below 2005, with emissions from these sectors expected to be reduced by only 2–4% (Environmental Protection Agency, 2020c). The same projections show that, assuming full implementation of the Climate Action Plan, non-ETS EU emissions reduction obligations for 2030 will be met.

Ireland's emissions profile is atypical by European standards (Figure 1.2), with an outsized proportion of greenhouse gas emissions (34% in 2018) arising from the

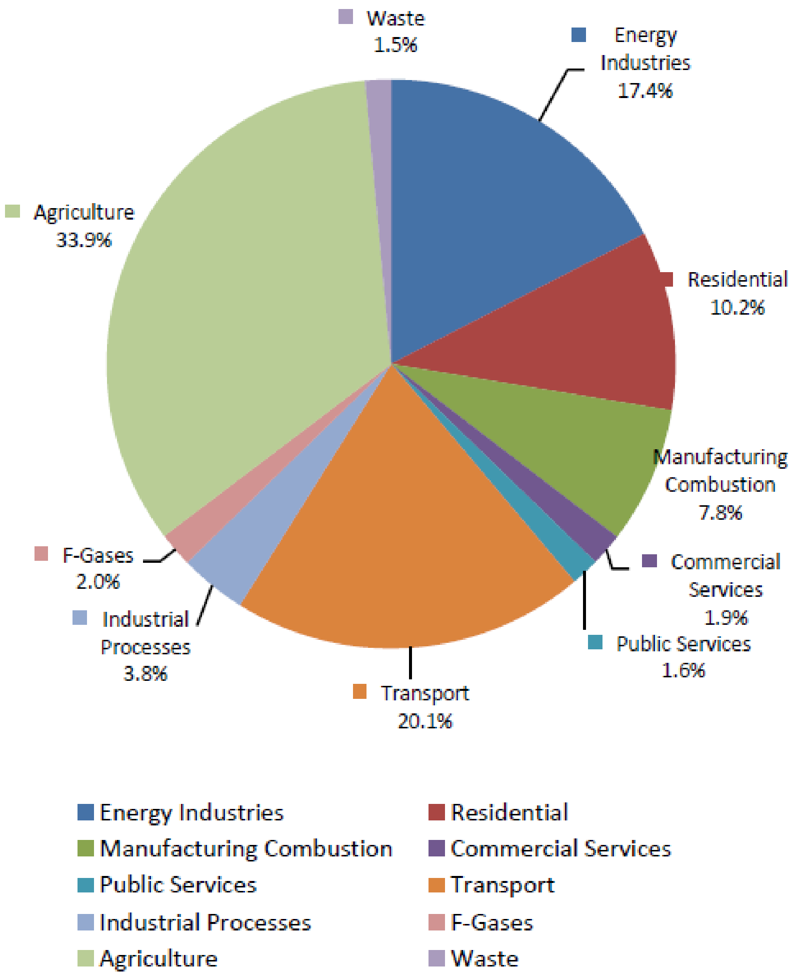


FIGURE 1.2: Irish Greenhouse Gas Emissions by Economic Sector in 2018 (Environmental Protection Agency, 2020b)

agriculture sector (Environmental Protection Agency, 2020a). Electricity accounted for 19.3% of Ireland's greenhouse gas emissions in 2017, further emphasising the importance of decarbonising this sector (Department of Communications Climate Action and Environment, 2019). Nevertheless, Ireland's emissions per capita from other sectors are still higher than the European average. In short, the contribution from agriculture does not excuse the poor performance in reducing emissions in other sectors.

In terms of Irish energy system targets, more progress has been made in increasing the share of RES-E than with emissions reduction. The Irish Environmental Protection Agency projects a decrease in greenhouse gas emissions in Ireland's energy industry from 20% of total emissions in 2020 to 16% of total emissions in 2030 (Environmental Protection Agency, 2020c), suggesting that this sector is reducing its carbon intensity. According to the Sustainable Energy Authority of Ireland (SEAI), in 2018, renewable energy contributed 11% to gross final energy consumption. RES-E accounted for 33.2% of electricity generation in the same year (Sustainable Energy Authority of Ireland, 2019). Nevertheless, the figures are still short of the EU targets.

There are financial consequences for Ireland's failure to meet its emissions reduction targets in the form of fines from the EU, which could amount to €275 million if the 2020 targets are missed (Green News, 2020). The consequences from the avoidable greenhouse gas emissions are even more concerning. While the Irish Government's Climate Action Plan (Department of Communications Climate Action and Environment, 2019) outlines how it plans to go about reaching the emission reductions targets, the current shortfall in reductions suggests rapid and significant changes are required across the Irish economy to actually reach these targets.

A range of incentive policies for renewable energy schemes are in place or planned to encourage renewable electricity generation in the Irish electricity sector. Most notable of the present schemes is the Renewable Electricity Support Scheme (RESS), which will provide support for renewable electricity projects through a series of auctions out to 2027. According to the Climate Action Plan, facilitating microgeneration grid access and remuneration is set to begin in 2021. The Offshore Renewable Energy Development Plan (OREDP) will focuses on utilising Ireland's abundant offshore renewable energy resources, such as wind, wave and tidal energy.

These schemes are likely to change the structure of Ireland's electricity industry. The market power of its strategic firms[6] could potentially be affected, driving down electricity prices for the benefits of consumers but simultaneously creating political challenges. The prospects for a just transition[7] could be harmed if company profits are rapidly reduced and cause employment vulnerability. But communities could be empowered to engage directly with the energy transition and individuals motivated to become active energy citizens.

[6]The term *strategic firm* will be used in this thesis to describe firms which have the market power to act strategically in the electricity industry and affect prices.

[7]Ireland's National Economic and Social Council (NESC) describe the necessary steps to avoid employment vulnerability and ensure a just transition in Ireland in a recent report (National Economic and Social Council, 2020).

1.2 Research Question

This master's thesis will address the Irish energy transition by asking the following question:

> *"What are the climate, economic and social implications of Ireland's renewable electricity incentive policies in the energy transition?"*

A stylised industrial organisation model will be adapted from the existing literature to examine this question. The research will seek to add to the industrial organisation body of work on the electricity industry by investigating the policy implications in the specific case of Ireland's electricity sector, which in many respects is representative of other European countries. In addition, the research will relate to the growing body of literature investigating the potential effects of a mix of different climate and energy policies, and to the literature on community energy via a micro-economic approach.

The thesis is structured as follows. Chapter 2 is a literature review of the key issues in this thesis and the industrial organisation modelling approaches to understanding them. Chapter 3 offers an outline of Ireland's electricity sector, with a brief review of the industry's history and an account of its structure in 2020. Chapter 4 describes the method used to construct an industrial organisation model of Ireland's electricity industry. Chapter 5 provides a numerical illustration of the stylised model. Chapter 6 discusses the numerical illustration results in the context of the economic issues that may be encountered during Ireland's energy transition. Chapter 7 will conclude the thesis and offer a set of recommendations to overcome the economic obstacles to increased distributed generation of electricity in Ireland.

Chapter 2

Literature Review

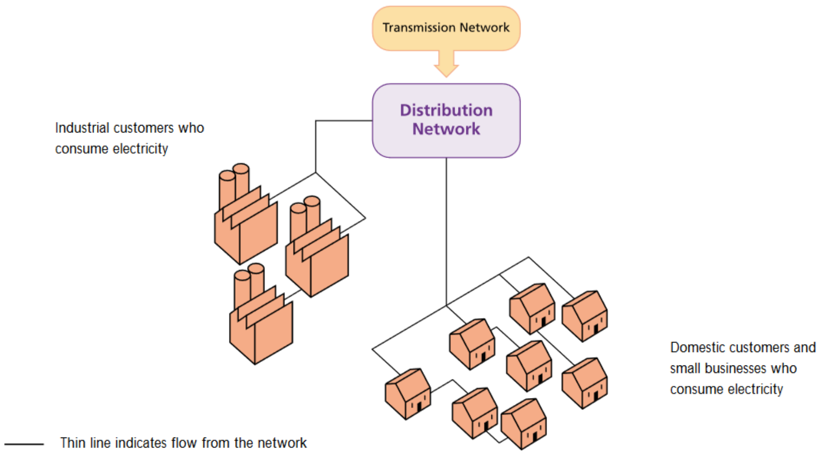
2.1 Decentralisation, Distributed Generation and Community Energy

It is clear from the European Green Deal and Ireland's national energy ambitions that Irish energy transition will involve decentralisation of the energy system. Bauknecht et al. (2020) provide a framework for assessing decentralised electricity from an economic and social perspective. They make use of four infrastructure dimensions in their framework: *connectivity*, meaning to what level of the grid the electricity generating units are connected, *proximity*, meaning how close to demand the generators are located, *flexibility*, which describes whether electricity storage occurs on the distribution grid level or the transmission grid level, and *controllability*, that is the ability of the system to balance supply and demand on the distribution or transmission level. They do not provide a definitive answer as to whether decentralisation will reduce electricity system costs, but they note potential social benefits, like democratic participation in the electricity system, that could occur due to increased decentralisation through the dimensions of connectivity, proximity and flexibility.

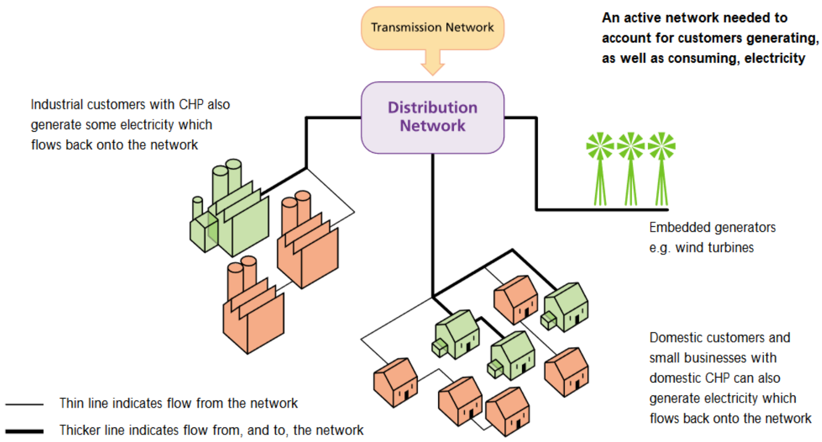
Perhaps the key aspect of energy system decentralisation is distributed electricity generation. Newbery et al. (2018) follow the Pepermans et al. (2005) definition of distributed generation as "electric power generation within distribution networks or on the customer side of the network" [p.702]. Generally, distributed generation consists of small-scale technologies in close proximity to locations where the electricity is used, such as homes and businesses. These technologies cover a range of functions, including microgeneration[1] of electricity using solar PV or micro-turbines, electricity storage in batteries, and heating using heat pumps. Distributed generation creates the possibility of "self-sufficiency" for electricity consumers. At present, electricity in Ireland is mostly supplied by a centralised energy system of large fossil-fuel plants, with the recent addition of electricity generated from wind turbines. The urgent pressure of anthropogenic climate change combined with technological progress in wind and solar energy has now initiated this shift towards distributed generators of electricity, which requires critical technological innovations such as a smart grid to effectively function (Newbery et al., 2018). The distribution of electricity generation in a renewable energy system is inevitable, since it is necessary to overcome intermittency[2] by taking advantage of differences in energy flows across space. A graphic of the key distinctions between the conventional centralised network and a decentralised distributed is provided in Figure 2.1.

[1] The Commission for Regulation of Utilities (CRU) define microgeneration as generators that produce less than 11kW (Commission for Regulation of Utilities, 2020).

[2] Intermittency or variability is a fundamental characteristic of renewable energy technologies since they depend on energy flows that change over time, such as solar irradiance and wind patterns.



(a)



(b)

FIGURE 2.1: Graphic comparing the (a) conventional centralised electricity system and a (b) decentralised distributed electricity system (OfGEM, 2002)

There are numerous benefits to decentralised energy systems that involve distributed generation technologies. Bouffard and Kirschen (2008) highlight that decentralised electricity system can offer improved reliability and security of supply, better energy efficiency, and drastically reduced greenhouse gas emissions, while Koirala et al. (2016) note the ability of distributed generation to reduce energy poverty and increase energy democracy. Arcos-Vargas et al. (2018) demonstrate that even a conservative installation of solar PV panels in residential facilities in Spain and France could be economically beneficial and reduce emissions, contributing to those countries' Paris Agreement commitments.

The literature on distributed generation also discusses the range of issues related to developing a decentralised energy system. Koirala et al. (2016) divide these into technological issues, socio-economic issues, environmental issues, institutional issues, and regulatory issues. Of most interest to the research in this thesis are socio-economic issues such as energy justice, institutional issues like ownership and support schemes, and regulatory issues around the reconfiguration of the energy industry.

These issues create challenges for the uptake of distributed generation. In their paper reviewing the literature on the economics of distributed generation with a focus on the UK system, Allan et al. (2015) point out a variety of barriers to distributed generation. These include potential discriminatory access to the grid and planning applications in favour of established centralised firms (a problem that occurs in the Irish system at present), uncertainty over the continued policy support, costly regulatory issues for smaller-scale firms and organisations, and a lack of information amongst consumers regarding the costs and benefits.

Ruggiero et al. (2015) carried out a study on the prospects and barriers in the transition to distributed energy generation in Finland by directing a questionnaire at a panel of 26 experts in the distributed energy value chain and carrying out 15 qualitative semi-structured interviews with energy industry and non-industry actors. They found that the main barriers concerning interviewees are the impacts on the electricity grid, lack of standard procedures for grid connection and low rates for prosumers, and the lack of incentives for established energy companies in facilitating the market for the energy of small electricity prosumers.

Other issues include grid defection (consumers disconnecting from the grid and using small-scale electricity generation technologies and battery storage instead), which can lead electric utility companies to a financial "death spiral" (Parag and Sovacool, 2016; Newbery et al., 2018). Such an adverse consequence for these companies could have negative effects on society through the loss of jobs, political unrest, and distributional concerns if certain groups in society cannot afford to generate their own electricity. It is therefore important that energy policies do not incentivise activities that benefit a small number in society but also lead to lower quality energy services for the majority. There are also financial matters such as high transaction costs and lack of access to credit, incentive problems like biased subsidies, and lack of competition in electricity markets which can lead to pricing issues (Parag and Sovacool, 2016; Yaqoot et al., 2016). Significant electricity market reform is needed to meet the requirements of a distributed generation system. A key reform which will be investigated in this thesis is creating mechanisms for the sale of surplus electricity generated by prosumers (household-to-community level) back to the grid (Newbery et al., 2018; Ruggiero et al., 2015).

Community energy is often regarded as having the potential to transform the electricity system from both an economic and social point of view. Such community schemes may involve a transformation of the community itself. A shift is envisaged from passive consumers of electricity to active energy citizens regulating their own demand and emphasising sustainability in all aspects of their communities. Community energy projects are increasingly being thought of as potential key actors in the energy transition since they offer citizens the opportunity to participate in the decision making and accrued benefits from renewable energy technology (Bauwens, 2016).

The benefits from community energy in many ways overlap with the general benefits of distributed generation, but have some more specific advantages. Brummer (2018) provided an extensive review of the benefits and barriers to community energy in the UK, Germany and the USA. The paper highlighted the economic benefits to the community and marginalised regions, and how the effects of participation can lead to a greater understanding and acceptance of renewable energy. It can also help raise awareness about climate change, and thus help reach national renewable energy targets. Furthermore, there are social benefits of enhanced community cohesion, pride, and power to make autonomous decisions. However, the concept of community energy is complex and difficult to define precisely.

Moroni et al. (2019) provide a taxonomy for energy communities, using two pairs of options: *place-based* and *non-place-based* energy communities, and *single-purpose* and *multi-purpose* energy communities. These distinctions have important effects on the functions of such communities. Hoffman and High-Pippert (2010) note that the term community energy has been used to describe everything from solar PV panel installation on residential buildings to landowner groups participating in large wind turbine projects, and urban cooperatives providing heating and cooling services. With this in mind, Klein and Coffey (2016) [p.870] offer the following inclusive definition:

"a project or program initiated by a group of people united by a common local geographic location (town level or smaller) and/or set of common interests; in which some or all of the benefits and costs of the initiative are applied to this same group of people; and which incorporates a distributed energy generation technology (for electricity, heat, or transportation) based on renewable energy resources (solar, wind, water, biomass, geothermal) and/or energy conservation/efficiency methods/technologies."

The issue of incentives for renewable technology generally, and specifically for community energy, is crucial for the energy transition. Community energy schemes could have implications for the market power of strategic firms in the electricity sector, as the ownership of electricity generation technology becomes distributed amongst citizens. Furthermore, substantial deployment of renewable technologies is required to rapidly reduce carbon emissions while community energy can help with achieving public acceptance and a Just Transition. Several papers have investigated the incentives for electricity companies to invest in renewable technologies using industrial organisation models. These models help to uncover the implications of increased renewable penetration on prices and market power.

2.2 Incentive Policies

While there are theoretically many ways to promote decarbonisation, such as capping emissions like the EU ETS does, or taxing conventional technologies that cause emissions, as carbon taxes do, policies to incentivise and support investment into renewable energy technology have emerged as a key policy instrument in the energy transition. Gawel et al. (2017) conceive this process as a two-stage public choice problem of *instrument choice* and *instrument change*. Looking at the case of Germany, they found that the initial stage of choosing the policy instrument for RES-E support was supported by the conventional energy lobbies, because the support scheme was generally in their interest. Faced with the challenge of managing high-levels of renewables in the energy system, the support scheme now requires amendment (the second stage of the problem), but changes have so far been symbolic in the face of opposition from the established energy interests. The authors recommend that Germany should incrementally expose their RES-E producers to market risks. Their analysis is relevant for most nations in Europe due to the integrated EU energy strategy.

Butler and Neuhoff (2008) compared various mechanisms to support wind power development in the UK and Germany, including a feed-in-tariff, quotas and auctions. Feed-in-tariffs guarantee a price for renewable electricity irrespective of the wholesale market price. They showed through empirical research that the feed-in-tariff model applied in Germany achieved cheaper prices for wind energy, greater competition and more deployment. Winkler et al. (2016) used the PowerACE electricity market model to look at the different market impacts of various support schemes. They found that capacity-based (meaning the support is independent of the levels of generation enacted) support schemes reduced the market impact of renewables and maximise their market value, and that more market-oriented support schemes are generally riskier. They concluded that sliding feed-in premium schemes might be an effective compromise between market participation and low risk for plant operators. Under sliding feed-in-premiums schemes, renewable electricity generators sell their renewable electricity on the wholesale market and also receive an additional premium that varies to ensure the firms receive remuneration at an agreed level, often called the strike price. If the market price is below the strike price, the premium received is the difference between the strike price and the market price. If the market price is above the strike price, the firms must pay the difference and reduce their income.

Dressler (2016) analysed feed-in-tariffs and different kinds of feed-in-premiums for renewable electricity in the European Union in an industrial organisation duopoly framework (explained the next section), focusing on producer strategies and competition in the wholesale electricity market. In her model, the replacement of the feed-in-tariff with a floating premium (equivalent to a sliding premium) had no effect on producers strategies, but using a fixed premium changed the market structure, making renewable producers become strategic market participants. Fixed premiums offer a guaranteed and unchanging additional revenue on top of the market price. Dressler showed that for high levels of renewable energy, the fixed premium led to lower competition than the feed-in-tariff. She showed that the level of the fixed premium is also important.

2.3 Industrial Organisation

Industrial organisation is a field of economics concerned with the strategic behaviour of firms, regulatory policy, antitrust policy, and market competition. Research in the field tries to understand how various industries operate, how to improve those industries' contribution to economic welfare, and how to formulate better government policy in regulation of the industries. Industry does not specifically refer to the manufacturing sector, but more generally applies to any large-scale business activity. Industrial organisation is built on the neoclassical foundations of the theory of the firm. This set of economic theories attempt to describe and explain the role of a firm in terms of its existence, behaviour, structure and market interactions (Chen, 2019; Church and Ware, 2000).

In 1989, economists Bengt Holmstrom and Jean Tirole posed two questions which form the basis of industrial organisation. The first was about why firms exist, or what role they fill in society. The second question follows the first and asks what the scale and scope of a firm's operations are. Taken together, these two questions led the field of industrial organisation to investigate how markets and industries compete with one another in the context of real-world complications, such as government intervention, transaction costs, barriers to entry, and more. In his book, Cabral (2017) [p.3] defined industrial organisation as "the economics of imperfect competition". In essence, industrial organisation is the study of oligopolies, where oligopolies are markets in which control over the supply of a commodity is in the hands of a small number of producers, and where each one can, to a significant degree, influence prices and affect competitors.

There is a small but growing literature of papers using industrial organisation models to research the electricity industry. Many papers utilise the Cournot competition framework, in which firms with market power compete in an oligopoly[3] by choosing quantities of a commodity to produce. In a seminal paper for the research area, Allaz and Vila (1993) demonstrated, using a model with two Cournot duopolists, that the presence of forward markets benefits the consumer. This research paved the way for the use of Cournot competition models to analyse the electricity sector.

Twomey and Neuhoff (2010) used a Cournot model to investigate oligopoly pricing in electricity markets with a fringe of intermittent renewable generation from wind turbines, looking at a variety of cases, including perfect competition, perfect monopoly, and a duopoly with forward contracts. Filomena et al. (2014) adopted a Cournot competition model to understand the relationship between different technologies' cost structures and the portfolio of technologies adopted by generation firms. They found that portfolio diversification occurs even with risk neutral firms and technologies with different cost expectations. Lambertini et al. (2017) constructed an oligopoly of n firms to explore the relationship between competition and innovation when research and development aims at reducing polluting emissions. They uncovered an inverted-U relationship, where "green" innovation first increases with competition, then ultimately decreases.

