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Least cost energy system pathways towards 100% renewable energy in Ireland by 2050

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Abstract

Studies focusing on 100% renewable energy systems have emerged in recent years; however, existing studies tend to focus only on the power sector using exploratory approaches. This paper therefore undertakes a whole-system approach and explores optimal pathways towards 100% renewable energy by 2050. The analysis is carried out for Ireland, which currently has the highest share of variable renewable electricity on a synchronous power system. Large numbers of scenarios are developed using the Irish TIMES model to address uncertainties. Results show that compared to decarbonization targets, focusing on renewable penetration without considering carbon capture options is significantly less cost effective in carbon mitigation. Alternative assumptions on bioenergy imports and maximum variability in power generation lead to very different energy mixes in bioenergy and electrification levels. All pathways suggest that indigenous bioenergy needs to be fully exploited and the current annual deployment rate of renewable electricity needs a boost. Pathways relying on international bioenergy imports are slightly cheaper and faces less economic and technical challenges. However, given the large future uncertainties, it is recommended that further policy considerations be given to pathways with high electrification levels as they are more robust towards uncertainties.

Keywords: 100% Renewable Energy, Electrification, Energy System Optimization Model, Uncertainty Analysis

1 Introduction

1.1 Policy Context

At the 16th Conference of the Parties (COP) meeting in Cancun in 2010, it was formally agreed that global warming should be limited to 2°C temperature rise relative to pre-industrial levels [1]. The Paris agreement adopted in 2015 [2] aims to keep the global temperature rise well below 2°C and contains the ambition to pursue efforts to limit the temperature increase even further to 1.5°C. While the exact amount of carbon emissions associated with global warming below a certain temperature threshold is uncertain [3,4], limiting global mean temperature increase at any level essentially requires global carbon emissions to become net zero by a certain point in the 21st century [5].

Recently, more ambitious climate action goals of zero emission pathways are gaining momentum. Since 2019, the European Union has had an 80%-95% reduction target in greenhouse gas (GHG) emissions relative to 1990 levels by 2050 [6] and as of 2019 is considering further reducing emissions to net zero GHG emissions by 2050 [7]. In the United States, the Green New Deal was proposed in the 116th Congress with goals of achieving net-zero GHG emissions [8]. In June 2019, the UK became the first G20 economy to legislate for a legally binding net zero 2050 target [9].

Renewables such as wind, solar, hydro, ocean and bioenergy represent a critical decarbonization option. With the rapid cost reductions in wind and solar energy, renewable electricity has become the preferred source of power generation over the past few years [10]. Renewables will need to account for 52%-67% of primary energy by 2050 under the 1.5°C-consistent pathways projected by IPCC [11]. Energy consumption comprises large amounts of renewable electricity but also negative emissions technologies and renewable fuels for heating and transport. The global energy transformation pathway towards well below two degrees projected by IRENA also indicates over two-thirds of total energy consumption from renewables [12]. Besides avoiding GHG emissions, transition towards a high renewable energy system comes with several other co-benefits, such as addressing the challenge of fossil fuel depletion [13], ensuring security of energy supply, stabilizing energy prices, as well as reducing pollutants and health risks [14].

Renewables are well recognized as critical tools in climate mitigation, and policies that support renewable energy are present in nearly all countries in the world. Over half of the Nationally Determined Contribution (NDC) [15] submitted to the United Nations Framework Convention on Climate Change (UNFCCC) set specific renewable energy targets [16]. The European Union is committed to a binding target of 32% renewable by 2030 [17]. The Green New Deal also contains the goal of meeting 100% electricity demand with renewable electricity.

However, renewable energy targets under current policy framework are not ambitious enough compared with decarbonization targets, with significant variation in scope and comprehensiveness [18].Many countries and regions have set 100% renewable targets in power generation, including Bangladesh, Cambodia, Colombia, Portugal, Sweden, California. On the other hand, policy targets on renewables outside the power sector are far less ambitious. Targets for 100% renewable energy systems are mainly taking place in cities, such as Frankfurt, Hamburg, Vancouver and Hague [18]. At present, Denmark is the only country with a 100% renewable target in total final energy consumption by 2050.