Acemoglu et al. (2017) used a Cournot oligopolistic framework to investigate whether diversification of energy portfolios amongst conventional energy companies conflicts with the benefits from increasing the supply of renewables. They showed that the merit order effect (a process in which more renewables lower electricity prices) is reduced if the supply of renewables come from the conventional energy companies which also use thermal generation. The researchers then extended their analysis to include forward contracts and correlated imperfectly observed shocks. They concluded that the merit order effect is reduced in all cases and overall societal welfare declines with greater diversification. The merit order effect is a key phenomenon in electricity markets and will relate to issues of market power in this thesis through the effect of renewable energy in driving down wholesale market prices.

Teirilä (2017) modelled the electricity market coupled with a capacity market as a two-stage game and applied it to the Irish electricity market. The paper explored concerns that an update to the Irish market design could lead to opportunities to abuse market power by dominant firms, and found that there is indeed potential for this abuse. This thesis will further explore issues of market power in the Irish electricity sector.

Genc and Reynolds (2019) employed an industrial organisation approach in their paper investigating how the ownership of renewable capacity changes market outcomes. By constructing a theoretical model of an oligopoly with two asymmetric Cournot firms facing a competitive fringe and applying this to the Ontario wholesale electricity market, their findings indicated that the ownership of new renewable generation capacity affects market outcomes in imperfectly competitive markets. Their model suggested that an increase in renewable energy owned by the competitive fringe firms has a larger price reducing effect than an identical increase in renewable energy owned by a strategic Cournot firm. The researchers noted that the policy implication of their results is that regulators should consider the impacts of how/to whom green certificates are allocated. Their model framework will be adopted for the research undertaken in this thesis.

[3] Oligopoly is described as a market structure with a small number of firms, none of which can prevent other firms from having significant influence (Investopedia, 2020).

Chapter 3

Ireland's Electricity Sector

Before discussing the theoretical industrial organisation model of Ireland's electricity industry, it is important to understand the Irish electricity sector's history, its key actors, and the policies that affect it.

3.1 The Historical Context

The island of Ireland has long made use of both fossil-fuels and renewable sources of energy. The harvesting of peat (a highly carbon intensive fuel) from bogs and the use of wind energy both began hundreds of years ago. Peat was the main fuel in Ireland by the end of the 1500s after the island's woodland stock had been depleted. In the 1800s, it began to be extracted on an industrial scale. Coal, another emissions culprit, was first discovered in 1638 in the province of Leinster. However, the amount of coal indigenous to Ireland is relatively small and significantly less than the peat stock. The earliest recorded use of a windmill in Ireland was in 1281, and by 1840, there were over 250 of them in operation. These sources of energy are still used in various forms in the Irish electricity system to this day (*Ireland 2050*).

Gaffney et al. (2017) provide a comprehensive overview of the last 100 years of Irish electricity policies and the associated electricity industry. Much of the following historical context is sourced from their excellent paper.

3.1.1 Pre-1970s: Hydro and Peat

Electricity was first used in Ireland in 1880 to provide street lighting in Dublin, generated from coal-fired plants (mainly from imported supplies). The industry rapidly developed over the next 40 years into a variety of public and private supply schemes across the country using hydro, coal, gas from coal-gasification, peat and wind power to generate electricity. Indigenous forms of electricity in Ireland were then investigated by the British Board of Trade due to coal rations during the First World War. They identified peat and hydroelectric schemes as candidates for development.

Following the establishment of the Irish Free State in 1922, several significant strides forward for the Irish electricity industry were taken. Work on a hydroelectric scheme at Ardnacrusha on the River Shannon began in 1925 and was completed in 1929. This was one of the first major developments by the Irish Free State and a source of great pride for the fledgling nation. The plant delivered 85MW of output and, in its early years, was enough to meet the entire national electricity demand, making Ireland's electricity generation 100% renewable for a short period of time. The Shannon Electricity Act 1925, set the intention for the state to create a public body to generate, manage and distribute the electricity from Ardnacrusha across the country. The Electricity (Supply) Regulation Act, 1927 established the state-owned

Electricity Supply Board (ESB). Lang (1969) suggested that this may have been the first fully nationalised electricity undertaking outside of the Soviet Union.

The ESB took a unified approach to the electricity sector and decided against selling electricity in bulk to other distributors. The body quickly acquired all municipal and private electricity suppliers and harmonised the supply of electricity nationwide. The outcome was a vertically integrated state-owned company with a monopoly on the entire Irish electricity industry. This complete market internalisation within the ESB remained in place until the electricity market liberalisation of the early 2000s.

When Ardnacrusha was commissioned in 1929, the ESB had already built a transmission and distribution network ready to transfer the electricity across the country (see Figure 3.2). This was a pivotal step in the electrification of rural Ireland. Over the next decade, the electricity generation capacity steadily increased through additional hydroelectric schemes and peat-fired plants. When the Second World War arrived, Ireland remained neutral but coal scarcity once again forced the use of alternative fuel sources. Peat in particular was touted as a viable option thanks to it being the only widely-available indigenous fuel and its socio-economic advantages for rural Ireland. These advantages explain the continued dependence on peat for the decades to come. In the mid-1960s, significant investment had been made into peat as a generating fuel. Ireland's generating capacity was 26% hydro, 39% peat, and 35% oil, with the first two energy sources supplied from native resources (Lang, 1969).

Due to the immense challenges of the Second World War period, rural electrification proceeded slowly in Ireland until the advent of the Rural Electrification Scheme, 1946 and the Electricity Supply Amendment Act, 1955. These pieces of legislation accelerated the process, with the ESB connecting over 420,000 customers in rural Ireland between 1946 and 1979 (Gaffney et al., 2017).

3.1.2 1970s–2000s: Oil Crises and Security of Supply

Ireland's economy grew in the years after the Second World War, and more hydroelectric schemes and fossil-fuel fired power plants were commissioned to meet the increasing demand. By 1970, 46% of electricity was generated from indigenous peat and hydro, while 54% came from imported oil. This oil dependency caused serious problems for the Irish electricity industry in the years that followed.

The 1970s were a tumultuous period for energy industries across the world. Two oil crises destabilised the supply of oil, and thus electricity, and caused significant price volatility – although perhaps less than is commonly suggested – and price increases (Regnier, 2007). The first oil crisis was due to an embargo on oil exports by the Organisation of Arab Petroleum Exporting Countries (OPEC) after the United States became involved in the Yom Kippur war between Israel and a coalition of Arab states. This caused the price of oil to increase fourfold. The second oil crisis was a result of the Iranian revolution in 1979 and the Iran-Iraq war the following year. Iranian oil production only fell by 4%, but widespread panic, perhaps due to the crisis that occurred only six years previously, meant the price of oil doubled. This caused many economic issues across the globe. In Ireland, electricity prices increased by almost a factor of two in the next five years. But all the while, the Irish electricity industry became more dependent on oil, reaching a level of 64% of primary energy by the end of the 1970s (Gaffney et al., 2017).

The issue of security of supply, which continues to motivate EU and Irish energy policy, became starkly clear to the Irish state during the oil crises. However, as early as the 1950s, the ESB had warned the government of the risk of over-dependence on a limited range of electricity generation sources. The discovery of natural gas off the south coast in 1973, and the technical viability of nuclear power, meant the government became more focused on diversification. Assessing the alternatives to hydropower and peat (neither of which had much potential for expansion at that stage), nuclear power appeared the only new option. Neither solar, wind, tidal nor wave energy technologies were significantly developed enough at that point, while imported coal was more expensive than oil.

But the state's plans for nuclear power in Ireland caused controversy and there were widespread protests. Public resistance combined with government hesitancy to commit to a capital intensive project that could be under utilised (the minimum generating capacity of the plant was 500MW, seen as too large for Ireland at the time) ultimately led to the project being shelved. When the nuclear disaster occurred at Three Mile Island in Pennsylvania in 1978, nuclear power became impossible from a political perspective. Instead, the government decided to pursue coal as a source of energy. This decision would have major ramifications for Ireland's climate commitments in later years.

Between 1979 and 1987 a coal-fired plant was constructed at Moneypoint in Co. Clare. It was Ireland's first large-scale coal-fired plant and has a maximum output of 915MW, second only to the iconic Poolbeg Generating Station in Dublin. The Moneypoint plant is due to cease operations in 2025 due to its significant CO_2 emissions, with the power station emitting 681,047 tonnes of CO_2 equivalent in 2019 (Independent.ie, 2020). It has become a source of notable debate between climate activists and policy-makers in recent decades.

The 1990s saw Ireland's wind power industry begin to develop, motivated at the time by a desire to increase security of supply. A demonstration project in Co. Mayo performed well and in 1994 the government began to support alternative energy sources. A range of schemes and policy measures were introduced, beginning with the Alternative Energy Requirement (AER) competitive bidding processes, initiated in 1993. The wind power industry in Ireland has expanded rapidly since this time, reaching an installed generation capacity of 3,676 MW in 2018 (Sustainable Energy Authority of Ireland, 2019). It now has the third highest contribution to national electricity demand of IEA wind member countries (Gaffney et al., 2017).

3.1.3 2000s: Market Liberalisation

The structure of the Irish electricity sector and its associated regulations were transformed from the early 2000s onwards by the European Union's intention to liberalise electricity markets across the continent. Since the EU's inception, the liberalisation of markets has been a central goal of the project. Through a series of policy directives, the European electricity sector has become a transnational competitive market, tending closer and closer to a system which facilitates the free flow of energy across borders.

There are several motivations for liberalising the electricity markets of EU Member States. The primary aims are to have a secure and expanding supply of energy, develop a more competitive internal energy market, and deliver electricity in a cost effective manner. Ultimately, by improving security of supply and reducing prices, the goal is to improve social welfare across the European Union. A series of liberalisation directives were set out by the EU to achieve these goals, collectively referred to as energy packages (*Internal energy market*).

The First Energy Package was adopted in 1996 to create a new regulatory framework for electricity sectors across the EU. The package prescribed the unbundling of vertically integrated monopolies such as the ESB, increasing market competition and allowing consumers to choose between suppliers. Prior to this reform, the ESB had internalised the entire electricity market. The organisation had two main divisions: ESB Power Generation met the demand of ESB Customer Supply.

The Electricity Regulation Act in 1999 took the framework from First Energy Package and transposed it into national legislation. The act set down the plans to create a national regulatory authority that would oversee the liberalisation of the electricity markets. This was initially called the Commission for Electricity Regulation (CER), went through a series of name and responsibility changes, and is now called the Commission for Regulation of Utilities (CRU). The Electricity Regulation Act also outlined the intention to form an independent transmission system operator, which became EirGrid. However, the fundamentally transformative aspect of the act was to open the wholesale and retail electricity markets to competition. In February 2000, the markets were opened to competition (Gaffney et al., 2017).

The Second Energy Package was adopted in 2003 and included some adjustments to ensure the rights of access to the network and prevent issues of market dominance, but primarily focused on allowing industrial and domestic consumers to be "free to choose" their electricity supplier from a range of competitors. This decision led to the creation of the Single Electricity Market (SEM), the cross-border trading platform for electricity on the entire island of Ireland, combining both the Republic of Ireland and Northern Ireland. The SEM went live on the 1st of November 2007.

The Third Energy Package, adopted in 2009, aimed to further liberalise the internal EU energy market, making some amendments to the previous package and forming the foundation for the future development of the electricity markets. It outlines the EU Target Model, a list of guidelines, procedures and codes that will facilitate an EU-wide wholesale electricity market. The update of the SEM to become the Integrated Single Electricity Market (I-SEM), was put in motion to ensure that the island of Ireland could be as compliant with the EU Third Energy Package directives while retaining the benefits of the SEM.

3.1.4 Irish Renewable Energy Policy from the 1990s

A series of AER bidding processes were undertaken in the 1990s and early 2000s, with mixed results. The bidding process, similar to the Renewable Energy Support Scheme (RESS), worked by offering the lowest bids in each category a Power Purchase Agreement (PPA) of up to 15 years. The ESB, still the monopolist, purchased the generated electricity. The ESB was then compensated through a Public Service Obligation (PSO) levy, funded by electricity consumers.

In 1996, a national strategy for Ireland, 'Renewable Energy — A Strategy for the Future', was published. This document set down wind connection targets of 31 MW per year from 2000 to 2010. It also highlighted key issues that continue to be relevant in the Irish electricity industry, such as access to the electricity grid for third parties and the potential of small-scale renewable projects for self-sufficiency (International Renewable Energy Agency / Global Wind Energy Council, 2013, pp. 94–100).

Overall, the initial phases of the AER were successful in terms of the number of proposed projects, but ultimately the levels of commissioned and deployed capacity were disappointing. For example, AER 3 launched in 1997, aiming for 100MW of new capacity. 160MW were awarded, but by 2000, only a paltry 37.51MW had been installed. The lack of project execution was due to a variety of reasons, such as site access, planning permission and profitability.

Following the mixed successes of AER 3, the 1999 'Green Paper on Sustainable Energy' revised the national strategy. It increased ambitions by setting the target to install 500MW of renewable energy capacity by 2005 (later revised to 2007). Moreover, the document laid out concrete proposals regarding the liberalisation of the electricity market, updating the planning process, and improving grid connection.

When the AER ultimately did not deliver the results that were hoped, the Irish government altered its strategy. The Renewable Energy Feed-in-Tariff (REFIT) schemes were first launched in 2006, and aimed to double the contributions of renewable energy technologies to electricity generation by the year 2010 (from 5.2% to 13.2%). The bidding process of the AER was replaced by a feed-in-tariff that was funded by the PSO. Generators entered into a 15 year PPA with a licensed supplier.

REFIT 1 was open for applications until the end of 2009. It covered small wind (<5MW), large wind (>5MW), hydroelectricity and biomass gas. A substantial 1242MW of capacity was installed. By 2010, Ireland had exceeded its 13.2% target, but the rate of new installations then began to fall due to the economic recession. REFIT 2 came into operation in 2012 and was open for applications until the end of 2015. It provided for a further 4000MW of renewable capacity. REFIT 3 was also open for applications until the end of 2015, but focused on incentivising the addition of 310MW of capacity composed of combined heat and power, biomass combustion and biomass co-firing (*REFIT Schemes and Supports*).

3.2 Ireland's Electricity Sector in 2020

The evolution of the Irish electricity industry has followed a path from heavy dependency on fossil fuels to a modern structure with significant penetration of renewable energy. The following section will outline the Irish electricity generation profile today, the key actors in the sector, the concept of the Integrated Single Electricity Market (I-SEM) and the present energy and electricity policy regime.

3.2.1 Ireland's Electricity Generation Profile

Ireland now has large levels of wind penetration and a heavy dependency on natural gas in its fuel mix for electricity generation. According to the Energy in Ireland 2019 report from the Sustainable Energy Authority of Ireland (SEAI) (Sustainable Energy Authority of Ireland, 2019), the total electricity generated in 2018 was 30,896GWh. Natural gas was the most-used fuel with 16,014GWh (51.8%), followed by renewables, which generated a combined 10,195GWh (33%). Wind was by far the most significant contribution to the renewable generation, with 8,640GWh (27.96%). The contribution of the various energy sources can be clearly seen in Figure 3.1.

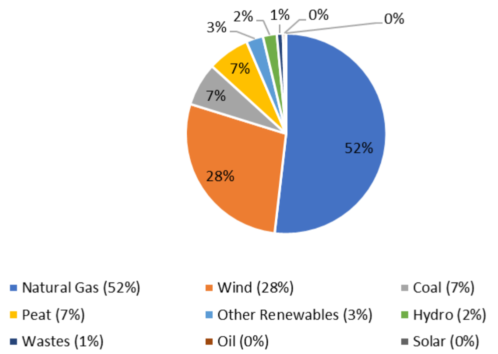
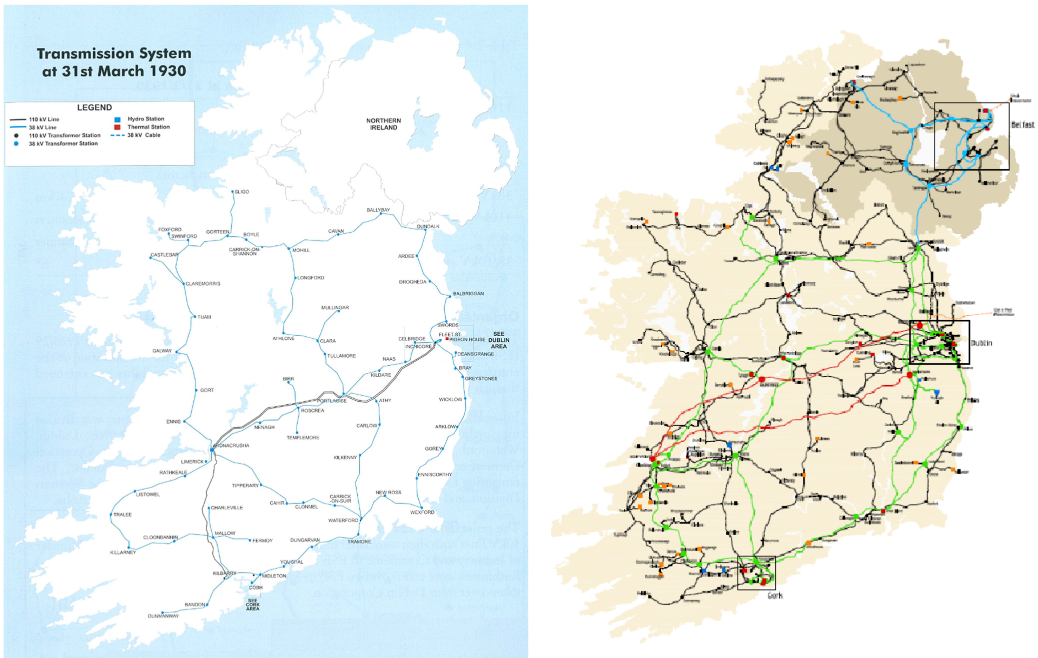


Figure 3.1: Percentage share of electricity generated by fuel in Ireland in 2018 (Sustainable Energy Authority of Ireland, 2019)

The SEAI report indicates the energy trends in Ireland in 2018 compared with 2017, with a special focus on the renewable energy targets. Notably, the percentage of electricity generated from renewable sources of energy increased by 3.1% from 2017 to 2018, to reach 33.2%. The 2020 target is 40%. The use of coal as a fuel for electricity generation fell by a significant 41%, while peat fell 3.2% and wind increased by an impressive 16.1%. Overall, energy use increased by 1.6%, but energy-related CO_2 emissions fell by 1.2%, suggesting the Irish energy and electricity industries are moving towards a decoupling of energy use and energy emissions, albeit slowly.

3.2.2 Ireland's Grid and the Integrated Single Electricity Market

A wide area synchronous electricity grid, meaning a regional scale grid that operates on the same utility frequency, connects the electricity sectors of the Republic of Ireland and Northern Ireland. There are two undersea interconnections to the UK National Grid, the Moyle Interconnector between Scotland and Northern Ireland, and the East-West Interconnector between Dublin and Wales. A proposed connection between Ireland and France, called the Celtic Interconnector, is expected to be operational by 2025. The highly developed transmission system can be seen in detail in Figure 3.2, a stark contrast to the sparse network off the 1930s.



(a) (b)

FIGURE 3.2: Comparison between the Irish transmission grid in (a) 1930 (Gaffney et al., 2017) and (b) 2020 (*Smart Grid Dashboard*)

The Integrated Single Electricity Market (I-SEM) is the wholesale electricity market arrangement encompassing the entire island of Ireland, thus including both the Republic of Ireland and Northern Ireland. It came into effect in 2018 to replace the previous Single Electricity Market (SEM) arrangements. The goal is to facilitate the integration of the Irish wholesale electricity market with the European markets. Specifically, the I-SEM is intended to enable the participation in energy markets of a broad range of firms and actors and thus increase competition. It also aims to increase opportunities to trade across different time frames and to provide the participants with several hedging opportunities, while using interconnectors to integrate efficient system balancing. To these ends, the I-SEM is made up of several different energy markets (EirGrid, 2016).

The Capacity Market generally takes place years before the delivery of energy and involves generators selling capacity at a certain strike price. Financial markets for Contracts-for-Difference (CfDs) and Financial Transmission Rights (FTRs) provide traders with the ability to hedge against future market fluctuations. Two ex-ante markets, the Day-Ahead Market and the Intraday Market operate before the delivery of physical energy. These are pan-European markets, operated by the European Market Coupling Operator, which allow market participants to adjust their positions as conditions fluctuate closer to real-time delivery. These changing conditions could be due to unusual weather either reducing or increasing demand. The Balancing Market then involves remuneration for requests by the transmission system operator (TSO) to generators or suppliers to provide balancing services to ensure energy supply is equal to energy demand. These markets are summarised in Figure 3.3.

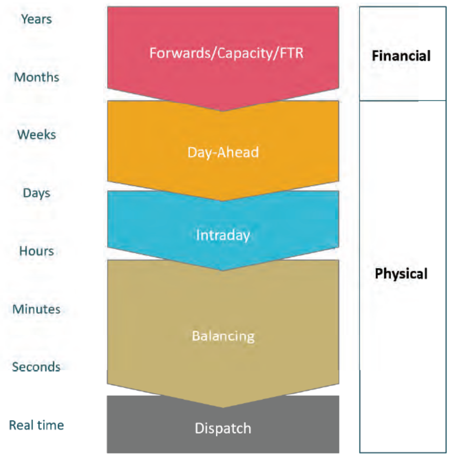


FIGURE 3.3: I-SEM Market Time Frames (EirGrid, 2016)

3.2.3 Electricity Industry Economic Actors

A range of actors play various roles in the Irish electricity industry, in generation and supply, operation and maintenance, and regulation. A profile of the key organisations in the industry is provided below to offer the necessary information and context for the modelling chapter that follows.

Electricity Supply Board (ESB)

The ESB was initially created in 1927 to take charge of Ireland's nascent electricity industry. It internalised the entire electricity market at its inception, monopolising the industry until the year 2000. Following the introduction of the First Energy Package in 1996 and the Electricity Regulation Act, 1999, the company retained ownership of the transmission and distribution networks, but relinquished responsibility for the transmission network to EirGrid. When the electricity market opened to competition in 2000, the ESB ceased to be the monopolist. Its market share in owning and operating the installed generation capacity fell from 95% in 2000 to 51% in 2015 (Gaffney et al., 2017).

The supply arm of the ESB was rebranded in 2012 to become Electric Ireland. A separate arm of the organisation, ESB Networks, finances, builds and maintains the transmission system and carries out all functions related to the distribution system, such as planning, construction, maintenance and operation. The company remains a state-owned for-profit entity, aiming to "produce and deliver clean, secure and affordable energy" and "develop energy services to meet evolving market needs", according to its strategic objectives as stated on its website (*About ESB*).

EirGrid

EirGrid is a state-owned company that was established following the First Energy Package and subsequent Electricity Regulation Act 1999, to manage and operate Ireland's transmission network. As Ireland's TSO, its stated goal is to meet the needs of all electricity users, in the most cost effective way, by ensuring electricity is always available.

EirGrid's Strategy 2020–2025 (EirGrid, 2020) is shaped by the impending transformation of the electricity sector as it is driven by the need to decarbonise in the face of climate change. EirGrid's stated primary goal is to lead the island of Ireland's electricity sector on sustainability and decarbonisation. It says it will be necessary to connect an additional 10,000MW of renewable electricity generation to Ireland's transmission network and transform the country's power system to reliably perform with 95% renewable energy by 2030.

Since the wholesale electricity market (I-SEM) covers the entire island of Ireland, EirGrid works closely with SONI, the TSO for Northern Ireland. The Single Electricity Market Operator (SEMO) is a joint venture between EirGrid and SONI responsible for the operation of the I-SEM, and is considered part of the larger EirGrid Group.

Commission for Regulation of Utilities

The Commission for Regulation of Utilities (CRU) is Ireland's independent energy and water regulator. The organisation has a wide range of responsibilities, tasked with ensuring the proper regulation of vital utilities while dealing with customer protection and safety.

Initially established as the Commission for Energy Regulation in 1999 following the early steps in market liberalisation, the responsibilities of the CRU have grown over time to include the supply of water in addition to energy. There are four key functions of the CRU. Firstly, it performs economic regulation of the energy industry to protect customer interests, ensure security of supply, and promote competition in the generation and supply of electricity and in the supply of natural gas. Its regulations and market monitoring in this regard feature heavily throughout this thesis. Secondly, the CRU carries out economic regulation of water to protect the interest of customers by monitoring the performance of Irish Water, Ireland's state-owned water utility company, and ensuring its services are provided in a cost-efficient way. Thirdly, it resolves customer complaints relating to energy companies and Irish Water. Fourthly, it focuses on energy safety regulation to protect lives across the energy sector, such as electrical contractors and those involved in petroleum extraction and exploration activities. Regarding the I-SEM in particular, the CRU administers market codes, deals with the licensing, and performs important monitoring of the operation of the market and the conduct of participants such as the strategic electricity generation firms (Commission for Regulation of Utilities, 2020).

Strategic Firms

The CRU provides bi-annual electricity and gas retail market monitoring reports with detail on market share and energy prices. The most recent report covers Q2 2019 and provides indications as to which firms can be considered strategic in the Irish electricity industry (Commision for Regulation of Utiles, 2019). In the Irish domestic electricity market, Electric Ireland (47.7%), Bord Gáis (19.13%) and SSE Airtricity (12.82%) were the three largest firms by MWhs consumed (Figure 3.4).

In terms of the all-island wholesale market, Electric Ireland (30%) was the largest, followed by SSE Airtricity (14%), then Energia Group (12%) and Bord Gáis Energy (12%). In view of these figures, Electric Ireland, Bord Gáis, and SSE Airtricity will be considered as the three strategic firms in the Irish electricity sector, although this is evidently an approximation.

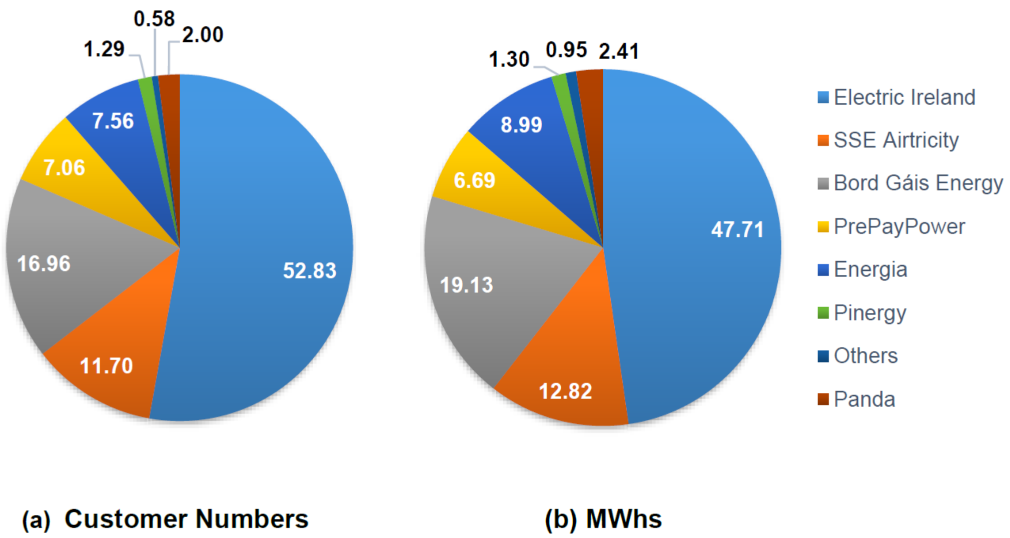


FIGURE 3.4: Domestic Market Share of Electricity Firms in Ireland in Q2 2019 (Commision for Regulation of Utilies, 2019)

Electric Ireland was formerly the market monopolist, so its position as the dominant firm in both the domestic retail market and the all-island wholesale market is unsurprising. In terms of its fuel mix, the most recent available figures from the Electric Ireland website provide information on the year 2018. The firm used primarily natural gas (55.1%) and renewables (35%), with the remaining 10% a combination of other fossil-fuels such as coal (5.3%) and peat (3.6%) (*Fuel Mix Disclosure 2018*).

Bord Gáis Energy has been in operation since 1976 when it was founded by the Irish government (as Bord Gáis Éireann) to take the place of several private gas companies. Following the adoption of the Third Energy Package, the Irish gas market underwent significant changes. Bord Gáis Éireann was required to unbundle into a network operator and a supply arm. Bord Gáis entered the deregulated electricity market in 2009, but due to the conditions of the EU/IMF bailout programme following the 2008 recession, the Irish government was required to sell state owned assets to reduce its debt. Bord Gáis Energy was sold to a consortium of various energy companies (Centrica, Brookfield Renewable Energy and iCON Infrastructure). Bord Gáis Energy is now a private limited company as part of the Centrica Group.

The Bord Gáis Energy fuel mix, with figures provided only to the year 2018, is similar to Electric Ireland. Natural Gas (69.77%) is its major energy source, followed by renewables (25.05%), with coal and peat playing a minor role (Bord Gáis, 2018). Bord Gáis also provides a "Green Source Products" option for customers which, via Green Source Verification process, guarantees a 100% renewable energy source.

SSE Airtricity was founded as Eirtricity in Ireland in 1997 and then acquired by SSE plc in 2008. According to its website, it provides 100% green electricity and operates 720MW of onshore wind farms across Ireland (*SSE Airtricity: About Us*). SSE Airtricity also invests in local communities close to its wind farms through the SSE Airtricity Community Fund. Energia also provide electricity from only 100% renewable energy sources.

3.2.4 Energy and Electricity Policies

As noted in Section 3.1, the energy and electricity priorities of the Irish state have evolved over time and as such the policies intended to realise those priorities have also developed. The primary energy and electricity goals of the Irish state are now to reduce emissions and decarbonise the generation of electricity to meet the targets set out by the European Union (Department of Communications Climate Action and Environment, 2019). To achieve this goal, there are three key policy instruments in place: the EU's Emissions Trading Scheme, the carbon tax and the Renewable Electricity Support Scheme (RESS).

The electricity industry in Ireland, and other heavy industries such as mining, are subject to the EU's Emission Trading Scheme. The EU ETS is a "cap and trade" system that operates in all EU countries along with Liechtenstein, Norway and Iceland. It covers the emissions from over 11,000 energy-intensive installations such as power stations and industrial plants. Over 45% of the EU's emissions are from these installations. A *cap* is set on the total amount of greenhouse gases that can be emitted by the installations covered by the system. This cap is reduced over time to reduce the total emissions. Companies receive or buy emissions permits, which they can *trade* with one another as required. The price of permits, which is essentially a carbon price, fluctuates as the firms trade. Due to the number of firms involved across the EU, it is reasonable to consider Irish firms as price takers. Each year, companies must give up enough permits to cover all of their annual emissions. It is argued by the European Commission that such a trading system ensures emissions are reduced cost-effectively, while creating a carbon price that responds to market signals and stimulates investment in low-carbon technologies. The EU ETS is currently about to enter phase 4 (2021-2030), which is focused on strengthening the Market Stability Reserve, a mechanism intended to reduce any permit surplus and improve the system's resilience to shocks (European Commission, 2020a).

The carbon tax in Ireland applies to all non-ETS sectors, taxing emissions from the direct use of fossil-fuels such as kerosene, liquid petroleum gas and fuel oil. It was first introduced in 2010 at €10 per tonne of CO_2 emissions, which increased to €20 per tonne of CO_2 in 2014. The carbon tax was then raised to €26 per tonne of CO_2 in 2020, and is set to progressively increase each year to €100 per tonne of CO_2 by 2030. The electricity industry is exempt from this tax due to its inclusion in the EU ETS (*Carbon tax*).

The first RESS auction (RESS-1) is set for completion in August 2020. The motivation for replacing the previous renewable electricity support scheme, REFIT, was to allow the government to respond to changes in the energy industry, such as falling technology costs, market conditions, and changing objectives in renewable electricity policy. At present, the objective of RESS is to deliver on the EU-wide renewable energy target of 32% RES by 2030 (Department of Communications Climate Action and Environment, 2018).

Microgeneration Supports

Supports for microgeneration of electricity in Ireland are considered to be seriously inadequate as present, when the potential of household-to-community level renewable electricity generation is taken into account. The Sustainable Energy Authority of Ireland (SEAI) offers a grant to homeowners for the installation of Solar PV panels and battery energy storage systems. This grant is capped at €4,800, depending on the number of panels and batteries to be installed (*Solar Electricity Grants*). There are also some limited tariff schemes in place by electricity suppliers in Ireland for household generated electricity, but all are pilot schemes designed to encourage customers to purchase electricity from the supplier in question. The suppliers do not have the capability to directly sell on the units of electricity purchased from households.

The main issues with microgeneration in Ireland are grid access, metering and remuneration. The CRU published an information paper on this issue in May 2020 (Commission for Regulation of Utilities, 2020). Essentially, the paper lays out the legislative context for microgeneration with several principles, foremost of which states that individual customers who wish to be active energy citizens and contribute to the electricity system decarbonisation by generating their own electricity from renewable sources will receive a market based price for their exports. It highlights the fact that the ESB has a process in place to facilitate the connection of microgeneration to the network and that every legacy analogue meter in Ireland will be upgraded to a smart meter by 2024. It also notes that there should not be unfair outcomes for customers who do not have the means to make these microgeneration investments, an issue that is discussed further in Chapter 6.

For projects above the microgeneration level, a formal grid connection is needed. There are upfront costs to be paid for the assessment of the connection process, while the final connection fee can be even greater. This causes a significant barrier to entry to the electricity market for schemes such as community energy projects.

Community Energy

Community energy in Ireland is relatively untapped. Chapter 4 of the 2015 White Paper on the Irish energy transition (Department of Communications Climate Action and Environment, 2015) stated the importance of community engagement in the planning of the energy system. It proposed a range of supports for community energy schemes, such as mandated participation in renewable energy projects, access to the grid for such projects with a mechanism for communities to receive payment, and funding for community led projects.

The RESS includes plans for a certain number of MWhs to be set aside in each auction for community energy schemes. The RESS High Level Policy Design Paper (Department of Communications Climate Action and Environment, 2018, p. 2) states that "providing pathways for increased community participation will be a cornerstone of the new scheme". The paper outlines a community category for each RESS auction, which is set to a limit of 10% of capacity of the second auction, although experts in the Irish energy sector have suggested the actual capacity will be much lower. There are also intended to be citizen investment opportunities for projects that are to be supported by the RESS.

Outside of the RESS, there are few state supports for community energy. The SEAI funds energy efficiency in communities through its Better Energy Communities scheme. In 2019, the scheme provided €25.3m of government funds primarily for retrofitting purposes but also for the integration for control systems and of renewable energy sources. The supported projects were evaluated based on their community benefits and other criteria such as energy savings (*SEAI Community Grants*).

One of the leading expert groups on community energy in Ireland is the Tipperary Energy Agency. As a social enterprise, it provides cost effective professional services regarding renewable energy and sustainability projects. It has pioneered major projects such as Ireland's only community operated wind farm in Templederry. This project then developed into Community Power (*Our Story*), Ireland's first community-owned energy supplier. Since 2016, Community Power generates 15GWh of electricity from its wind farm in Templederry, while also purchasing electricity from small-scale hydro and wind generators across Ireland and delivering this electricity to its customers. There are also a small number of energy cooperatives along Ireland's west coast, such as the Aran Islands' energy cooperative (*Aran Islands Energy Co-op*).

The effects of incentivising significant community energy projects to participate in the Irish electricity industry will be investigated with a stylised oligopoly model in the next chapter, while the future for community energy in Ireland will be discussed in further detail in Chapter 6.

Chapter 4

Model

To address the research question presented in Section 1.2, the stylised oligopoly electricity industry model framework by Genc and Reynolds (2019), discussed in Section 2.3, is adapted to represent the Irish electricity industry. This oligopolistic model framework was selected to capture the market structure of the Irish electricity industry, which despite the market liberalisation since the early 2000s, is still dominated by a small number of firms. As such, the model framework has been expanded from two to three strategic firms. Based on the considerations in Chapter 3 regarding the strategic firms in Ireland's electricity industry, these three firms reasonably approximate Electric Ireland (Firm 1), Bord Gáis (Firm 2) and SSE Airtricity (Firm 3). The profit functions of the firms have been adapted to match the policy regime in Ireland. A competitive fringe is modelled to represent the development of community energy projects. Four scenarios are outlined, each capturing different market structures that may plausibly occur in the Irish electricity industry. Different combinations of incentive policies for the strategic firms and community fringe are considered in each scenario.

4.1 General Model Structure

The general structure of the model is as follows. Wholesale electricity market demand is modelled linearly, $D(p) = a - bp_l$, where p_l is the wholesale market price for electricity (the subscript denotes the scenario in question). a and b are demand parameters. Each strategic firm i has the capability to generate thermal electricity q_i from conventional fossil-fuel plant capacity and to generate renewable electricity r_i from capacity that uses renewable sources (the subscript denotes the firm). In each scenario, the total thermal electricity produced by the strategic firms is $Q_l = q_1 + q_2 + q_3$ and the total renewable electricity produced by the strategic firms is $R_l = r_1 + r_2 + r_3$ (the subscript on R_l and Q_l denotes the scenario). No distinction is made in the model between the installation of generation capacity and the production or output of electricity. The community fringe have supply function $r_f = a_f + b_f p_f$, where a_f and b_f are supply parameters. This assumes that the community fringe will generate more renewable electricity if the price they are offered increases. Strategic firms are then left with with residual demand $D^{res}(p_l) = D(p_l) - r_f$.

Each strategic firm i is subject to costs of producing conventional thermal electricity, $c_i^q(q_i)$, and costs of producing renewable electricity, $c_i^r(r_i)$. The cost functions are both differentiable and convex. The thermal electricity cost function for each firm is approximated to increase linearly with thermal electricity output. This functional form is chosen based on the rationale that new fossil-fuel fired power plants are relatively site-independent. Thus, if a firm wishes to produce more electricity, they simply invest in a new power plant, which approximately costs the same as the previous power plants. Thus, $c_i^q(q_i) = x_i^q q_i$.

The renewable electricity cost function for each firm is approximated as a quadratic function. This functional form is chosen since renewable electricity generation is more site dependent. Solar PV arrays require locations with the least cloud cover possible, while wind farms require high wind speeds. If it is assumed that the most ideal locations, with low connectivity costs and optimum geographical qualities, are chosen first, then it is plausible that the costs of investing in additional capacity will increase as more capacity is installed. Thus, $c_i^r(r_i) = x_i^r(r_i)^2$.

Each strategic firm also participates in the EU Emissions Trading Scheme. This involves purchasing permits for their greenhouse gas emissions. Irish firms are considered price-takers in the EU ETS market and each firm must pay the same price for emissions permits. The more a firm emits greenhouse gases, the more permits the firm must purchase. Therefore, this scheme is represented in the model as a cost, c^{ets}, that increases linearly with the emissions produced by each firm. Following Arce and Sauma (2016), an emissions coefficient γ determines the emissions produced per unit of thermal output.

Under the Renewable Energy Support Scheme (Department of Communications Climate Action and Environment, 2018), strategic firms which successfully bid for renewable capacity in the scheme's auctions receive financial support via a floating premium, $prem(p_l, p_s) = p_s - p_l$. The premium, which is the difference between the market price for electricity and the strike price p_s agreed at auction, guarantees that each firm is paid the strike price for each unit of renewable electricity produced. If the market price is greater than the strike price, the floating premium is negative and the firms must pay the state. In the general model structure, the firms are offered p_r for their renewable electricity.

In all scenarios, the inverse demand function has the following form, obtained by solving the residual demand function for the price,

$$p_l = \frac{1}{b_l}(a_l - R_l - Q_l) \tag{4.1}$$

where a_l and b_l are scenario-specific parameters. This function demonstrates how the strategic firms exert market power; through their independent choices they determine the total thermal electricity and total renewable electricity, which in turn affects the wholesale market price. The wholesale market price then determines the market demand. Given the assumptions about prices and costs, the general profit function for firm i in Scenario l is,

$$\pi_i = p_l q_i - \gamma c^{ets} q_i - x_i^q q_i + p_r r_i - x_i^r (r_i)^2$$

By redefining the costs for each firm due to their thermal output (the ETS costs and production costs) as $\gamma c^{ets} + x_i^q = \tilde{x}_i^q$, the profit function becomes,

$$\pi_i = p_l q_i - \tilde{x}_i^q q_i + p_r r_i - x_i^r (r_i)^2 \tag{4.2}$$

The total emissions produced in each scenario is given by the following sum, where q_i^* is the thermal output of firm i is the given scenario,

$$E_i = \gamma \sum_{i=1}^{3} q_i^* \tag{4.3}$$

4.2 Scenarios

The four scenarios represent the following situations. The first scenario describes the Irish electricity industry at present, with three strategic firms and no grid access or support for the community fringe who generate electricity from renewable sources. The second scenario represents the Irish electricity industry with the addition of grid access for the community fringe, who are offered a fixed price for the additional electricity they export to the grid. The third scenario remunerates the community fringe for their renewable electricity with a price that reflects the market price of electricity. The fourth scenario offers a market price to both the strategic firms and the community fringe for the renewable electricity they produce.

The first and second scenario are similar in the sense that the markets for thermal electricity and renewable electricity separate, with thermal electricity remunerated at the wholesale market price and renewable electricity remunerated at a predetermined strike price. They are connected by the same market demand, but the addition of the community fringe reduces the residual demand faced by the firms.

In the third scenario, the markets for thermal electricity and renewable electricity remain separate for the strategic firms, but the community fringe affects the market demand differently, since they receive the wholesale market price for their electricity. The community fringe is motivated by increasing price levels to supply more electricity to the market. This dampens the quantities and associated prices likely to be chosen by the strategic firms. In the final scenario, the market separation of thermal and renewable electricity does not occur, since all electricity supplied is remunerated at the wholesale market price.

These scenarios lead to particular choices for the demand parameters in each scenario, provided in Table 4.1.