1.2 Status of Research

Renewable energy targets should be set in line with carbon reduction targets within a robust climate policy framework. This is because emissions reduction ambitions are one of the most important drivers for large scale development of renewable energy. Within the existing literature, certain research gaps can be identified between existing studies on renewable energy and studies on deep decarbonization in terms of sectoral coverage and analytical approach.

Deep decarbonisation analyses generally take an optimization approach for the entire energy system with integration between power, heat and transport systems. An example of a long-term, optimization approach is the Integrated Assessment Model (IAM). IAMs have been widely used to project long-term global low carbon transition pathways, such as the IPCC SR1.5 report on 1.5 °C global warming [11], 2050 energy roadmaps by [12] and energy technology perspectives from IEA [19]. These analyses seek a single least cost pathway with optimal balance between electrification, renewables and other low and negative carbon technologies, and point to the long-term transition pathways.

Compared to analysis on deep decarbonization, the approaches of i) system solutions and ii) least cost optimization are not sufficiently addressed within the current 100% renewable energy literature. According to a recent review on 100% renewable energy studies [20], currently there is no uniform definition of 100% renewable energy and the majority of studies on 100% renewable energy only focus on the power sector. Some of the 100% renewable energy studies propose a 100% renewable power system and electrify all energy sectors. For example, Jacobson has proposed a 100% renewable energy system solely based on water, wind and solar for the 50 US states [21] and 139 countries in the world [22]. This study concluded that meeting system-wide 100% renewable energy penetration with water, wind and solar is technically and economically feasible. Achieving a 100% renewable power system is a key starting point, followed by the electrification of the parts of heat and transport that can be electrified, with electro-fuels used for sectors that cannot be electrified. However, the scale of the challenge of achieving a system-wide 100% renewable energy system with just renewable electricity is apparent when compared with the current situation where electricity accounts for approximately 20% of energy end use, with heat and transport accounting for the remaining 80%. The analysis by Jacobson was met with criticism [23] stating that there were key methodological oversights, including invalid modelling tools, modelling errors and implausible assumptions.

Another key difference between studies on deep decarbonization and 100% renewable energy is the analytical approach. While studies on deep decarbonization tend to apply the cost optimal approach to determine a single best pathway, renewable studies are usually carried out with simulation models in an exploratory manner. An example of a simulation model widely used for assessing the performance of system-wide 100% renewable energy scenarios is the EnergyPLAN model [24–29]. It has been pointed out that the difficulty in balancing bioenergy consumption and electrification is a major challenge in analysis using the EnergyPLAN model [30]. Compared to long-term optimization models, simulation models based on an overnight approach are suitable in assessing the feasibility and performance of power systems with high intermittent renewable sources such as wind and solar. However, in simulation models, the technology portfolio and energy mixes are based on exogenous assumptions, which restricts insights to the system-wide technological challenges involved, e.g. critical cross-sectoral insights may be overlooked when assessing the entire energy system that includes electricity, heat and transport. Such challenges could be better addressed by an

optimization approach that calculates a least cost pathway which strikes a balance between electrification, renewables and other low and negative carbon technologies.

1.3 Paper Objectives

This paper aims at addressing these research gaps between renewable energy studies and deep decarbonization studies with key contributions as follows.

In terms of informing decision making, this paper contributes to the evidence base through exploring least cost-pathways towards system-wide 100% renewable energy supply, focusing on one EU member country Ireland. A first step in exploring feasibilities of 100% renewables in Ireland was carried out with the simulation model EnergyPLAN [31] based on exogenous assumptions regarding technology portfolio and energy mixes. In this paper we explore the challenges of 100% renewables with a different approach by applying bottom-up energy systems optimization modelling (ESOM) to determine optimal energy transition pathways, outlining when and how to transition to a 100% renewable energy system in a cost-efficient manner. To date, there has been a limited application of system-wide optimization approaches in addressing 100% renewable energy system. Only a few studies have been carried out for Europe [32] and at a global scale [33][34]. Least cost pathways for Ireland will contribute to the evidence base for policy making regarding integrating 100% renewables.