Scenario	a_l	b_l
1	a	b
2	g	b
3	l	m
4	l	m

TABLE 4.1: Scenario Demand Parameters

The scenario demand parameters are obtained by solving the residual demand function for the price in each scenario, and are defined as follows,

$$g = a - a_f - b_f p_s \tag{4.4}$$

$$l = a - a_f \tag{4.5}$$

$$m = b + b_f \tag{4.6}$$

The profit function of firm i in Scenario $= 1, 2, 3$,

$$\pi_i = p_l q_i - \tilde{x}_i^q q_i + p_r r_i - x_i^r (r_i)^2$$

and in Scenario $l = 4$,

$$\pi_i = p_l q_i - \tilde{x}_i^q q_i + p_l r_i - x_i^r (r_i)^2$$

Under the neoclassical micro-economic theory of the firm, the firms' objective is profit maximisation. In the context of this industrial organisation model, this means that in each scenario, every firm seeks to maximise their profit function by optimising their thermal output, q_i, and their renewable output, r_i. The optimisation is carried out with information about the output choices of the other strategic firms. Mathematically, this translates to $\frac{d\pi}{dq_i} = 0$ and $\frac{d\pi}{dr_i} = 0$, given the values $q_j, r_j (j \neq i)$.

Maximising with respect to thermal outputs for Scenarios $l = 1, 2, 3$ leads to,

$$\begin{aligned}\frac{d\pi}{dq_i} = \frac{dp_l}{dq_i} q_i + p_l - \tilde{x}_i^q &\overset{!}{=} 0 \\ -\frac{1}{b_l} q_i + p_l - \tilde{x}_i^q &\overset{!}{=} 0\end{aligned}$$

which implies,

$$p_l = \frac{q_i}{b_l} + \tilde{x}_i^q \tag{4.7}$$

Equation 4.7 demonstrates the well understood principle in the micro-economic theory of the firm that the profit maximisation behaviour of the strategic firms implies that the marginal revenues (LHS of Equation 4.7) equal marginal costs (RHS of Equation 4.7). The marginal costs have two components: (i) production costs $\tilde{x}_i^q$ and (ii) the costs due to the loss of revenues for all sold thermal units q_i due to a price reduction of $\frac{1}{b_l}$, since the price falls with increased supply. In Scenario $l = 4$, the profit maximisation implies the following,

$$\frac{d\pi}{dq_i} = \frac{dp_l}{dq_i}\left(q_i + r_i\right) + p_l - \tilde{x}_i^q \overset{!}{=} 0$$

and so,

$$p_l = \frac{q_i + r_i}{b_l} + \tilde{x}_i^q \tag{4.8}$$

Similarly to the other scenarios, profit maximisation by the strategic firms leads to the first-order condition Equation 4.8, with marginal revenues equalling marginal costs. However, the marginal costs in Scenario 4 also include the loss of revenues from renewable outputs r_i due to the price reduction, since renewables are remunerated at market price in this scenario. Maximising with respect to renewable outputs in Scenarios $l = 1, 2, 3$ leads to,

$$\frac{d\pi}{dr_i} = \frac{dp_l}{dr_i} q_i + p_s - 2x_i^r r_i$$

which implies,

$$p_s = \frac{q_i}{b_l} + 2x_i^r r_i \tag{4.9}$$

Again, to maximise profits, the marginal revenues from renewable output (the strike price p_s) are equal to the marginal costs, which are the revenue lost due to the price reduction of increasing thermal output and the renewable production costs. In Scenario $l = 4$,

$$\frac{d\pi}{dr_i} = \frac{dp_l}{dr_i}\left(q_i + r_i\right) + p_l - 2x_i^r r_i \overset{!}{=} 0$$

therefore,

$$p_l = \frac{q_i + r_i}{b_l} + 2x_i^r r_i \tag{4.10}$$

This situation is similar to the thermal output optimisation in Scenario 4 in Equation

4.8, in which the marginal costs include production costs and the loss of revenues from both thermal and renewable electricity. There are several other interesting insights that can be gleaned from analysing the theoretical model. From Equation 4.7, for Scenarios $l = 1, 2, 3$,

$$q_i = b_l\Big(p_l - \tilde{x}_i^q\Big) \tag{4.11}$$

Summing over all strategic firms,

$$Q_l = b_l\Big(3p_l - \sum_i^3 \tilde{x}_i^q\Big)$$

$$Q_l = 3\Big(a_l - R_l - Q_l\Big) - b_l \sum_i^3 \tilde{x}_i^q$$

Rearranging and using $\bar{x}^q = \frac{1}{3}\sum_i^3 \tilde{x}_i^q$,

$$R_l = a_l - \frac{4}{3}Q_l - b_l\bar{x}^q \tag{4.12}$$

Inserting this expression into Equation 4.11,

$$q_i = \frac{Q_1}{3} + b_l(\bar{x}^q - \tilde{x}_i^q) \tag{4.13}$$

From Equation 4.13, thermal outputs in Scenarios $l = 1, 2, 3$ are revealed to be one-third of the total output, with the addition or subtraction of another term, depending on how much the firm gains or loses from its thermal production costs being above or below the strategic firms' average production costs. For Scenario $l = 4$, Equation 4.8 leads to,

$$q_i = b_l\Big(p_4 - \tilde{x}_i^q\Big) - r_i = b_l\Big(p_4 - \tilde{x}_i^q\Big) - \frac{\tilde{x}_i^q}{2x_i^r} \tag{4.14}$$

Summing over all three strategic firms,

$$Q_4 = m\Big(3p_4 - \sum_i^3 \tilde{x}_i^q\Big) - \sum_i^3 \frac{\tilde{x}_i^q}{2x_i^r}$$

$$Q_4 = 3\Big(l - R_4 - Q_4\Big) - m\sum_i^3 \tilde{x}_i^q - \sum_i^3 \frac{\tilde{x}_i^q}{2x_i^r}$$

$$R_4 = l - \frac{4}{3}Q_4 - m\bar{x}^q - \frac{1}{3}\sum_i^3 \frac{\tilde{x}_i^q}{2x_i^r}$$

Inserting into Equation 4.14,

$$q_i = \frac{Q_4}{3} + m(\bar{x}^q - \tilde{x}_i^q) + \frac{1}{2}\Big(\frac{1}{3}\sum_i^3 \frac{\tilde{x}_i^q}{x_i^r} - \frac{\tilde{x}_i^q}{x_i^r}\Big) \tag{4.15}$$

Similarly to the situation in the first three scenarios, the differences in thermal output by each firm depends on the differences in the production thermal costs. However, since the renewable output is also remunerated at market price in Scenario 4, the renewable production costs also play a role. Using Equations 4.7, 4.8, 4.9 and 4.10, the renewable outputs in Scenarios $l = 1, 2, 3$ can be written as,

$$r_i = \frac{p_s - p_l + \tilde{x}_i^q}{2x_i^r} \tag{4.16}$$

Equation 4.16 shows that the renewable output of each firm increases with thermal production costs, while it decreases with renewable production costs. The level of the strike price p_s is clearly highly important here. If it is lower than the wholesale market price for electricity, the renewable output is dampened. In Scenario $l = 4$, since $p_s = p_l$, the equation for r_i reduces to,

$$r_i = \frac{\tilde{x}_i^q}{2x_i^r} \tag{4.17}$$

4.2.1 Scenarios Summary

The inverse demand functions and profit functions of firm i in each scenario are summarised below in Table 4.2.

Scenario	Inverse Demand Function	Profit Function of Firm i
1	$p_1 = \frac{1}{b}(a - R_1 - Q_1)$	$\pi_i = p_1 q_i - \tilde{x}_i^q q_i + p_s r_i - x_i^r (r_i)^2$
2	$p_2 = \frac{1}{b}(g - R_2 - Q_2)$	$\pi_i = p_2 q_i - \tilde{x}_i^q q_i + p_s r_i - x_i^r (r_i)^2$
3	$p_3 = \frac{1}{m}(l - R_3 - Q_3)$	$\pi_i = p_3 q_i - \tilde{x}_i^q q_i + p_s r_i - x_i^r (r_i)^2$
4	$p_4 = \frac{1}{m}(l - R_4 - Q_4)$	$\pi_i = p_4 q_i - \tilde{x}_i^q q_i + p_4 r_i - x_i^r (r_i)^2$

TABLE 4.2: Scenarios Summary

The explicit solutions for the thermal and renewable outputs in each scenario are provided in Appendix A.

4.3 Results

In order to understand the effects of the various mixtures of incentive policies, the model is analysed to reveal some instructive results. Firstly, the impacts of increasing renewable output on thermal output and the wholesale market price are investigated.

Proposition 1 *The following results hold in equilibrium in Scenario 1, 2, 3.*

(i) The thermal output of firm i decreases with increased renewable output by the same firm. That is, $\frac{dq_i^*}{dr_i} < 0$.

(ii) The thermal output of firm i decreases with increased renewable output by another firm j, k. That is $\frac{dq_i^*}{dr_{j,k}} < 0$.

(iii) The wholesale market price for electricity decreases with increased renewable output by firm i. That is, $\frac{dp^*}{dr_i} < 0$.

Proposition 1 (i) shows that, *ceterus paribus*, firms will reduce their thermal output as they install more renewable capacity. Proposition 1 (ii) shows that, *ceterus paribus*, firms decrease their thermal output in response to greater renewable output by other firms. Proposition 1 (iii) demonstrates the well-established merit order effect, by which the market price for electricity decreases thanks to the addition renewable capacity. These results demonstrate that incentivising renewable output has beneficial effects for both climate change, through the reduction of greenhouse gas emissions associated with thermal output, and for electricity consumers, through the reduction of electricity prices. However, this reduction in prices could have other implications for the strategic firms. These will be discussed in Chapter 6.

It is important to note that the above propositions only hold in Scenarios 1, 2, and 3, in which the strategic firms receive the strike price for their renewable output. The following propositions address Scenario 4.

Proposition 2 *The following results hold in equilibrium in Scenario 4.*

(i) The thermal output of firm i decreases with increased renewable output by the same firm. That is, $\frac{dq_i^*}{dr_i} = -1$.

(ii) The thermal output of firm i does not change with increased renewable output by another firm j, k. That is $\frac{dq_i^*}{dr_{j,k}} = 0$.

(iii) The wholesale market price does not change if firm i increases its renewable output. That is, $\frac{dp^*}{dr_i} = 0$.

Proposition 2 (i) and (iii) are related. Since any firm decreases its thermal output by the same amount it increases its renewable output, any changes in renewable output do not effect the total electricity supplied to the market, and so the price is also unaffected. Furthermore, Proposition 2 (ii) shows that the behaviour of other firms regarding renewable output does not have the same thermal output decreasing effects as in Scenarios 1, 2 and 3. These results suggest that that removing incentive policies for renewable electricity will remove the additional positive side effects of additional renewable output.

The next chapter will provide a numerical illustration of the stylised model in light of the propositions just outlined.

Chapter 5

Numerical Illustration

5.1 Parametrisation

Any numerical illustration of the stylised model of Ireland's electricity industry outlined in Chapter 3 is dependent on the choice of parameters. While a detailed empirical study to determine accurate values for the necessary parameters is beyond the scope of this thesis, plausible values will be used to provide a numerical illustration of the model. The rationale for the choice of these parameters is provided in this section. The parameters and associated values for electricity demand and supply are chosen to correspond to demand and supply over the course of one year. The period of one year is chosen to smooth out diurnal and seasonal fluctuations in electricity demand and allow for straightforward comparison of the numerical illustration results with the empirical reality. The year selected is 2025, since this year could plausibly include the range of policy combinations under analysis, allowing time for renewable electricity installations and community energy to develop. In terms of units, electricity will be quantified in Megawatt hours [MWh]. This is to reflect the fact that prices and costs are generally provided in euros per megawatt hour [€][MWh]$^{-1}$. Emissions will be measured in tonnes of carbon dioxide [tCO_2].

5.1.1 Demand and Supply Parameters

The linear electricity demand is $D(p) = a - bp$. a can be viewed as the maximum electricity demand, that is the demand if electricity is free. b is the change in electricity demand due to an increase by one unit in the price of electricity. The 2019 EirGrid All-Island Generation Capacity Statement (EirGrid & SONI, 2019) provides a range of forecasts for the electricity demand on the entire island of Ireland over the next decade. They implement multiple linear regressions based on economic parameters such as Gross Value Added, personal consumption and Gross National Product to project annual demand over up to the year 2028. The forecasts for the Republic of Ireland and Northern Ireland are calculated separately since they are in different legal jurisdictions. Notably, it is anticipated that the growth of data centres installations in the Republic of Ireland could have a significant impact on the electricity demand, with the median scenario in EirGrid's statement suggesting 29% of demand will come from data centres and other large energy users by 2028.

EirGrid's forecasts for the all-island electricity demand in 2025 have a range between 44.6 [TWh] for the low-demand scenario and 52.6 [TWh] for the high-demand scenario. Therefore, a plausible value for the first demand parameter can be chosen as $a = 77 \times 10^6$ [MWh]. This suggests that electricity demand in 2025 if electricity had zero price would be roughly 62% greater than the median demand forecasted by EirGrid for that period. Selecting b is more challenging. Certain upper and lower bounds can be reasonably estimated (annual demand is likely to decrease more than

1000MWh if the price increases by €1, but less than 1TWh). Within these bounds, the value for b is chosen on the basis of the model producing a plausible wholesale electricity market price and a market demand within EirGrid's forecasts. This leads to $b = 49 \times 10^4$ [MWh]^2[€]$^{-1}$.

The fringe demand parameter a_f determines the minimum amount of electricity supplied by the fringe. b_f gives the additional electricity generated per unit increase in the price offered for renewable electricity. The linear supply function selected for the community fringe is assumed as a local approximation of the true supply function. Thus, the values for a_f and b_f can be chosen such that they produce plausible levels of community fringe electricity generation. The plausibility can be assessed by looking at the policy design for the RESS auctions and determining the minimum amount of community energy schemes set to be auctioned. It is suggested in the RESS High Level Policy Design paper (Department of Communications Climate Action and Environment, 2018) that up to 10% of every auction will be set aside for community schemes. 7,000GWh is the maximum set cumulative capacity for delivery by 2025 under the RESS. 10% of this figure is 700,000MWh, which suggests a plausible value for the minimum supplied fringe capacity can then be chosen as $a_f = 500,000$ [MWh].

The value for b_f challenging to select. However, experts in the Irish electricity industry do not expect community energy schemes to account for more than 5% of the electricity capacity in the country by 2030. Based on this figure, a value can be chosen for the parameters that generates fringe output within 1%-5% of total capacity. This leads to $b_f = 10000$ [MWh]^2[€]$^{-1}$.

5.1.2 Costs and Prices

Each firm is subject to three different costs: the costs of producing thermal electricity $c_i^q(q_i) = x_i^q q_i$, the costs of producing electricity from renewable sources $c_i^r(r_i) = x_i^r$ and a cost due to the EU-ETS c^{ets} which depends on the emissions produced from each unit of thermal electricity. The values of the cost coefficients for each firm were chosen based on the following reasons, but also to ensure that their relative shares of the wholesale electricity market reflected the situation in reality, described in Section 3.2.3.

Due to its position as the former monopolist, Electric Ireland's cost function is chosen to increase slower than the other firms. Bord Gáis's is then chosen to be steeper, with SSE Airtricity's cost function chosen to increase most rapidly, since they operate only four fossil-fuel fired plants in Ireland. A report by financial advisory firm Lazard provides the levelised costs of electricity for a range of technologies. Gas is given as between 150–199 [€][MWh]$^{-1}$. Given that thermal electricity generation in Ireland is predominately using gas technology but also includes oil and coal which is generally cheaper, the thermal electricity cost functions are then selected as: $x_1^q = 25$, $x_2^q = 37$, and $x_3^q = 48$.

Electric Ireland is chosen to have the smallest renewable electricity cost coefficient thanks to its dominant market position. SSE Airtricity's role as a producer of almost exclusively renewable electricity in Ireland informs the choice of its renewable cost coefficient as less than Bord Gáis's cost coefficient. The choice of these parameters is then based on Scenario 1, the status-quo scenario, outputting the appropriate ratios for each firm between their conventional and renewable outputs (see Section 3.2.3). Thus, $x_1^r = 1.6 \times 10^{-6}$ [€], $x_2^r = 7.3 \times 10^{-6}$ [€], and $x_3^r = 4.2 \times 10^{-6}$ [€].

The EU-ETS carbon price is taken from projections from a working paper by the European Roundtable on Climate Change and Sustainable Transition (Marcu et al., 2019). They list a range of forecasts (p.28) by various organisations for the price per tonne of CO2 emitted, from 15 [€][tCO_2]$^{-1}$ to 42 [€][tCO_2]$^{-1}$. Therefore, $c^{ets} = 35$ [€][tCO_2]$^{-1}$, is taken as a plausible value for the carbon price.

The strike price is another exogenous parameter given to the model. Poyry, an energy consulting firm carried out an analysis of the benefits accruing to consumers from the RESS. They look at a range from 50–65[€][MWh]$^{-1}$. Thus, the strike price value can be reasonably chosen as $p_s = 65$ [€][MWh]$^{-1}$.

5.1.3 Emission Coefficient

The emission coefficient γ determines the intensity of greenhouse gas emissions per unit generated of thermal electricity. EirGrid's Smart Grid Dashboard provides data for the CO_2 intensity over time, reaching back as far as the previous month (*Smart Grid Dashboard*). For the time period 10th June 2020 to 9th July 2020, the average CO_2 intensity was 343.5 [gCO_2][kWh]$^{-1}$, or 0.3435 [tCO_2][MWh]$^{-1}$. The SEAI list the CO_2 intensity as 343.5 [gCO_2][kWh]$^{-1}$ for the year 2018 (Sustainable Energy Authority of Ireland, 2019). Using these figures, and projecting a continued reduction in CO_2 intensity to 2025, a value of $\gamma = 0.3$ [tCO_2][MWh]$^{-1}$ is chosen.

5.1.4 Parameter Values

Based on the rationale provided above, the following values for the parameters are tabulated below.

Parameter	Value	Unit
a	77×10^6	[MWh]
b	49×10^4	[MWh]^2[€]$^{-1}$
c^{ets}	35	[€][tCO_2]$^{-1}$
x_1^q	25	[€][MWh]$_{-1}$
x_2^q	37	[€][MWh]$_{-1}$
x_3^q	48	[€][MWh]$_{-1}$
x_1^r	1.6×10^{-6}	[€][MWh]$_{-2}$
x_2^r	7.3×10^{-6}	[€][MWh]$_{-2}$
x_3^r	4.2×10^{-6}	[€][MWh]$_{-2}$
γ	0.3	[tCO_2][MWh]$^{-1}$
p_s	65	[€][MWh]$^{-1}$
a_f	5×10^5	[MWh]
b_f	10×10^3	[MWh]^2 [€]$^{-1}$

Table 5.1: Parameter Values

5.2 Numerical Illustration Results

Using the parameters outlined in the previous section and the scenario solutions provided in Appendix A, the following results were obtained for the numerical illustration.

Quantity	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Unit
Firm 1 Thermal	13,657,399	13,271,429	13,396,143	7,968,750	[MWh]
Firm 2 Thermal	7,777,399	7,391,429	7,396,143	9,809,075	[MWh]
Firm 3 Thermal	2,387,399	2,001,429	3,585,687	598,214	[MWh]
Total Thermal	23,822,196	22,664,287	24,377,973	18,376,040	[MWh]
Firm 1 Renewable	11,602,424	11,848,579	11,939,911	11,093,750	[MWh]
Firm 2 Renewable	3,364,915	3,418,867	3,438,885	3,253,425	[MWh]
Firm 3 Renewable	7,158,066	7,251,839	7,286,633	6,964,286	[MWh]
Fringe Output	/	1,150,000	1,089,132	1,236,250	[MWh]
Total Renewable	22,125,406	23,669,284	23,754,560	22,547,710	[MWh]
Firm 1 Profits	919,433,900	904,986,165	861,642,406	923,671,875	[€]
Firm 2 Profits	259,508,859	248,395,561	221,611,880	418,526,648	[€]
Firm 3 Profits	287,968,443	258,669,961	252,113,659	318,088,170	[€]
Wholesale Market Price	63.37	62.58	58.91	73.62	[€][MWh]$^{-1}$
CO_2 Emissions	7,146,659	6,799,286	7,313,392	5,512,812	[tCO_2]
Fringe %	/	2.5	2.4	3.0	%
RES-E Total %	48.2	51.1	49.4	55.1	%

TABLE 5.2: Numerical Illustration Results

5.2.1 Visual Comparisons by Scenario

The key indicators for reaching climate change targets and ensuring electricity markets remain competitive are greenhouse gas emissions and the wholesale electricity market price, respectively.

Figure 5.1 compares the wholesale electricity market price in each scenario. The lowest price occurs in Scenario 3, suggesting the most competition and lowest market power for the strategic firms is found when renewable electricity of the strategic firms is supported with a sliding premium but the community fringe is remunerated at market price. In contrast, the highest price occurs in Scenario 4. This implies a connection between the sale of renewables by the strategic firms on the wholesale market and market power for strategic firms. The wholesale market price marginally decreases with the addition of the community fringe in Scenario 2, compared to Scenario 1, showing that all consumers will slightly benefit in such a situation.