A methodological contribution in this paper is the provision of an integrated modelling framework for assessing deep decarbonization targets and renewable energy targets together. Existing studies on 100% renewable energy pathways and deep decarbonization have been undertaken separately with little comparison and integration of the two approaches. Without a consistent analytical framework, insights from 100% renewable energy analysis may be limited and inconsistent with insights from deep decarbonization scenarios, leading to suboptimal policy decisions. In this paper various scenarios are developed in a single model to compare renewable energy target and decarbonization targets side by side, providing insights that could help policy makers develop renewable energy policies in accordance with carbon mitigation ambitions. A key focus in this paper is on the economic implications and a key research question is how cost effective of a 100% renewable target in carbon mitigation compared to focusing only on carbon mitigation.

Another methodology innovation in this paper is the incorporation of a global sensitivity analysis to assess critical parametric uncertainties. Projecting decades into the future is inherently uncertain. Assumptions in technology costs, energy costs and renewable energy potentials are prone to uncertainties. The long-term projections of these assumptions are highly questionable and may have significant impacts on the results of long-term optimization models. A majority of existing ESOM analyses rely on simple scenario analysis and overlook these parametric uncertainties due to the computational burden and a lack of modelling infrastructure that facilitates systematic uncertainty analysis [35]. In this paper, a novel modelling feature for a TIMES model is developed to facilitate batch generation of scenario ensembles for a global sensitivity analysis. We focus on critical uncertainties related to 100% renewable energy, including bioenergy import costs and availabilities and investment costs of renewable technologies. The uncertain parameters are perturbed simultaneously to generate 500 scenarios. The results help identify the most impactful sources of uncertainties and assess the robustness of renewable technologies under uncertainties. To our knowledge, this paper is the first one that develops and applies the global sensitivity analysis to a TIMES model.

The paper is outlined as follows. Section 2 provides a detailed description of the model assumptions and scenario setup. Section 3 presents the results and a discussion. Section 4 provides concluding remarks.

2 Methodology

2.1 Energy transition pathways towards 100% renewable

Long term energy transition pathways have been widely used in exploring pathways towards a low carbon future, offering insights on energy transition, economic implications and environmental impacts [11]. Global carbon mitigation transition pathways [36] indicate that limiting global temperature rise to 1.5°C requires a rapid shift away from fossil fuels towards low carbon energy including different combinations of renewables, reduced energy use, improvements in energy efficiency, nuclear energy and carbon dioxide removal technologies. Pathways of 100% renewable energy have rarely been considered before and were first mentioned in the IPCC SR1.5 report [11]. The IPCC report points out that 100% renewable energy pathways with significantly higher wind, solar and electrification levels compared to existing decarbonization pathways may expand the range of possible pathways once the underlying assumptions are plausible.

Energy system transition pathways at a national or regional scale are typically developed from energy systems optimization models (ESOMs). The classification of energy models can be based on underlying methodology (simulation, optimisation, economic equilibrium), analytical approach (top-down, bottom-up, hybrid [37]), and sectoral coverage (whole energy system [38], power system [39], etc.). ESOMs can be characterised as bottom-up, optimization models that cover the whole energy system. ESOMs provide an integrated, technology-rich representation of the whole energy system for analysing energy dynamics over a long-term, multi-period time horizon. Solutions of ESOMs are computed based on an optimization approach using linear programming techniques. Examples of ESOMs include TIMES [40], MESSAGE [41], ESME [42], OSeMOSYS [43] and TEMOA [44].

In the context of Ireland, carbon mitigation transition pathways from ESOMs have played a role in informing the development of carbon mitigation policies. Ireland has set legally binding climate targets for 2020 [45] and 2030 [46] with an ambition for net-zero GHG emissions by 2050 [47]. Various aspects of a future low carbon economy been analysed, including trajectories towards 2°C consistent emission reduction targets [48,49], feasibility of net zero emissions [50], security of supply dimensions of a decarbonized energy system [51] , and impacts of bioenergy availability [52]. Previously, ESOM based transition pathways [53] have been used to inform the Climate Action and Low Carbon Development Act 2015 [54], a 2015 Energy White Paper [55] published by the Department of Communications, Climate Action and Environment that set out a framework to guide policy and the actions that the Irish Government intended to take in the energy sector, and analysis [56] that informed the national mitigation plan [57].

These previously published analyses have grappled with some of the policy challenges for Ireland. Ireland has one of the largest potential wind energy resources in the world and at present is exploiting a significant portion of this potential: in 2018, 28.1% of Ireland's electricity came from wind energy. There are technical challenges associated with increasing this share, since Ireland is a small island with limited interconnection to neighbouring power systems in the UK; increased electrification is becoming more difficult. In parallel, the importance of decarbonising other sectors (heat & transport) grows. To date however, policy discourse has been disproportionally focused on the electricity sector to the neglect of heat and transport. Recent progress in decarbonising and increasing the share of renewables in the heat and transport sectors has either worsened or stalled. These challenges underline the importance of adopting a whole-energy system approach, since some of the greatest challenges are in sectors (heat and transport) that would be missed by an exclusive focus on electricity.

Long term transition pathways towards 100% renewable energy systems have not been explored in

Ireland before. Ireland is not on track to meet its climate targets and the gap in renewable energy penetration is particularly evident (Table 1). Ireland has a national target of 16% renewable share in gross final consumption by 2020; however, as of 2018, renewables only contribute to 11% in total final energy consumption. In 2018 wind generation accounted for 28.1% total electricity generated, and total renewable generation accounts for 33.2% of gross electricity consumption; however, electricity only accounts for 18.9% of TFC [58] and more efforts are required in the transport and heat sector which had a 7.2% and 6.5% renewable energy share respectively. Being aware of the gap between climate policies and decarbonization ambition, the government of Ireland has developed the Climate Action Plan [47] that sets more ambitious targets in line with a net zero by 2050, including a 70% renewable penetration in power generation by 2030. Insights from this paper have the potential to contribute additional evidence base for policy setting appropriate long-term renewable targets to inform policy making in renewable energy.

It should be noted that the focus of this paper is on long term transition pathways rather than debating the feasibility of a 100% renewable energy system. Due to computational burden, ESOMs have historically applied stylized temporal representation with 12-20 time slices in each model year. Majority of existing 100% renewable energy studies have applied high temporal resolution to analyse the performance an energy system with high intermittency based on an overnight approach. Compared to these studies, the strength of long-term optimisation modelling is the provision of optimal pathways offering authoritative results for politician in how and when to transition towards a 100% renewable energy system [59].The technical feasibility of a 100% renewable energy system has already been extensively assessed within the current literature. The majority of existing studies suggest that 100% renewable is technically and economically feasible with various key challenges addressed, including meeting peak demand with battery storage [60], management of low-demand periods [61], high investment costs in flexibilities and new capacities [62], extreme weather conditions [63], access to renewable data [64], constraints on geographical allocation of storage technology [65], and government regulations [66]. The importance of flexibility measures [67–69], storage [70] and interconnectors [71], centralised and decentralised electricity [72–74] are also addressed within the current literature. It has been pointed out that the major barriers towards 100% renewable electricity are political, institutional and cultural [75]. Few studies have argued against 100% renewable energy. An example is a review study based on a scoring system [76], which points out that existing studies cannot meet criteria in consistency with demand forecast, reliability in meeting in-time demand, identifying transmission and distribution requirements, and provision of essential ancillary services. This finding was criticized by another review [77], arguing that the methodology is problematic and the feasibility criteria chosen are critical but can be addressed at low economic costs.