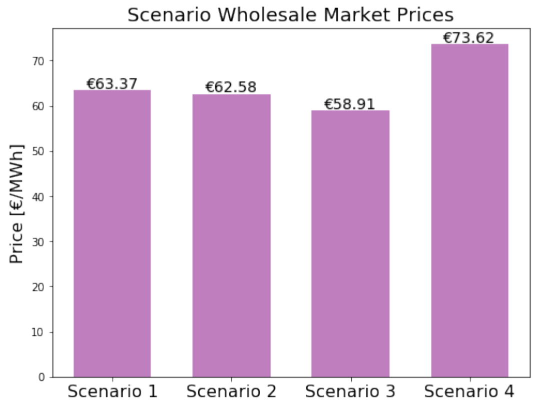


FIGURE 5.1: Scenario Wholesale Electricity Market Prices

Figure 5.2 reveals the effects of the incentive policies on the levels of greenhouse gas emissions in the model. Total thermal output and emissions are compared simultaneously, since emissions are simply the thermal output scaled by γ (Equation 4.3). The highest emissions are in Scenario 1, with no competitive fringe. With the introduction of the competitive fringe in Scenario 2, thermal output and its associated emissions fall, since the strategic firms' residual market demand is reduced. A combination of factors cause the emissions to slightly increase in Scenario 3 compared to Scenario 2, with the lower price, driven down by the community fringe competing at market price, leading to higher market demand, which is in turn met by higher levels of conventional output. The lowest emissions are in Scenario 4, in which both strategic firms and the competitive fringe are offered the wholesale market price for renewable electricity. This drives up the wholesale market price and causes the producers to switch to using renewables.

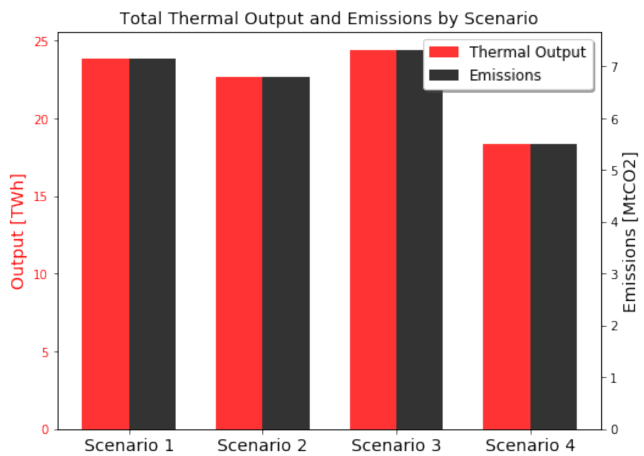


FIGURE 5.2: Total Thermal Output and Emissions across scenarios.

5.2.2 Visual Comparisons by Firm

Comparing the renewable outputs, thermal outputs, and profits of each firm is straightforward and intuitive if the values are grouped together by firm, as done below.

Figure 5.3 shows the renewable outputs grouped by firm. In all scenarios, Firm 1 (representing Electric Ireland, the former monopolist) produces the most renewable electricity. Each firm's renewable output slightly increases from Scenario 1 to Scenario 2 and then in Scenario 3, with a marked decrease in Scenario 4. The community fringe does not produce electricity in the first scenario, while it produces the most in Scenario 4. This is due to the linear relationship between community fringe output and wholesale market price (highest in Scenario 4).

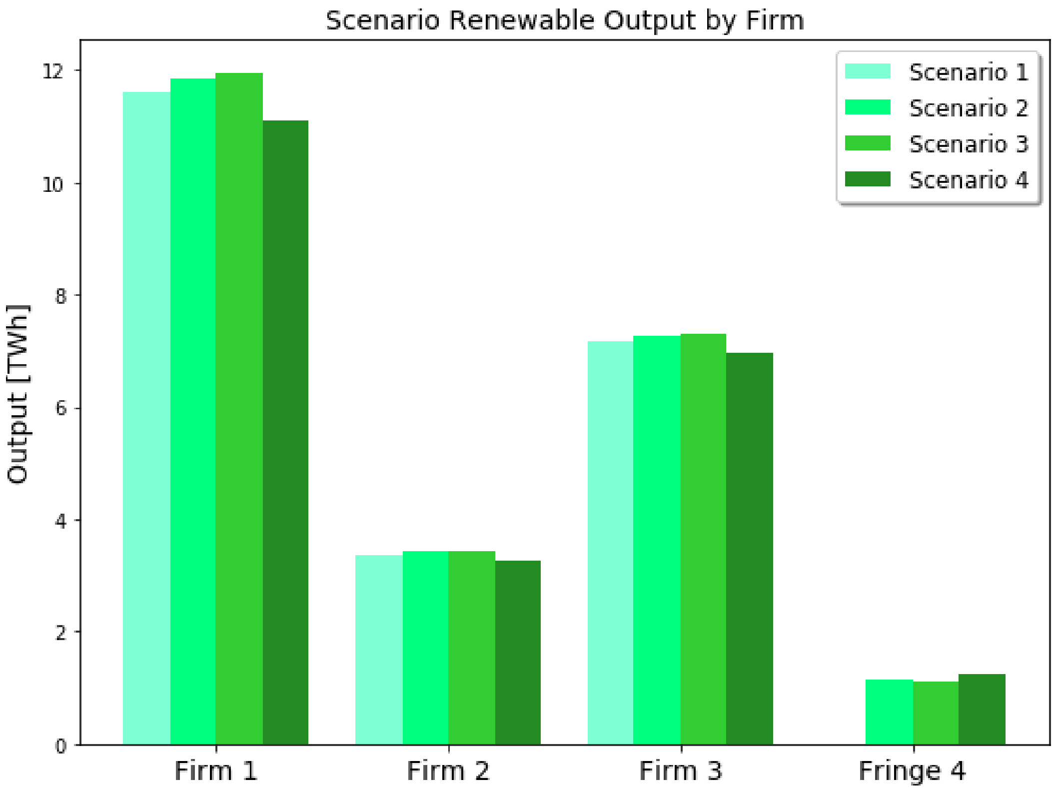


Figure 5.3: Scenario Renewable Outputs by Firm

The scenario highest renewable output (Scenario 3) is also associated with the highest emissions, while the lowest renewable output is in the scenario with the lowest emissions (Scenario 4). The low market price in Scenario 3 leading to high demand for electricity. This relationship points to an important distinction: it is not simply incentivising renewable electricity generation that is important to reduce emissions; the renewable electricity must replace conventional carbon-intensive thermal electricity generation. Figure 5.4 shows the contribution of each firm to the total renewable output in each scenario. In Scenario 4, the additional output by the fringe plays an important role in crowding out thermal output and its associated emissions.

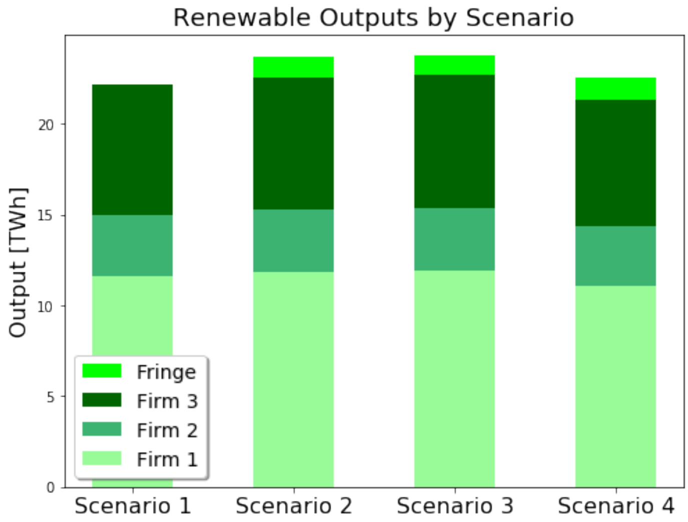


FIGURE 5.4: Renewable Output of each Firm by Scenario

Figure 5.5 displays the thermal electricity output of each firm. Firm 1 unsurprisingly produces the most thermal electricity, a pattern that occurs across every scenario except for Scenario 4. In the final scenario, Firm 1 drastically cuts its thermal output while Firm 2's thermal output increases. This is due to the relative differences in thermal and renewable production costs of each firm, explicitly outlined in Equation 4.15. Firm 3 increases its thermal output in Scenario 3 relative to the other scenarios, but then massively cuts thermal output in the final scenario, when the market price is high and it can greater profit from producing renewable electricity.

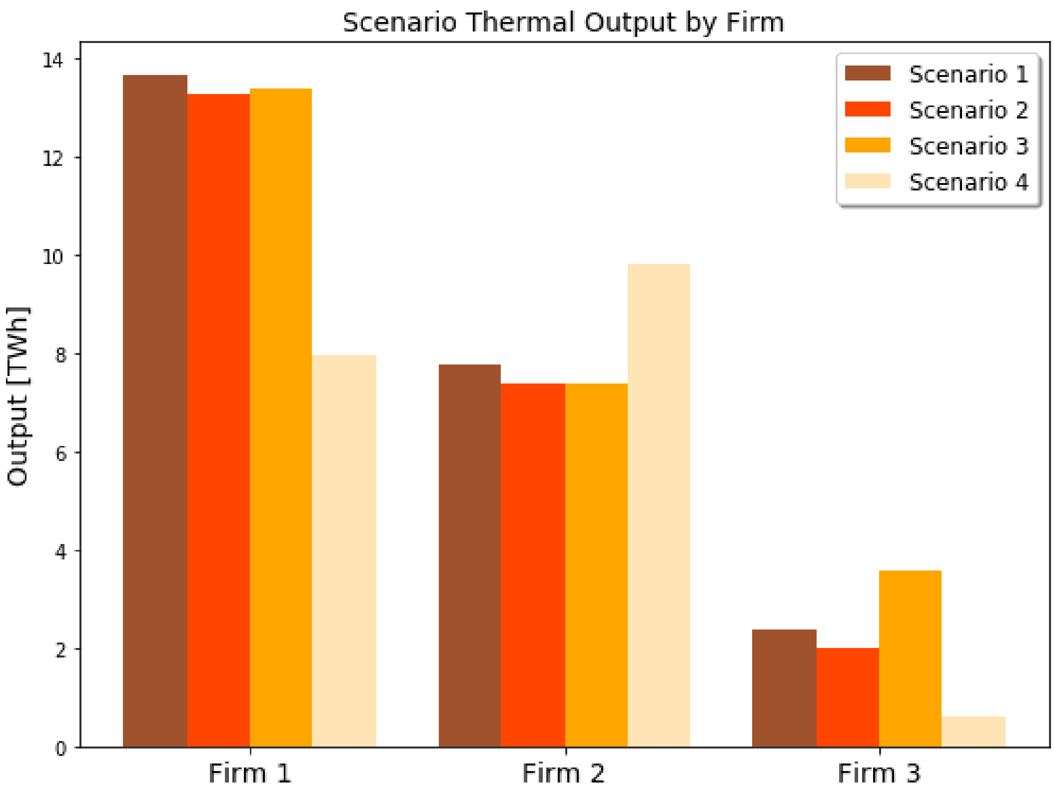


FIGURE 5.5: Scenario Thermal Outputs by Firm

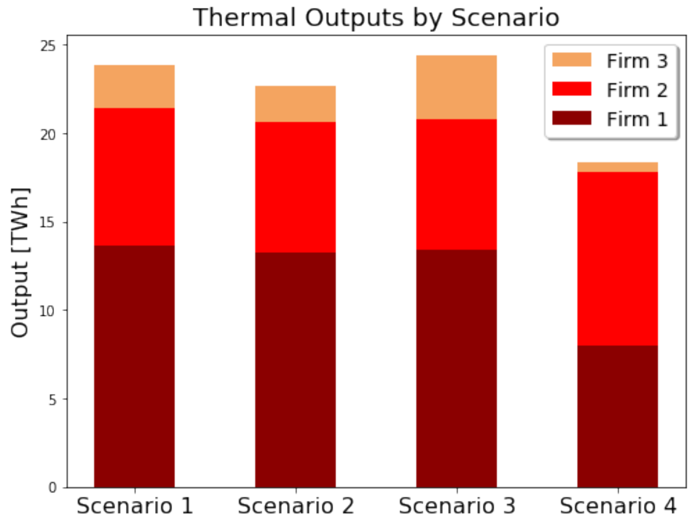


FIGURE 5.6: Thermal Output of each Firm by Scenario

Figure 5.7 shows how the profits of each firm changes by scenario. Firm 1 makes the most profits in each scenario by virtue of the simple fact that it has lower costs than both other firms. However, despite the high market price in Scenario 4, Firm 1 makes a similar level of profits as it does in Scenario 1. In Scenario 4, Firm 2 makes more profits than Firm 3, but in the other scenarios they make similar amounts, despite their different generation portfolios. At certain prices, it is clear that in an oligopoly some firms can benefit more than others, all depending on their relative costs.

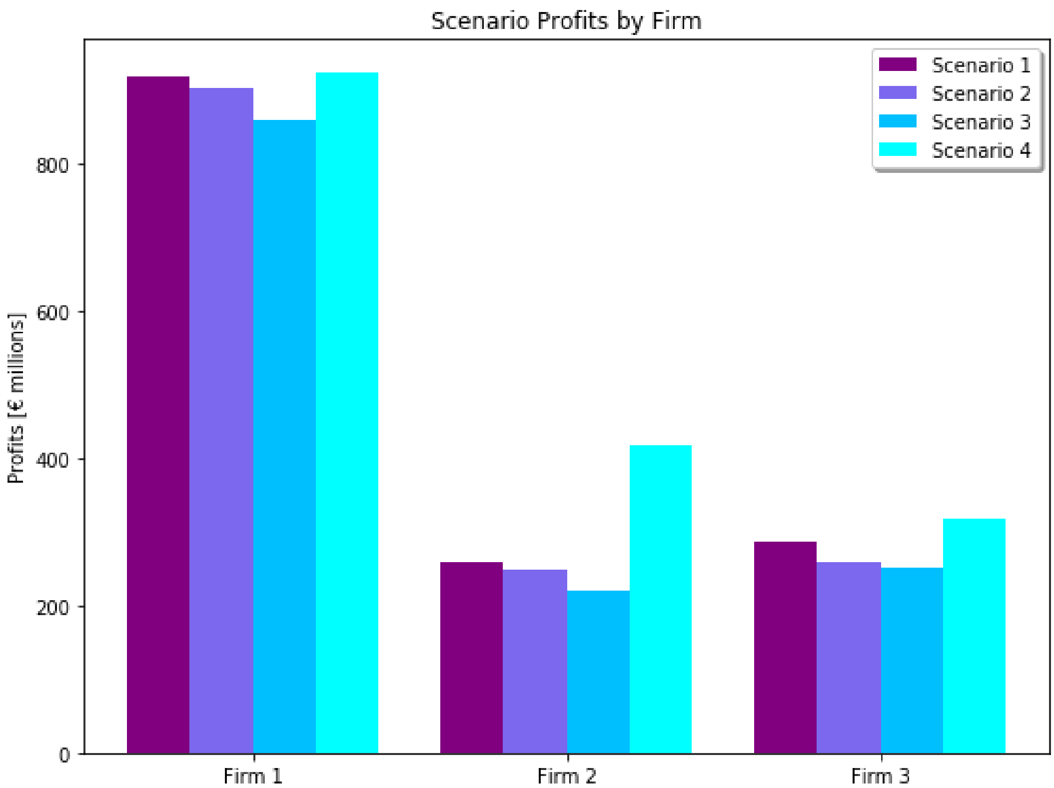
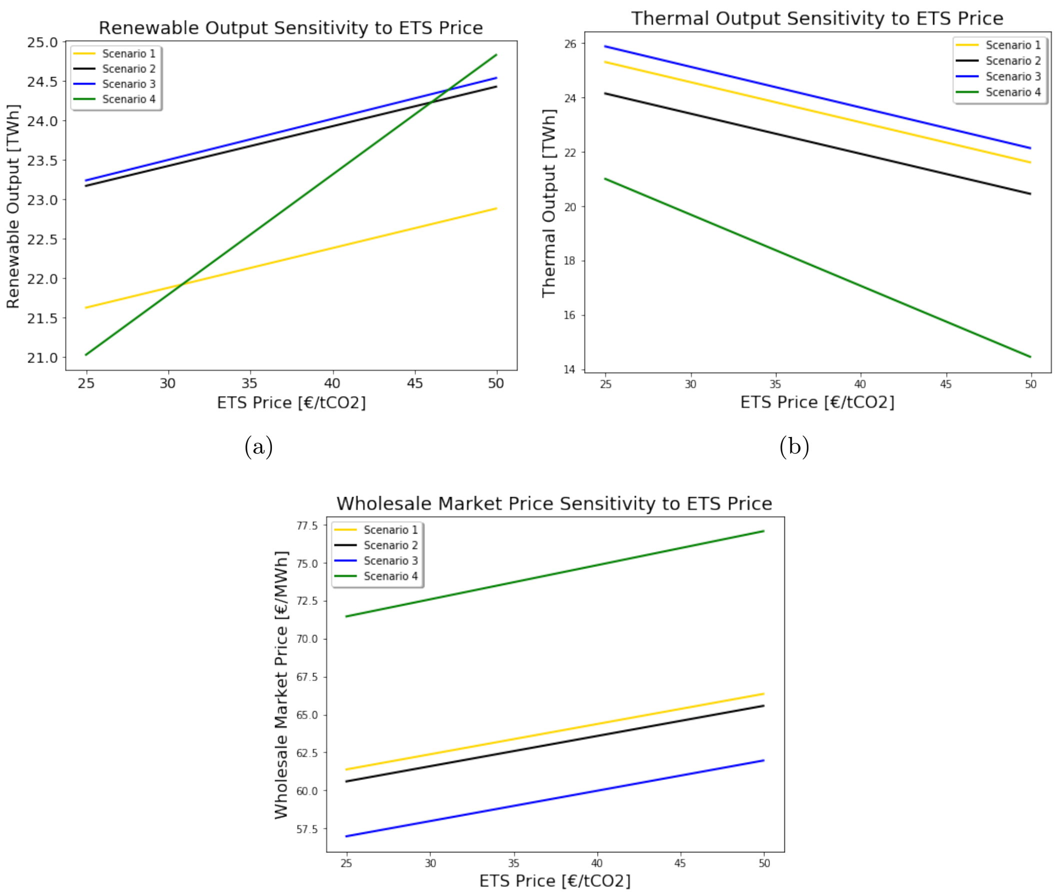


FIGURE 5.7: Scenario Profits by Firm

5.3 Sensitivity Analysis

5.3.1 ETS Carbon Price



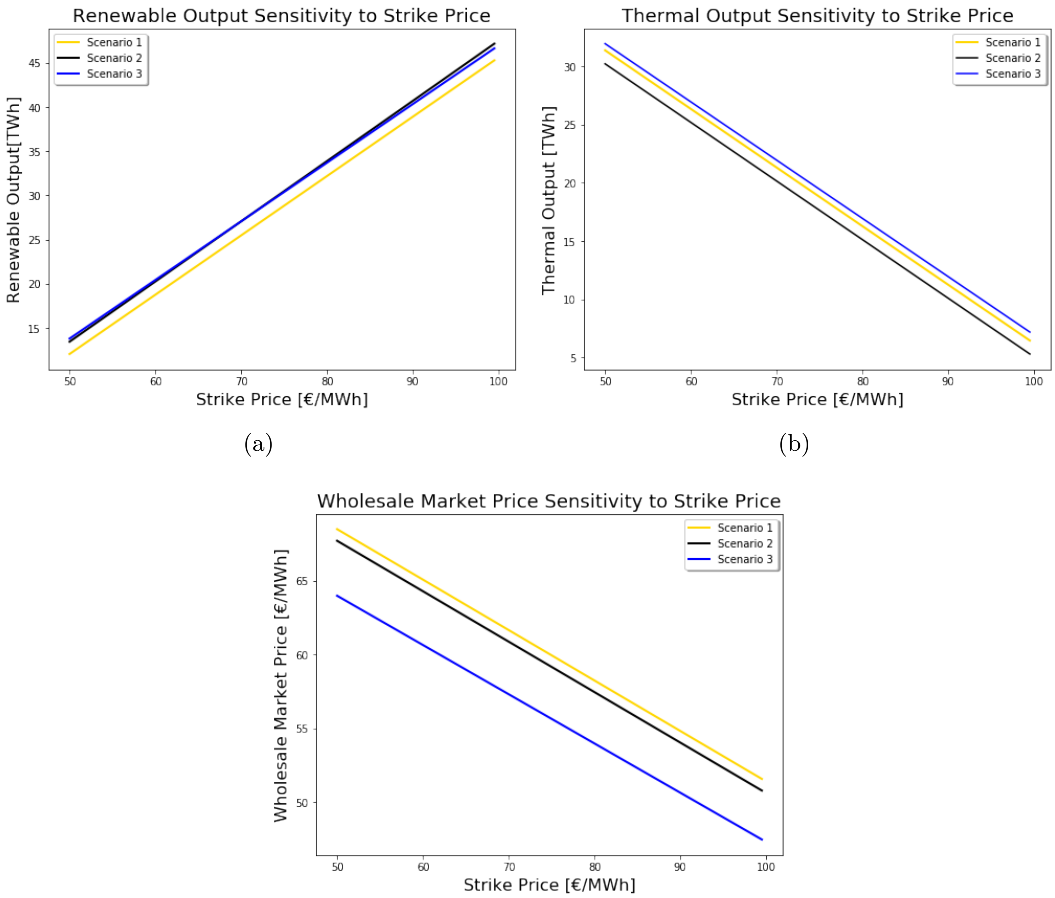
(a) (b) (c)

FIGURE 5.8: Sensitivity to the ETS Carbon Price of (a) Renewable Output (b) Thermal Output and (c) Wholesale Market Price

Both thermal electricity and renewable electricity outputs change with the ETS carbon price, c^{ets}, in all scenarios. As would be expected, the renewable output increases and thermal output decreases as the price of carbon rises. Most notably is the renewable output sensitivity to the ETS carbon price in Scenario 4, which increases much steeper than in the other scenarios. Similarly, thermal output decreases more steeply in Scenario 4 with increasing carbon prices. This demonstrates the important role that carbon prices play in incentivising both investment in renewable electricity and disincentivising investment in thermal electricity generation.

The wholesale market price also notably increases with carbon price at the same rate in every scenario. The increases in renewable output are outweighed by the decreases in thermal output, leading to reduced supply and therefore a higher price.

5.3.2 Strike Price



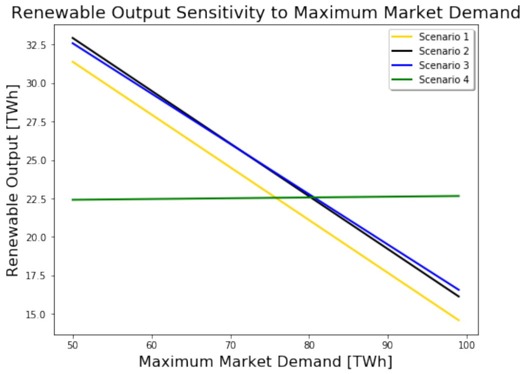
(a) (b) (c)

FIGURE 5.9: Sensitivity to the Strike Price of (a) Renewable Output (b) Thermal Output and (c) Wholesale Market Price

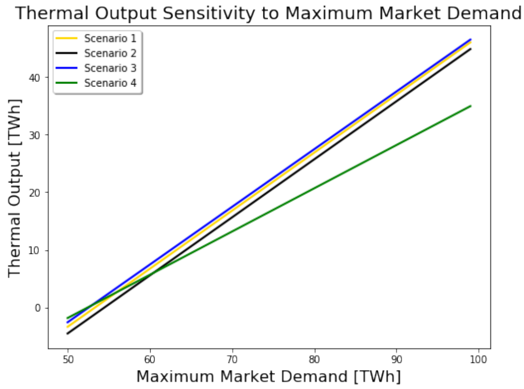
In the scenarios in which the strike price p_s is applicable (Scenarios 1, 2 and 3), the following is observed. Renewable output increases linearly with higher strike price. Therefore, wholesale market price (thanks to Proposition 4.3 (iii)) decreases linearly with strike price. Thermal output reduces linearly with strike price as firms compensate for the increase in renewable electricity such that supply meets demand.

These direct relationship highlight the importance of setting the strike price at the right level to meet climate and social goals. Without a high enough strike price, there will be inadequate investment into renewable electricity and thermal electricity will be used to meet demand, emitting greenhouse gases. However, the price reducing effect of a high strike price also shows that it can increase competition and provide direct financial benefits to consumers.

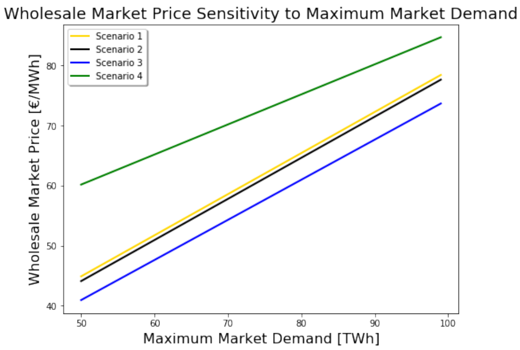
5.3.3 Maximum Market Demand



(a)



(b)

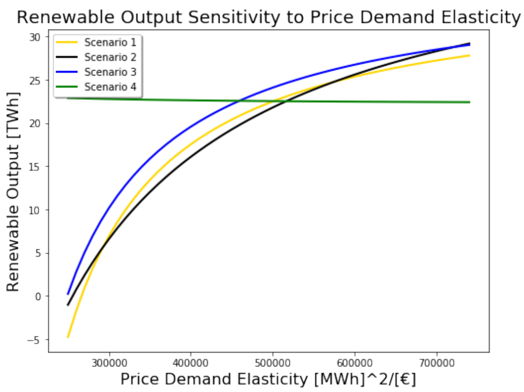


(c)

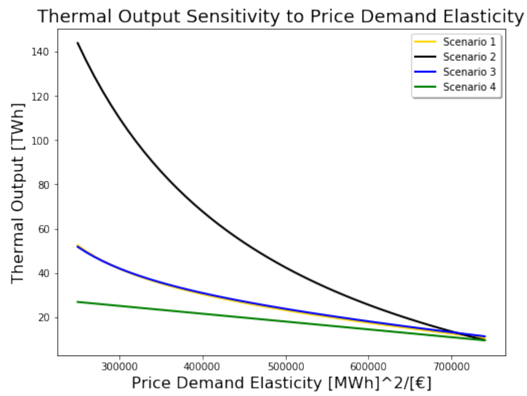
FIGURE 5.10: Sensitivity to the Maximum Market Demand of (a) Renewable Output (b) Thermal Output and (c) Wholesale Market Price

In Scenarios 1–3, the renewable output decreases with increased maximum market demand (parameter `a`), while in Scenario 4, the renewable output is independent of maximum market demand and depends purely on the cost functions. Thermal output increases linearly with maximum market demand in all scenarios. The renewable output decreases because at high outputs, its productions costs increases quickly due to its quadratic cost function. The thermal cost function is linear, so it is more cost effective for the strategic firms to meet the additional demand with thermal electricity. The wholesale market price increases linearly with increased maximum market demand, as would be expected within a neoclassical framework.

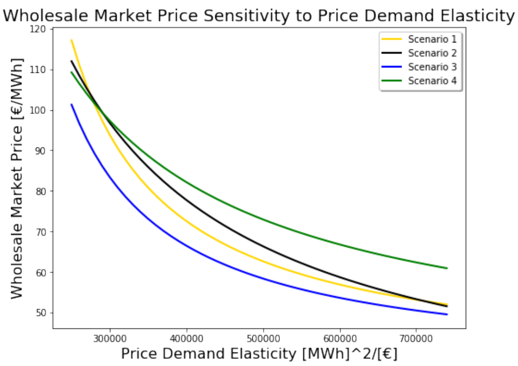
5.3.4 Price Demand Elasticity



(a)



(b)

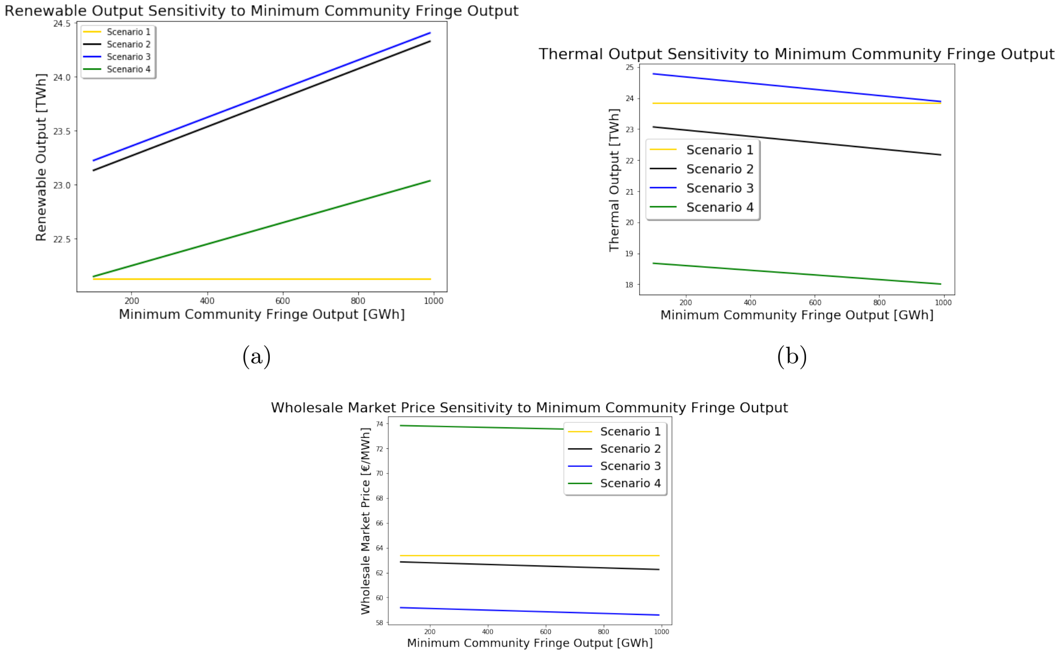


(c)

FIGURE 5.11: Sensitivity to the Price Demand Elasticity of (a) Renewable Output (b) Thermal Output and (c) Wholesale Market Price

In Scenarios 1–3, there is an increase in the total renewable output when the demand for electricity decreases more steeply with an increase in price (an increase in the parameter b). In Scenario 4, renewable output by the strategic firms is independent of the demand parameters, but increased price demand elasticity will slightly reduce market demand, leading to a minor reduction in renewable output. In all scenarios, thermal output decreases with an a more rapid decrease in demand due to changes in price. The same is true for the wholesale market price, thanks to the relationship between renewable output and price described by Proposition 4.3.

5.3.5 Minimum Community Fringe Output



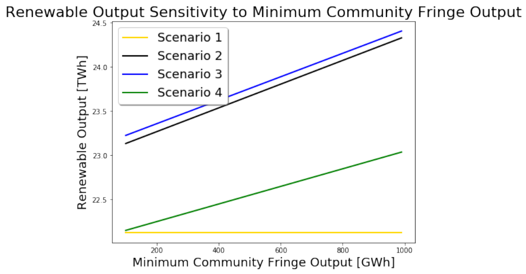
(a) (b)

(c)

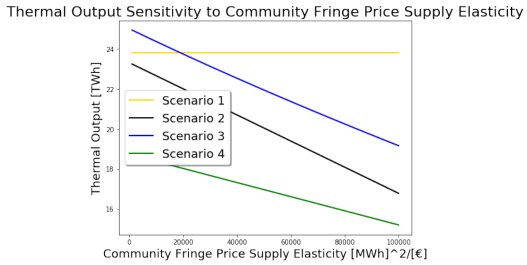
FIGURE 5.12: Sensitivity to Minimum Community Fringe Output of (a) Renewable Output (b) Thermal Output and (c) Wholesale Market Price

In Scenario 1, the community fringe does not output electricity, and so it has no effect on the total renewable output, the total thermal output or the wholesale market price. In Scenario 2, when the community fringe is remunerated with the strike price, the renewable output significantly increases with a higher minimum community fringe output a_f, while the thermal output decreases. In fact, with a higher minimum community fringe output, the renewable output increases and the thermal output decreases in all scenarios apart from Scenario 1. This indicates the emissions reduction benefit of additional community energy. There is a slight price reducing effect from a higher minimum community energy output level in every scenario (apart from Scenario 1), pointing to the additional consumer benefits from community energy that can occur. In general, the community fringe does not provide a significant output of renewable electricity compared to the levels of the strategic firms, and so it cannot have a large effect on the market.

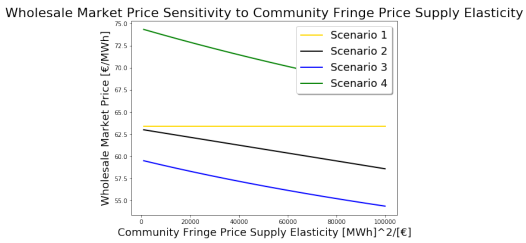
5.3.6 Community Fringe Price Supply Elasticity



(a)



(b)



(c)

FIGURE 5.13: Sensitivity to Community Fringe Price Supply Elasticity of (a) Renewable Output (b) Thermal Output and (c) Wholesale Market Price

Scenario 1 does not alter with community fringe parameters. In the other scenarios, the renewable electricity output increases with larger community price demand elasticity b_f (the rate at which the community fringe increases its electricity output as prices increase), while thermal electricity output decreases. This is because the community fringe produces solely renewable electricity, as as b_f gets larger, the responds to price increases by producing more electricity. In response, the strategic firms reduce their thermal output and increase their renewable output. The price also reduces with increased renewable output, following Proposition 4.3 (iii).

5.3.7 Average Thermal Cost Coefficient

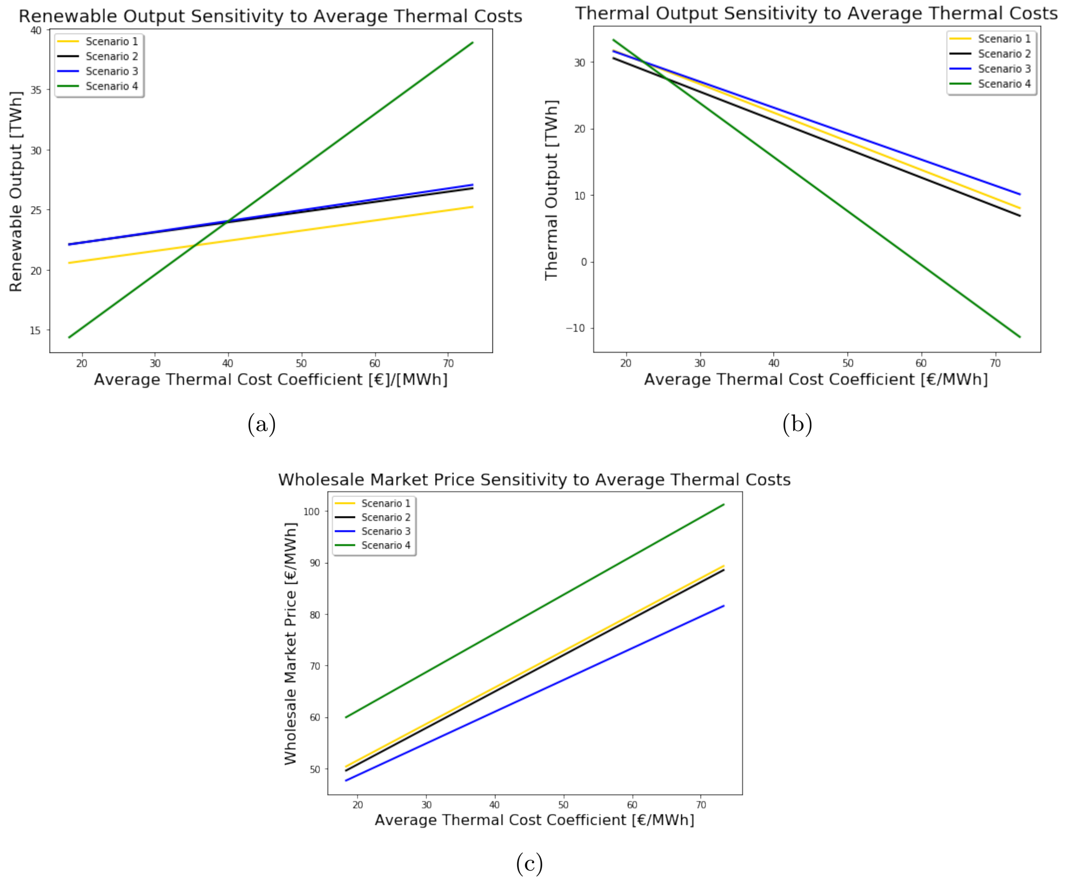
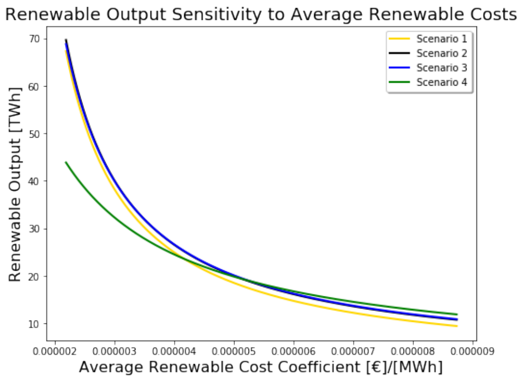


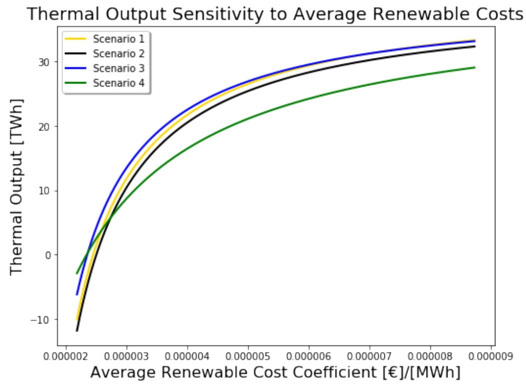
FIGURE 5.14: Sensitivity to Average Thermal Cost Coefficients of (a) Renewable Output (b) Thermal Output and (c) Wholesale Market Price

The sensitivity to average thermal costs is calculated by multiplying each firm's thermal cost coefficient x_i^q by the same amount around the value chosen in Section 5.1. This ensures that the relative costs remain the same. As would be expected, renewable output increases and thermal output decreases with increasing thermal costs. In Scenario 4, when the renewable electricity is remunerated at market price, the firms and community more dramatically replace thermal electricity with renewable electricity as thermal costs increase. The wholesale market price increases with average thermal costs as the supply of electricity falls.

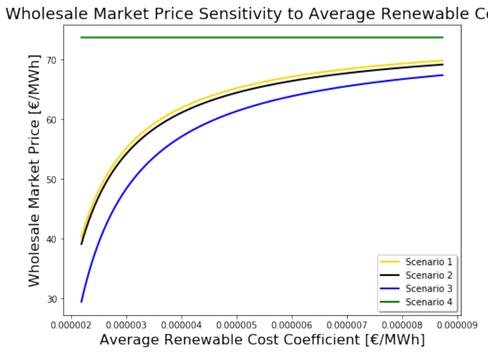
5.3.8 Average Renewable Cost Coefficient



(a)



(b)



(c)

FIGURE 5.15: Sensitivity to Average Renewable Cost Coefficients of (a) Renewable Output (b) Thermal Output and (c) Wholesale Market Price

The sensitivity to average renewable costs x_i^r is determined in the same way as the average thermal costs. Unsurprisingly, renewable output decreases with increasing renewable costs costs while thermal output increases to compensate for this. The wholesale market price increases with renewable costs in Scenarios 1,2, and 3 as the electricity supply falls. Interestingly, in Scenario 4, because both renewable and thermal output decrease and increase respectively by the same amount (see Proposition 4.3 (i) and (iii)), essentially cancelling one another out to leave the wholesale market price constant.

Chapter 6

Discussion

The results of the numerical illustration of the stylised oligopoly model of the Irish electricity industry have some interesting implications. It is important at this point to restate that these numerical illustration results are not intended to be a quantitative projection of the future Irish electricity industry structure, but rather to provide insight into the possible implications of the incentive policies used to encourage certain economic actors to generate renewable electricity. Section 6.1 discusses the robustness of these insights, addressing the economic assumptions and approximations that underlie the model, its dependency on parameters, and the plausibility of the results it produces. Section 6.2 takes a look at the climate, economic and social implications of the model. Section 6.3 then speculates on the future of the Irish electricity sector, extrapolating from the implications suggested by the model and noting other challenges and opportunities that may occur as the energy transition proceeds.

6.1 Robustness

6.1.1 Abstraction and Economic Assumptions

The model's level of abstraction and core economic assumptions determine the interpretation of its propositions and of the numerical illustration. Regarding the level of abstraction, it is first important to note that no distinction is made between the installation of electricity generation capacity by the strategic firms and the use of that capacity to generate and supply electricity to the wholesale market. The model abstracts beyond this distinction and assumes that firms will select what capacity to install and will make use of all installed capacity. This differs from the model by Genc and Reynolds (2019), who assume all available renewable capacity is utilised, since the marginal cost of renewable electricity supply is approximately zero. However, the analysis in this thesis is explicitly interested in the effects of incentivising community energy on the levels of renewable electricity in the electricity system. Therefore, it was necessary to allow firms to select what level of renewable capacity to install.

The strategic firms optimise their equilibrium outputs of thermal and renewable electricity to maximise profits. The parameters that set the wholesale market demand are determined exogenously, and neither the complexity of the I-SEM nor the relationship between electricity producers and suppliers are explored. Such a level of abstraction is necessary to ensure the model can provide insights into the climate, economic and social implications of incentivising community energy. Within the micro-economic industrial organisation framework, which lends itself to highlighting the issues of market power, the addition of further complexity could obscure the underlying relationships that are of interest to the thesis research question.

The structure of the model follows the assumptions of neoclassical economics. Each firm has *complete information* regarding the costs and objectives of every other firm, and of the community fringe too, and regarding the nature of the wholesale market demand for electricity. Each firm selects what production capacity to utilise based on the cost parameters of its own firm and the other firms, as well as parameters that decide the behaviour of the competitive fringe. Furthermore, the model assumes each strategic firm and the competitive fringe act with *perfect rationality*. The firm and community managers choose their equilibrium outputs to maximise profits. For individual consumers however, these assumptions of complete information and perfect rationality can be strongly critiqued. The field of behavioural economics has demonstrated that consumers instead act with bounded rationality on imperfect information (Jolls et al., 1998). These bounded rationality assumptions apply to firm managers too, but it can be argued that firm managers have far more complete information than the average consumer, especially regarding the costs and capabilities of rival firms in a well documented industry such as the electricity business. The objective for firm managers, that of maximising profits, is also far more clear and actionable than the utility maximisation objective of consumers.