Table 1 Ireland's current energy consumption and progress towards renewable targets (Source: [58])

	2005	2017	2020 Target
TPER (ktoe)	15803	14413	
Fossil Fuels	15306 (96.6%)	13058 (90.2%)	
Hydro	54 (0.3%)	59 (0.4%)	
Wind	96 (0.6%)	640 (4.4%)	
Biomass	180 (1.1%)	378 (2.6%)	
Other Renewables	40 (0.3%)	270 (1.9%)	
Import Dependency	89%	66%	
TFC (ktoe)	12606	11821	
Fossil Fuels	10324 (81.9%)	9055 (76.6%)	
Renewables	188 (1.5%)	472 (4.0%)	
Wastes (Non-Renewables)	0	70 (0.6%)	
Electricity	2094 (16.6%)	2223 (18.8%)	
Renewable share (GFC)	2.8%	10.6%	16%
RES-E	7.2%	30.1%	40%
RES-T	0	7.4%	10%
RES-H	2.8%	6.9%	12%
Emissions (Mt/% Rel. 2005)	45.7	36.8/-18%	20%

2.2 Model Assumptions

In this study we apply the ESOM model Irish TIMES to project transition pathways towards 100% renewable energy by 2050. TIMES (The Integrated MARKAL-EFOM System) [40] is an economic model generator for local, national, multi-regional, or global energy systems. The model is data-driven and includes a technology-rich database for representing energy dynamics over a multi-period time horizon. TIMES assumes that each agent has perfect foresight on the market's parameters and computes the inter-temporal dynamic equilibrium by minimising total discounted energy system cost over the entire time horizon with decisions made on equipment investment and operation, primary energy supply and energy trade for each region. The cost minimization considers investment costs of energy technologies, operation and maintenance costs, the cost of imports, profits from energy exports, and the residual value of technologies at the end of the horizon. TIMES is thus a vertically integrated model of the entire extended energy system. TIMES is now widely used by over 62 contracting parties supported by ETSAP (Energy Technology Systems Analysis Program), an Implementing Agreement of the International Energy Agency (IEA).

The Irish TIMES model is an instance of the TIMES model developed for Ireland. The original Irish TIMES dataset was extracted from the Pan European TIMES (Pan European TIMES model that includes EU27, Iceland, Norway, Switzerland and Balkans countries) project by the Energy Policy and Modelling Group at University College Cork, and was updated with more detailed local data, calibrated to the national energy system with macroeconomic projections from the Economic and Social Research Institute (ESRI). The time horizon in the Irish TIMES model used is from 2005 to 2050 with a time resolution of four seasons, each is comprised of day, night and peak time slice. The inputs to the Irish TIMES include, estimates of existing stocks of energy related equipment, characteristics of available future technologies, as well as present and future sources of primary energy supply and their potential. The projection of end-use energy service demands are based on exogenous assumptions, and are derived from the macroeconomic model COSMO [78] based on assumptions including population, number of household and GDP growth.

The potential for additional large hydro plants in Ireland is limited but further deployment of small hydro plants is possible [79]. The resource potentials for wind is assumed to be 6.9GW and 7.5GW for onshore and offshore generation [80]. The level of intermittent (non-dispatchable) renewable generation – namely wind, solar and ocean energy is limited to 50% at annual level and 70% at time slice level according to the report by Ireland's transmission system operator EirGrid [81]. The use of geothermal energy in Ireland is limited only to small installations in the residential and services sector mostly for space and water heating purposes. The potential of bioenergy available for import is set according to the current share of primary energy demand of Ireland as a fraction of EU's primary energy demand [82]. The potentials of domestic bioenergy is projected to 2,887 ktoe for the year 2030 and at 3,805 ktoe by 2050 [52]. Additional details on how demand is driven and technoeconomic inputs can be found in [48,49].

The original cost assumptions in Irish TIMES model are from the values in the PET model used in the Intelligent Energy— RES2020 project (RES2020). In this analysis, the input assumptions for renewable technologies are updated and refined according to the most recent data available and summarized in Table 2. Renewable technologies including solar, wind, ocean energy are updated according to JRC data [83]. The cost of residential and commercial heat pumps are updated with data from [84]. In addition, the hydrogen energy system is also added to the model using assumptions in production, storage and transmission from [85,86]. Some of the model assumptions

in technology deployment rates are relaxed to allow all energy service demands to be met using renewables and electricity by 2050.

Table 2 Technoeconomic assumptions of capital cost for renewable technologies.