The model utilises a Cournot competition framework in which each firm in the oligopoly compete for market share by independently choosing a quantity of their identical commodity, in this case electricity, to produce simultaneously. The model has numerous advantages, notably in its abilities to produce logical results regarding outputs and price, while yielding stable equilibria. Applying Cournot competition models to the electricity market is well established in the literature (Twomey and Neuhoff, 2010; Filomena et al., 2014; Acemoglu et al., 2017; Genc and Reynolds, 2019).

The choice of three strategic firms to make up the Irish oligopoly was based on the market shares of Electric Ireland, Bord Gáis Energy and SSE Airtricity provided in Section 3.2.3. There are numerous other small firms in the Irish electricity market which sell electricity on the wholesale market, such as Bord na Móna and Energia. However, the intention with this stylised model is not to provide a quantitative projection of the outputs of each firm in the year 2025. That goal would require a representation of each firm. Instead, the model set out to provide insight into the qualitative changes that may occur in the Irish electricity sector if more community energy is incentivised.

Assumptions about the functional form of the key variables are also important to discuss. Firstly, linear market demand and linear fringe supply are assumed. Locally, these can be considered reasonable approximations. The law of demand suggests that demand for a certain good decreases with an increase in the price of that good. There is no reason to believe electricity is any different in this regard. For small, local changes, therefore, a linear decrease in demand is a reasonable assumption. However, for larger changes in price, the wholesale market demand almost certainly changes in a non-linear fashion. A range of alternative functional forms for market demand could be selected, but to ensure tractability a straightforward linear market demand function was chosen. This is standard practice in micro-economic analyses of electricity markets (Baldick and Grant, 2004).

The approximations of the cost functions for thermal output and renewable output are also chosen to ensure the model remains tractable yet also mirrors reality to a reasonable degree. The motivations for the linear cost function for thermal output and quadratic cost functions are described in Section 4.1.

6.1.2 Plausibility of Results

The results of the model will now be compared to empirical reports and projections from reputable sources to offer an assessment of the plausibility of the results produced by the numerical illustration. These results are not intended as quantitative projections of the future state of the Irish electricity sector, but instead as a way to gain insights into the dynamics of the sector during the energy transition.

Prices

The CRU provides bi-annual updates on wholesale electricity prices (Commision for Regulation of Utilies, 2019). In 2019, the system marginal price for the first half of 2019 was approximately 53 [€][MWh]$^{-1}$. Considering electricity prices are expected to rise over the coming years due to increased levels of RES-E, the average wholesale market price in the numerical illustration of 64.62 [€][MWh]$^{-1}$ appears plausible.

Emissions and RES-E Percentage

The Environmental Protection Agency's 2019–2040 emission projections include, for the year 2025, emissions from the energy industries in the range of 7–8 million tCO_2 (Environmental Protection Agency, 2020c). The numerical illustration outputs an average of 6,693,037.25 tCO_2, which is extremely close to the projected range.

Ireland's RES-E target for 2030 is to produce 70% of electricity from renewable energy sources. The RES-E percentage in each scenario is provided in Table 6.1 below. Considering Ireland reached 33.2% RES-E in in 2018 (Sustainable Energy Authority of Ireland, 2019), these percentages are a plausible trajectory for the decarbonisation of Irish electricity generation.

	RES-E %
Scenario 1	48.2 %
Scenario 2	51.1 %
Scenario 3	49.4 %
Scenario 4	55.1 %

Table 6.1: Scenario RES-E Percentages

Market Demand

Each scenario also outputs wholesale market demand, based on the wholesale market price and the demand parameters. The values for market demand across scenarios are provided in Table 6.2, with an average value across scenarios of 45.3 [TWh]. This is within the range of 44.6 [TWh] and 52.6 [TWh] forecasted by EirGrid and SONI in their All-Island Generation Capacity Statement for 2019 to 2028 (EirGrid & SONI, 2019).

	Market Demand [TWh]
Scenario 1	45.9 [TWh]
Scenario 2	46.3 [TWh]
Scenario 3	48.1 [TWh]
Scenario 4	40.9 [TWh]

Table 6.2: Scenario Market Demand

6.2 Model Implications

The model implications are discussed first from a climate perspective, then an economic perspective, and finally a social perspective.

6.2.1 Climate and Energy Implications

As discussed in Chapter 1, rapidly decarbonising electricity generation is a critical milestone on the path to a zero-carbon economy. This decarbonisation is the motivating reason for incentivising electricity generation from renewable sources. There are two quantities in the numerical output that can be seen as relevant to the climate perspective: the emissions level and the RES-E percentage. Ireland's national target for renewable electricity by 2030 is 70%.

Comparing the emissions in each scenario in Figure 5.2, the introduction of the community fringe in Scenario 2 has the effect of driving down thermal output, and therefore emissions, compared to Scenario 1. Correspondingly, the RES-E percentage also increases, from 45.9% in Scenario 1 to 46.3% in Scenario 2, primarily due to the additional electricity from the community fringe. These changes are thanks to the community fringe reducing the residual demand that the strategic firms must meet with their supply. Even with the same ratio of thermal to renewable output by the strategic firms in such a situation, overall thermal falls, as do emissions.

In Scenario 3, the emissions are at their highest level. The community fringe participation in the wholesale market causes the strategic firms to select a higher total thermal and renewable electricity output to result in a lower wholesale market price. This lower wholesale market price leads to a higher market demand, as seen in Table 6.2. However, the RES-E percentage is also greater than the in Scenario 1 (48.1% compared to 45.9%. So, despite the fact that emissions are higher (only 2.3% higher compared to Scenario 1), more progress is made toward the RES-E targets.

Emissions are lowest and the RES-E percentage is highest in Scenario 4, by significant amounts. At first glance, this might suggest that the sale of renewable electricity on the wholesale market without any state support will incentivise greater use of renewable electricity, provided the costs of renewable technologies are sufficiently low compared to conventional thermal technologies. However, there are economic complications to this implication, discussed in Section 6.2.2, that may be undesirable.

The theoretical oligopoly model and the results of its numerical illustration imply that incentivising community energy will have direct consequences for climate and energy targets by reducing thermal output of the strategic firms and installing additional renewable capacity. Provided the costs of renewable technologies are low enough, the model further implies that the sale of renewable electricity on the wholesale market is the best incentive for cutting electricity industry emissions and incentivising renewable technology installation.

6.2.2 Economic Implications

While it is urgent that the energy transition is incentivised, it is also vital that it follows the principles of a just transition (Jasanoff, 2018). This means that no group in society is adversely affected or left behind during the energy transition. Through this lens, both the wholesale market price and the profits of the strategic firms are important quantities of the model to consider. In the Cournot framework, the market price (and the associated outputs) provides an indicator as to the levels of market power at play. High price and low output suggest undesirable levels of market power.

Conversely, it is a matter of concern if strategic firms are expected to lose significant profits. This concern could affect the implementation of policy proposals for two reasons. Firstly, to protect the interests of their shareholders, firms will lobby against policies which cut their profits. Secondly, reduced profits may lead to job losses, which could create political controversies, with workers livelihoods threatened. This would require compensation from government and the implementation of retraining programs to provide workers with the skills required to continue working in a rapidly changing industry. This issue, in a closely related case, has been centre stage in Irish climate and energy policy in recent years. Bord na Móna, the Irish peat company, will be forced to make many staff redundant as a result of a government decision to close down their peat-fired power plants to shut. A Just Transition fund has been established to retrain many of the Bord na Móna workers.

The wholesale electricity price remains relatively stable across each scenario, but there are some important changes to consider. The wholesale price falls slightly in Scenario 2 compared to Scenario 1, thanks to the introduction of the community fringe. This suggests a small double-dividend effect, in which the people involved in the community energy scheme benefit directly from its operation, while the wider public benefits from lower electricity prices and lower emissions. This change in wholesale price corresponds directly to a small drop in profits for each firm, but the change is not dramatic.

In Scenario 3, the community fringe competes on the wholesale market but the strategic firms continue to be remunerated for their renewable electricity at the strike price. This leads to the most competitive situation, in which the most electricity is supplied at the lowest price. From a social welfare perspective, low price and high output are a positive outcome. However, as discussed in Section 6.2.1, due to the additional thermal output, emissions are highest. The firm profits are also lowest in this scenario, leading to concerns of political viability.

Market power is highest in Scenario 4, with all electricity sold on the wholesale market. The wholesale market price is at its highest and total output is at its lowest. From an economic perspective this is undesirable, as the consumers pay more money for less electricity, highlighting the importance of increased competitiveness in electricity markets. The profits of each firm are largest in Scenario 4 too, drawing attention to an important socio-economic issue in the energy transition. As renewable technology costs continue to fall, there is the possibility of the economic benefits of the energy transition accruing to a small number of energy industry shareholders rather than the wider public. These results echo the findings of Acemoglu et al. (2017), who demonstrated using an industrial organisation model social benefits of renewable electricity are reduced if it is produced by the strategic firms who also use thermal generation.

It is interesting to note that in Scenario 4, Firm 3, which has the most expensive thermal costs but whose renewable costs are between those of the other firms', has vastly lower thermal outputs than in other scenarios, but does not compensate with additional renewable output. Contrastingly, Firm 2, which has high renewable costs but mid-range thermal costs, has its highest thermal output in Scenario 4 but only slightly increases its renewable output. This is demonstrative of how relative thermal and renewable costs determine the production strategies of each firm.

While the sensitivity analysis in Section 5.3 reveals the expected qualitative results, from an economic policy perspective the effect of an increased carbon price on renewable and thermal output is notable. From Figure 5.8, it is clear that in Scenario 4 especially, an ETS carbon price of 50 €/tCO_2 would be a sufficient incentive for electricity firms to produce more renewable than thermal electricity.

Analysing the wholesale market prices and profits of each firm shows that the highest market power occurs in Scenario 4, which also has the least emissions and the highest RES-E percentage. Therefore, the model implies a trade-off between market power and renewable electricity generation. The Irish state, and its regulatory bodies such as the CRU, should be wary of such circumstances as the energy transition proceeds in the later years of this decade.

In the first three scenarios, the strategic firms receive a fixed price for the renewables but sell their thermal electricity at market price. This means that if demand increases and drives up the wholesale market price above the strike price, firms would prefer to be selling electricity that is not covered by the scheme. This means there is an incentive for firms not to over-invest in renewable technologies if they think the market price will be above the strike price more often than not. However, it is the firms themselves who set the strike price in the RESS auctions. Analysing the strategic interactions that set this price is beyond the scope of this thesis.

6.2.3 Social Implications

The climate, energy and economic implications of the model and its numerical illustration addressed in the sections above converge when the focus is placed on their combined social effects. Consumers across Ireland will benefit from a competitive electricity industry if prices remain low and output remains high, but they will be negatively affected if Ireland does not adequately cut its emissions and reach its RES-E targets. There are health consequences for the population of continued greenhouse gas emissions and other pollutants, while fines from the EU for failing to reach the targets will reduce the Irish state's capability to provide public services. Yet, the social implications of the model go deeper than these issues. While over 95% of Irish people acknowledge that climate change is a real and dangerous threat (European Commission, 2019c), there is still progress to be made regarding trust in and acceptance of climate and energy policies. Uncertainties as to who will benefit most from the energy transition contribute to this lack of public acceptance. Ireland also has a significant problem regarding energy poverty.

The development of community energy could be a remedy for public doubts around the energy transition and widespread energy poverty. Increasing levels of community energy could have transformative social effects, enhancing the effects of decentralisation in the energy transition by heightening public participation and local democracy (Capellán-Pérez et al., 2018). However, this participation is contingent upon citizens having the time and capital to invest in such projects. It is vital that these issues are addressed through innovative measures that offer the opportunity of investment to all income groups in a community (Johnson and Hall, 2014).

The largest percentage of electricity generated by the fringe is in Scenario 4, where the highest price is available to the fringe. However, in this scenario the largest profits are also accrued by the strategic firms. While these profits are not necessarily a negative indicator, they do evoke questions about whether the benefits of the energy transition will be equitably distributed in the current Irish policy regime.

The implications of the model suggest that incentivising and facilitating community energy schemes lead to both emission reductions effects and economic benefits. While RESS includes community criteria that all renewable projects must meet, it is scant on detail regarding how many community energy projects that meet the definition provided by Klein and Coffey (2016) will be supported. Support for such a distributed energy system will require policies to guide the necessary institutional changes, with new roles for local government, a range of regulatory and safety requirements, and overcoming a range of technical obstacles such as delivering smarter grids (Johnson and Hall, 2014).

6.3 The Future of the Irish Electricity Sector

Some of the most significant changes of the energy transition are likely to unfold in the decade 2020–2030. For Ireland, a country whose dependence on fossil-fuels for electricity generation has waned since the 2000s with the growth of the wind industry, these changes will likely involve incentivising continued investment in renewable energy technologies, managing increasing levels of variable electricity generation from renewable sources on the grid and encouraging electricity consumers to become active energy citizens who participate in community energy schemes. The following section will speculate on the future of the Irish electricity sector, discussing the various incentive policies and market designs that may be implemented during the energy transition, the process of decentralisation and the role of distributed generation and community energy, as well as the technical challenges of the smart grid.

6.3.1 Incentive Policies and Market Design

The RESS is set to continue until at least 2025, at which point the last auction listed on the most recently available timeline (as of July 2020) will be complete. Scenario 1, considered a baseline in the numerical illustration, will not occur in reality as the community category for these auctions is now in place. A competitive fringe of community energy schemes utilising distributed generation technologies is guaranteed to be operating at some level by then, and therefore the electricity industry will be closer to Scenario 2, at least.

As outlined in the CRU's information paper (Commission for Regulation of Utilities, 2020), supports for microgeneration (<11KWh) are intended to be in place from 2021. This can be considered the introduction of a new incentive policy which could lead to a variety of market changes, such as the appearance of electricity aggregators who gather electricity production from households and sell it into the wholesale market. This could look to Scenario 3, in which a fringe of renewable electricity producers are remunerated at market price while the strategic firms continue to receive support from the RESS. The addition of these microgenerators and the high-levels of variable renewable electricity that will come with them, will require changes to market design on the European, national and local levels.

Newbery et al. (2018) provide policy recommendations for a European-level wholesale market design for a high-renewables system. They recommend more interconnection between EU Member States, while incentivising RES-E through capacity auctions as is done with the RESS. The paper also highlights an issue that arises when distributed generation technology is combined with batteries. If network charges are measured only by the amount of grid electricity consumed, wealthy consumers with distributed generation and energy storage will be able to benefit from the grid when necessary, but can avoid paying charges most of the time. This coud leave poorer customers paying more tariffs, unless a tariff reform is enacted. Ireland will need to be wary of such distributional effects as it shapes the market for a more decentralised energy system.

Parag and Sovacool (2016) outline potential market designs at the local level for increased distributed generation. Three potential prosumer market structures are described: peer-to-peer models, prosumers-to-grid models, and organised prosumer groups. Each is illustrated in Figure 6.1. The first option is the most organic and least structured market proposal, which involves contractual relationships for different services between agents, such as production, storage and consumption. These agents could be individuals, households or businesses. This is a highly bottom-up approach, and would involve prosumers competing directly with the strategic utilities for clients. The second model is a more structured approach that proposes a microgrid connected to the main grid. The final proposal seems the most likely to develop in the Irish context, whereby organised groups such as a community pool their prosumption resources into virtual power plants to generate revenue. Many of these proposed market designs may require the use of innovative digital technology solutions, such as employing Blockchain technology to record energy and electricity transactions (Dong et al., 2018). Zepter et al. (2019) investigate how a digital technology platform can be utilised to integrate prosumer communities into the wholesale electricity market, and show through a study on residential buildings in London that peer-to-peer trading and battery storage may lead to savings of up to 60%.

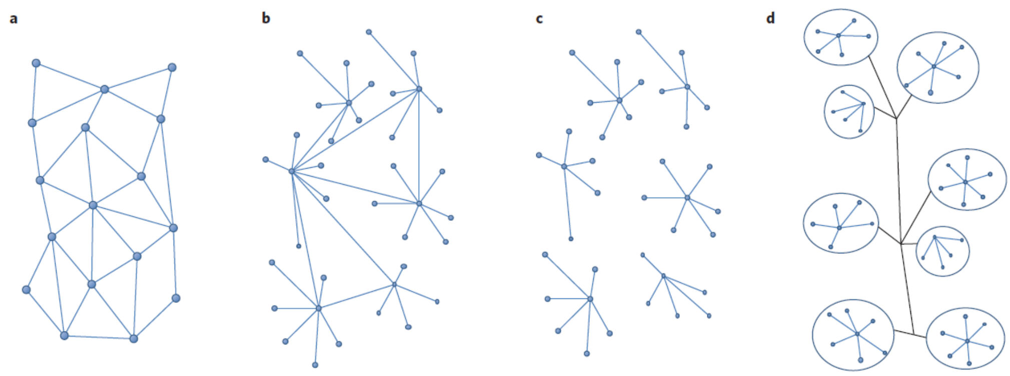


FIGURE 6.1: The structural attributes of four prosumer markets: (a) peer-to-peer model, (b) more structured approach that involves prosumers providing services to a microgrid that could be connected to a larger grid, (c) or operate as microgrid islands, (d) organised prosumer group model (Parag and Sovacool, 2016).

6.3.2 Decentralisation, Distributed Generation and Community Energy

One of the energy ambitions clearly stated by the Irish government is to have a larger degree of decentralisation in the energy system with increasing levels of distributed generation and numerous community energy schemes. One concern about such decentralisation is the possibility of *energy sprawl*, under which available land is occupied to build new energy facilities. Moroni et al. (2016) argue that this will not occur if distributed energy systems based on micro-plants (collections of PV panels on rooftops in a community scheme, for example) and micro-grids are implemented. They describe these innovations as combining to create a new energy system with *multi-layered density* combining technology, organisation and physical nodes of electricity generation. To realise the government's ambitions for distributed generation, new policy measures will be required, such as those suggested by Moroni et al. (2016), like removing protectionism for centralised production methods, changing local land use regulations to facilitate micro-power plant installations, and updating regulatory procedures to allow for a variety of contractual community schemes.

Mehigan et al. (2018) at University College Cork looked at distributed generation, describing the possible "topologies" of future electricity systems, for example *centralised with increased decentralisation* or *fully decentralised.* They also discussed the factors that might influence the role of distributed generation, such as existing infrastructure, technological change, and regulatory and political factors. Ireland appears well suited to distributed generation development from a geographic perspective with abundant wind resources (Goodbody et al., 2013) and adequate solar incidence for the economic feasibility of solar PV (Murphy and Mcdonnell, 2017).

The community energy schemes approximated by the competitive fringe in the oligopoly model could have a profound effect on the future of the Irish electricity sector. The details on how such community energy schemes emerge is worth speculating on, but is subject to inherent uncertainty since they depend on a multitude of factors. Ireland could follow some of the approaches taken in other countries.

Spain has seen the emergence of many renewable energy cooperatives, based on the well-established legal business form of cooperatives that has been long associated with agriculture and finance (Heras-Saizarbitoria et al., 2018). Citizen power plants – wind farms and photovoltaic plants owned and operated by groups of citizens – have emerged in Austria (Schreuer, 2016). Community energy has also received significant policy support in the UK (Seyfang et al., 2013). The Samsø Renewable Energy Island in Denmark has received widespread attention for its rapid energy system transformation. Sperling (2017) explored the reasons for its success, highlighting the importance of a strong, clear national energy policy and the active participation of the local community. Learning from international approaches to community energy will no doubt benefit similar endeavours in Ireland.

Some community energy schemes are already in place in Ireland, such as the Templederry wind farm, the Dingle Sustainable Energy Community, and the Aran Islands Energy Co-op (Figure 6.2). These pioneers can lead the way in community energy models that can be adopted in other places across Ireland, but they will require policy and regulatory support in the process. A proposal was jointly put forward by Friends of the Earth, the Tipperary Energy Agency and Dingle Sustainable Energy Community regarding community engagement in Ireland in the energy transition. They outline arrangements for local-governments, local energy agencies and market supports to facilitate the growth of community energy during the energy transition in Ireland (Donnelly et al., 2019).

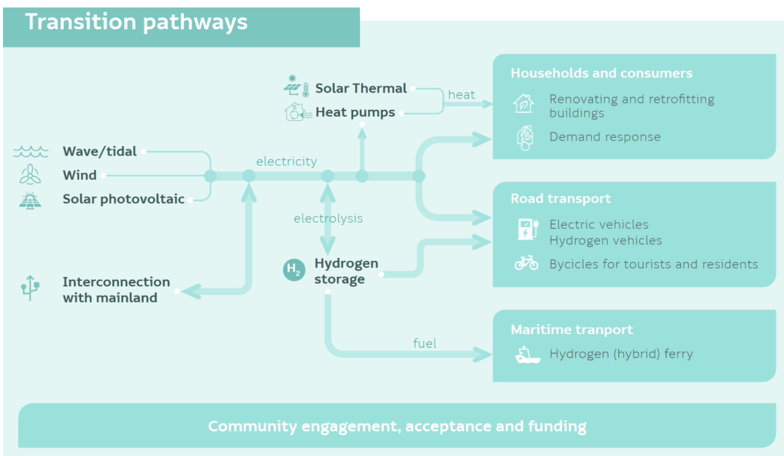


FIGURE 6.2: The vision for the clean energy transition pathway by the Aran Islands Energy Co-op (*Aran Islands Energy Co-op*).

In terms of infrastructure, interconnection with other grids exists and future interconnection is underway, but allowing for bi-directional power flows is as yet not possible. Installing smart meters in homes and businesses will be a key technical step to facilitating distributed generation. Smart meters will allow energy consumers to become actively participating energy citizens, enable the development of the smart grid, and unlock the potential of energy communities. The CRU is responsible for coordinating the roll-out of smart meters across Ireland in the National Smart Metering Programme (Commission for Regulation of Utilities, 2017). There are three phases in the plan, beginning in 2019 and set for completion in 2024, ultimately installing 2.25 million smart meters across the country. Scenario 4 in the numerical illustration (Chapter 5) has the highest level of fringe electricity generation. In a situation akin to Scenario 4, in which there are significant levels of fringe production of renewable electricity, smart demand response will be critical to using electricity efficiently on national and community levels.

From a policy point of view, while Ireland is preparing to remunerate microgeneration (Commission for Regulation of Utilities, 2020), and intends to support community energy through the RESS, these plans are yet to become a reality. As is clear from the model implications discussed in this chapter, many issues with market design will need to be overcome if Ireland is to reach high levels of decentralisation and distributed renewable electricity generation.

Chapter 7

Conclusion

This thesis offers an insight into the effectiveness the current incentive policies in place in Ireland for the generation of electricity from renewable sources and the economic implications for Ireland's electricity industry of incentivising the development of community energy. The stylised oligopoly model implies that a trade off exists between promoting renewable electricity capacity installation and increasing market power for the established strategic electricity firms in Ireland's electricity market during the energy transition.

The implications of the numerical illustration of the model are used as a basis to argue that increased decentralisation of electricity generation through distributed technologies utilised in community energy schemes is not only a necessary feature of the energy transition from a technical point of view, but also has climate, economic and social benefits. In the case of Ireland, the existing renewable electricity policies serve to incentivise renewable electricity capacity installation in both a centralised and decentralised fashion, by supporting both strategic firms and community energy, respectively. It is shown that there is a potential for strategic firms to disproportionately benefit from renewable electricity support schemes compared to distributed generation in community energy programs.

As with every model, what is omitted is as important as what is included. To make a stylised model tractable, it is necessary to make a number of assumptions and approximations. A number of possible improvements to the model will now be noted to point to where the research could go from here, followed by related areas of potential research.

Firstly, empirical work could be done, in a similar manner to Genc and Reynolds (2019) with their Cournot competition model, to determine the parameter values and the cost function structures. This would likely produce more precise wholesale market prices and electricity outputs. The emission coefficients for each firms could also be empirically investigated, thereby accounting for the differences in ETS carbon price that must be paid for more carbon-intensive forms of electricity generation such as coal and peat-fired power plants compared to gas-fired power plants.

Following Dressler (2016), forward markets could be included to introduce an additional layer of complexity that corresponds directly to the real market structure. This could investigate whether the results found by Allaz and Vila (1993) hold to the same degree in the market structure and policy regime of the Irish electricity industry.

The import of electricity via interconnectors could also be modelled as this, in addition to the competitive fringe, would reduce the residual demand faced by the strategic firms. Ireland's grid is interconnected with the UK grid in two locations, and set to be further integrated with the French grid with the Celtic interconnector. There is the possibility that this would have the effect of mitigating the market power effects seen in Scenario 4, for example.

One key quantity that determines the implications of the model utilised in this thesis is the strike price. This is set by the RESS bidding auctions. Understanding the strategic interactions of established firms in this bidding process could shed further light on the incentives in place under this auction-based support scheme. Such research could provide a more holistic view of electricity producer strategies in the Irish electricity industry.

Another area of research touched upon in this thesis is the distributional effects of energy system decentralisation and increased distributed generation of electricity. While much research is focused on the benefits of decentralisation, with active energy citizens and more flexibility, there are also risks of exacerbated inequalities if these benefits are only available to richer groups in society. Investigating the conditions under which this exacerbation could occur in the Irish context, identifying policies to avoid and potentially reduce inequality due to energy system decentralisation, and highlighting the possible widespread benefits from such policies, would be a valuable contribution to Irish energy policy.

Community energy clearly shows the potential for significant environmental, economic and social benefits. Community energy schemes are developing around the world, with many different approaches under trial. But without evidence-based renewable electricity incentive policies that take into account distributional issues and market power, it is possible that these benefits will not be fully realised. The goal of this thesis is to contribute the emergence of community energy and its associated benefits by adding to the knowledge base on the topic in Irish and international energy economics research.

Appendix A

Explicit Scenario Solutions

A.1 Scenario Systems of Linear Equations

The system of linear equations for each scenario are obtained from the profit maximisation procedure for Firm i. For Scenarios $l = 1, 2, 3$, substituting the inverse demand function, Equation 4.1, into the thermal first-order condition, Equation 4.7, gives an expression for the equilibrium thermal output of Firm i in terms of the equilibrium thermal outputs of Firm j and Firm k. For Scenario 4, Equation 4.1 is inserted into Equation 4.8. Similarly, the inverse demand function, Equation 4.1 is inserted into the renewable first-order condition, Equation 4.9, to obtain an expression for the equilibrium renewable output of Firm i in terms of the equilibrium thermal output of Firm i. This reveals a system of six linear equations in six variables, the equilibrium thermal output and equilibrium renewable output of Firms i, j, k. These systems are presented below.

A.1.1 Scenario 1

Equilibrium thermal outputs are,

$$q_i^* = \frac{1}{2}\left(a - R - q_j^* - q_k^* - b\tilde{x}_i^q\right) \tag{A.1}$$

Equilibrium renewable outputs are,

$$r_i^* = \frac{1}{2x_i^r}\left(p_s - \frac{1}{b}q_i^*\right) \tag{A.2}$$

A.1.2 Scenario 2

Equilibrium thermal outputs are,

$$q_i^* = \frac{1}{2}\left(g - R - q_j^* - q_k^* - b\tilde{x}_i^q\right) \tag{A.3}$$

Equilibrium renewable outputs are,

$$r_i^* = \frac{1}{2x_i^r}\left(p_s - \frac{1}{b}q_i^*\right) \tag{A.4}$$

A.1.3 Scenario 3

Equilibrium thermal outputs are,

$$q_i^* = \frac{1}{2}\left(l - R - q_j^* - q_k^* - m\tilde{x}_i^q\right) \tag{A.5}$$

Equilibrium renewable outputs are,

$$r_i^* = \frac{1}{2x_i^r}(p_s - \frac{1}{m}q_i^*) \tag{A.6}$$

A.1.4 Scenario 4

Equilibrium thermal outputs are,

$$q_i^* = \frac{1}{2}\Big(l - R - r_i^* - q_j^* - q_k^* - m\tilde{x}_i^q\Big) \tag{A.7}$$

Equilibrium renewable outputs are,

$$r_i^* = \frac{\tilde{x}_i^q}{2x_i^r} \tag{A.8}$$

A.2 General Solution

The system of linear equations described above for the general model structure and each scenario were solved using Mathematica.

The equilibrium conventional output for each firm is,

$$q_i^* = -\frac{A_g}{B_g} \tag{A.9}$$

where,

$$\begin{aligned} A_g =& 2hax_i^r x_j^r x_k^r + h^2 a_f x_i^r x_j^r + h^2 a_f x_i^r x_k^r - 6ha_f x_i^r x_j^r x_k^r + h^2 b_f p_f x_i^r x_j^r \\ &+ h^2 b_f p_f x_i^r x_k^r - 6hb_f p_f x_i^r x_j^r x_k^r - 2\gamma c^{ets} x_i^r x_j^r x_k^r - hp_r x_i^r x_j^r - hp_r x_i^r x_k^r \\ &- hp_r x_j^r x_k^r + hx_i^q x_i^r x_j^r + hx_i^q x_i^r x_k^r - hx_j^q x_i^r x_j^r - hx_k^q x_i^r x_j^r - 6x_i^q x_i^r x_j^r x_k^r \\ &+ 2x_k^q x_i^r x_j^r x_k^r + 2x_k^q x_i^r x_j^r x_k^r \\ B_g =& h(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r) \end{aligned}$$

with $h \equiv \frac{1}{b}$. The equilibrium renewable output for each firm is,

$$r_i^* = -\frac{C_g}{D_g} \tag{A.10}$$

where,

$$\begin{aligned} C_g =& -2hax_j^r x_k^r - h^2 a_f x_j^r - h^2 a_f x_k^r + 6ha_f x_j^r x_k^r - h^2 b_f p_f x_j^r - h^2 b_f p_f x_k^r \\ &+ 6hb_f x_j^r x_k^r + 2\gamma c^{ets} x_j^r x_k^r - hx_i^q x_j^r - hx_i^q x_k^r + hx_j^q x_k^r + hx_k^q x_j^r \\ &+ 8p_s x_j^q x_k^r + 6hx_i^q x_j^r x_k^r - 2x_j^q x_j^r x_k^r - 2x_k^q x_j^r x_k^r \\ D_g =& 2(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r) \end{aligned}$$

A.3 Scenario 1

Equilibrium thermal outputs,

$$q_i^* = -\frac{A_1}{B_1} \tag{A.11}$$

where,

$$
\begin{aligned}
A_1 =& 2ahx_i^r x_j^r x_k^r - 2\gamma c^{ets} x_i^r x_j^r x_k^r - hp_s x_i^r x_j^r - hp_s x_i^r x_k^r - hp_s x_j^r x_k^r \\
& + hx_i^q x_i^r x_j^r + hx_i^q x_i^r x_k^r - hx_j^q x_i^r x_k^r - hx_k^q x_i^r x_j^r \\
& - 6x_i^q x_i^r x_j^r x_k^r + 2x_j^q x_i^r x_j^r x_k^r + 2x_k^q x_i^r x_j^r x_k^r \\
B_1 =& h(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r)
\end{aligned}
$$

Equilibrium renewable outputs,

$$
r_i^* = -\frac{C_1}{D_1} \tag{A.12}
$$

where,

$$
\begin{aligned}
C_1 =& -2ahx_j^r x_k^r + 2\gamma c^{ets} x_j^r x_k^r - hx_i^q x_j^r - hx_i^q x_k^r + hx_j^q x_k^r + hx_k^q x_j^r + \\
& 8p_s x_j^q x_k^r + 6x_i^r x_j^r x_k^r - 2x_j^q x_j^r x_k^r - 2x_k^q x_j^r x_k^r \\
D_1 =& 2(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r)
\end{aligned}
$$

A.4 Scenario 2

The equilibrium conventional output for each firm is,

$$
q_i^* = -\frac{A_2}{B_2} \tag{A.13}
$$

where,

$$
\begin{aligned}
A_2 =& 2ghx_i^r x_j^r x_k^r - 2\gamma c^{ets} x_i^r x_j^r x_k^r - hp_s x_i^r x_j^r - hp_s x_i^r x_k^r - hp_s x_j^r x_k^r \\
& + hx_i^q x_i^r x_j^r + hx_i^q x_i^r x_k^r - hx_j^q x_i^r x_k^r - hx_k^q x_i^r x_j^r \\
& - 6x_i^q x_i^r x_j^r x_k^r + 2x_j^q x_i^r x_j^r x_k^r + 2x_k^q x_i^r x_j^r x_k^r \\
B_2 =& h(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r)
\end{aligned}
$$

The equilibrium renewable output for each firm is,

$$
r_i^* = -\frac{C_2}{D_2} \tag{A.14}
$$

where,

$$
\begin{aligned}
C_2 =& -2ghx_j^r x_k^r + 2\gamma c^{ets} x_j^r x_k^r - hx_i^q x_j^r - hx_i^q x_k^r + hx_j^q x_k^r + hx_k^q x_j^r + \\
& 8p_s x_j^q x_k^r + 6x_i^r x_j^r x_k^r - 2x_j^q x_j^r x_k^r - 2x_k^q x_j^r x_k^r \\
D_2 =& 2(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r)
\end{aligned}
$$

A.5 Scenario 3

The equilibrium conventional output for each firm is,

$$
q_i^* = -\frac{A_3}{B_3} \tag{A.15}
$$

where,

$$\begin{aligned}A_3 =& 2ahx_i^r x_j^r x_k^r - 2\gamma c^{ets} x_i^r x_j^r x_k^r - hp_s x_i^r x_j^r - hp_s x_i^r x_k^r - hp_s x_j^r x_k^r \\ &+ hx_i^q x_i^r x_j^r + hx_i^q x_i^r x_k^r - hx_j^q x_i^r x_k^r - hx_k^q x_i^r x_j^r \\ &- 6x_i^q x_i^r x_j^r x_k^r + 2x_j^q x_i^r x_j^r x_k^r + 2x_k^q x_i^r x_j^r x_k^r \\ B_3 =& h(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r)\end{aligned}$$

The equilibrium renewable output for each firm is,

$$r_i^* = -\frac{C_3}{D_3} \tag{A.16}$$

where,

$$\begin{aligned}C_3 =& -2hax_j^r x_k^r - h^2 a_f x_j^r - h^2 a_f x_k^r + 6ha_f x_j^r x_k^r - h^2 b_f p_f x_j^r - h^2 b_f p_f x_k^r \\ &+ 6hb_f x_j^r x_k^r + 2\gamma c^{ets} x_j^r x_k^r - hx_i^q x_j^r - hx_i^q x_k^r + hx_j^q x_k^r + hx_k^q x_j^r \\ &+ 8p_s x_j^q x_k^r + 6hx_i^q x_j^r x_k^r - 2x_j^q x_j^r x_k^r - 2x_k^q x_j^r x_k^r \\ D_3 =& 2(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r)\end{aligned}$$

A.6 Scenario 4

The equilibrium conventional output for each firm is,

$$q_i^* = -\frac{A_4}{B_4} \tag{A.17}$$

where,

$$\begin{aligned}A_4 =& 2hax_i^r x_j^r x_k^r + h^2 a_f x_i^r x_j^r + h^2 a_f x_i^r x_k^r - 6ha_f x_i^r x_j^r x_k^r + h^2 b_f p_f x_i^r x_j^r \\ &+ h^2 b_f p_f x_i^r x_k^r - 6hb_f p_f x_i^r x_j^r x_k^r - 2\gamma c^{ets} x_i^r x_j^r x_k^r - hp_r x_i^r x_j^r - hp_r x_i^r x_k^r \\ &- hp_r x_j^r x_k^r + hx_i^q x_i^r x_j^r + hx_i^q x_i^r x_k^r - hx_j^q x_i^r x_j^r - hx_k^q x_i^r x_j^r - 6x_i^q x_i^r x_j^r x_k^r \\ &+ 2x_k^q x_i^r x_j^r x_k^r + 2x_k^q x_i^r x_j^r x_k^r \\ B_4 =& h(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r)\end{aligned}$$

The equilibrium renewable output for each firm is,

$$r_i^* = -\frac{C_4}{D_4} \tag{A.18}$$

where,

$$\begin{aligned}C_4 =& -2hax_j^r x_k^r - h^2 a_f x_j^r - h^2 a_f x_k^r + 6ha_f x_j^r x_k^r - h^2 b_f p_f x_j^r - h^2 b_f p_f x_k^r \\ &+ 6hb_f x_j^r x_k^r + 2\gamma c^{ets} x_j^r x_k^r - hx_i^q x_j^r - hx_i^q x_k^r + hx_j^q x_k^r + hx_k^q x_j^r \\ &+ 8p_s x_j^q x_k^r + 6hx_i^q x_j^r x_k^r - 2x_j^q x_j^r x_k^r - 2x_k^q x_j^r x_k^r \\ D_4 =& 2(hx_i^r x_j^r + hx_i^r x_k^r + hx_j^r x_k^r - 8x_i^r x_j^r x_k^r)\end{aligned}$$

Appendix B

Proposition Proofs

B.1 Proposition 1

The structure of Scenarios 1, 2 and 3 are generally the same. Therefore, the proof for Scenario 1 will be provided and relevant parameters can be substituted where necessary such that the proofs hold in the other scenarios. For Scenario 2, a is substituted with g. For Scenario 3, a is substituted with l and b is substituted with m. The price in Scenario 1 is given by,

$$p_1 = \frac{1}{b}(a - R - Q) = ah - Rh - Qh \tag{B.1}$$

where $\frac{1}{b} = h$. Totally differentiating the thermal output equilibrium conditions with respect to thermal and renewable outputs gives,

$$\begin{bmatrix} 2h & h & h \\ h & 2h & h \\ h & h & 2h \end{bmatrix} = \begin{bmatrix} dq_i^* \\ dq_j^* \\ dq_k^* \end{bmatrix} \begin{bmatrix} -h(dr_i^* + dr_j^* + dr_k^*) \\ -h(dr_i^* + dr_j^* + dr_k^*) \\ -h(dr_i^* + dr_j^* + dr_k^*) \end{bmatrix}$$

Calling,

$$A = \begin{bmatrix} 2h & h & h \\ h & 2h & h \\ h & h & 2h \end{bmatrix}$$

then,

$$detA = 4h^3$$

and,

$$A^{-1} = \frac{1}{4h^3} \begin{bmatrix} 3h^2 & -h^2 & -h^2 \\ -h^2 & 3h^2 & -h^2 \\ -h^2 & -h^2 & 3h^2 \end{bmatrix}$$

Thus,

$$\begin{bmatrix} dq_i^* \\ dq_j^* \\ dq_k^* \end{bmatrix} = \frac{1}{4h^3} \begin{bmatrix} 3h^2 & -h^2 & -h^2 \\ -h^2 & 3h^2 & -h^2 \\ -h^2 & -h^2 & 3h^2 \end{bmatrix} \begin{bmatrix} -h(dr_i^* + dr_j^* + dr_k^*) \\ -h(dr_i^* + dr_j^* + dr_k^*) \\ -h(dr_i^* + dr_j^* + dr_k^*) \end{bmatrix}$$

From this matrix equation,

$$dq_i^* = -\frac{1}{4}(dr_i^* + dr_j^* + dr_k^*) \tag{B.2}$$

B.1.1 Proposition 1 (i)

From equation B.2,

$$\frac{dq_i^*}{dr_i^*} = -\frac{1}{4} < 0 \qquad \square$$

B.1.2 Proposition 1 (ii)

From equation B.2,

$$\frac{dq_i^*}{dr_{j,k}^*} = -\frac{1}{4} < 0 \qquad \square$$

B.1.3 Proposition 1 (iii)

$$\begin{aligned}
\frac{dp^*}{dr_i^*} &= \frac{d}{dr_i^*}(ah - R_1 h - Q_1 h) \\
&= -h - h\Big(\frac{dq_i^*}{dr_i^*} + \frac{dq_j^*}{dr_i^*} + \frac{dq_k^*}{dr_i^*}\Big) \\
&= -h - h(-\frac{3}{4}) \\
&= -\frac{h}{4} < 0 \qquad \square
\end{aligned}$$

B.2 Proposition 2

The price in Scenario 4 is given by,

$$p_4 = \frac{1}{m}(l - R - Q) = l\mu - R\mu - Q\mu \tag{B.3}$$

where $\frac{1}{m} = \mu$. Totally differentiating the thermal equilibrium output in Scenario 4, equation A.7, gives,

$$\begin{bmatrix} 2\mu & \mu & \mu \\ \mu & 2\mu & \mu \\ \mu & \mu & 2\mu \end{bmatrix} = \begin{bmatrix} dq_i^* \\ dq_j^* \\ dq_k^* \end{bmatrix} \begin{bmatrix} -\mu(2dr_i^* + dr_j^* + dr_k^*) \\ -\mu(dr_i^* + 2dr_j^* + dr_k^*) \\ -\mu(dr_i^* + dr_j^* + 2dr_k^*) \end{bmatrix}$$

Calling,

$$A = \begin{bmatrix} 2\mu & \mu & \mu \\ \mu & 2\mu & \mu \\ \mu & \mu & 2\mu \end{bmatrix}$$

then,

$$detA = 4\mu^3$$

and,

$$A^{-1} = \frac{1}{4\mu^3} \begin{bmatrix} 3\mu^2 & -\mu^2 & -h^2 \\ -\mu^2 & 3\mu^2 & -\mu^2 \\ -\mu^2 & -\mu^2 & 3\mu^2 \end{bmatrix}$$

Thus,

$$\begin{bmatrix} dq_i^* \\ dq_j^* \\ dq_k^* \end{bmatrix} = \frac{1}{4h^3} \begin{bmatrix} 3\mu^2 & -\mu^2 & -\mu^2 \\ -\mu^2 & 3\mu^2 & -\mu^2 \\ -\mu^2 & -\mu^2 & 3\mu^2 \end{bmatrix} \begin{bmatrix} -\mu(2dr_i^* + dr_j^* + dr_k^*) \\ -\mu(dr_i^* + 2dr_j^* + dr_k^*) \\ -\mu(dr_i^* + dr_j^* + 2dr_k^*) \end{bmatrix}$$

From this matrix equation,

$$dq_i^* = -dr_i^* \tag{B.4}$$

B.2.1 Proposition 2 (i)

From equation B.4,

$$\frac{dq_i^*}{dr_i^*} = -1 \qquad \square$$

B.2.2 Proposition 2 (ii)

From equation B.4,

$$\frac{dq_i^*}{dr_{j,k}^*} = 0 \qquad \square$$

B.2.3 Proposition 2 (iii)

$$\begin{aligned} \frac{dp^*}{dr_i^*} &= \frac{d}{dr_i^*}(l\mu - R_4\mu - Q_4\mu) \\ &= -\mu - \mu(-1) \\ &= 0 \qquad \square \end{aligned}$$

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