	Cost Assumptions in deterministic scenarios (Euro/kw)				**Cost ranges for global sensitivity analysis** (% change)	
	2020	**2030**	**2040**	**2050**	**2050 Low**	**2050 High**
Power-to-Gas (Electrolysis)	1420	1169	935	935	-20%	+30%
Wave Energy	6310	5320	4040	3240	-54%	+76%
Tidal Energy	4920	4140	3150	2520	-54%	+57%
Solar Energy (Utility Scale)	600	480	440	390	-28%	+105%
Offshore Wind	2870	2570	2430	2330	-45%	+33%
Onshore Wind	1020	980	950	910	-20%	+14%
COM Solar	720	430	350	350	-17%	+131%
RSD Solar	920	600	490	420	-17%	+131%
COM HP Air	405	366	350	350	-15%	+20%
COM HP Ground	299	266	233	233	-15%	+20%
RSD HP Air	679	614	586	586	-15%	+20%
RSD HP Ground	1014	937	861	861	-15%	+20%
COM HP Air to Water	509	509	459	459	-15%	+20%
RSD HP Air to Water	700	700	631	631	-15%	+20%
Bioenergy import price					-60%	+80%
Bioenergy Import					-49%	+20%

2.3 Scenario Definition

2.3.1 Deterministic scenarios

As pointed out by Ó Gallachóir et al., equating the electricity generated from renewable sources with the primary energy supply is inaccurate in representing the contributions from renewables in replacing fossil fuels [87]. Therefore, the constraint of the level of renewable energy penetration rate is applied to the model based on the gross final consumption (GFC) instead of primary energy, and is based on the Directive1 2009/28/EC [88], which is the sum of (a) gross final consumption of electricity from renewable energy sources; (b) gross final consumption of energy from renewable sources for heating and cooling; and (c) final consumption of energy from renewable sources in transport. In this analysis, the calculation of renewable share excludes non-energy fuel use and oil consumption for aviation. The scenarios in this analysis include the following:
Base: The base scenario represents the pathway that delivers energy service demands without any policy instruments. The renewable energy share in the base scenario is 25% in 2050.
RE%: The renewable energy (RE) scenarios apply constraints to the minimum share of renewable energy in total final energy consumption. The renewable share constraint applied is included in the scenario name. For example, RE100% scenario has 100% constraint in renewable share in 2050. Renewable levels in intermediate model years are linearly interpolated.
Carbon Constraint: The CO2 scenario is used to compare the differences in renewable energy targets and decarbonization targets. The carbon constraint scenario sets annual emission constraints according to the EU climate & energy package and EU low-carbon economy roadmap from 2020 to 2050, achieving an 80% reduction in all energy related CO2 emissions by 2050 on 1990 levels. This scenario does not have any constraints applied on the renewable levels.

A range of alternative constraints are applied to the renewable energy scenarios to explore the impacts of bioenergy and levels of VRES allowed in the power system. The following constraints are applied to the RE% scenarios.
HighBioImport: The bioenergy potential in baseline scenarios are projected under the assumption that the current trend of bioenergy development will prevail [82]. The “High Bioenergy Availability” scenario assumes an optimistic view of global bioenergy potential due to increased planting and removal of barriers by investment.
VRES100%: The base scenario assumes that the maximum penetration of electricity from variable renewable energy sources (VRES) such as wind and solar is 50% at annual level and 75% at time slice level, in line with current practice from the electricity system TSO (EirGrid). 100% VRES scenarios relax constraint in VRES and allows penetration of 100% VRES in power generation, which exceeds the current long-term 75% target of the system TSO.
NoBioImport: International import of bioenergy is not available, and bioenergy can only be procured from indigenous sources.
NoBiomassPP: Biomass power plants are disabled.

Multiple alternative constraints may be applied to one scenario. For example, scenario with 75% renewable level and no bioenergy import is named as “RE75% (NoBioIMP)”. Scenario with 100% renewable energy, 100% VRES and disabled bioenergy import is named as “RE100%-100% VRES (No Bioenergy Import)”. The assumptions made in core scenarios and alternative constraints are summarized in Table 3.

Table 3 Scenario definition

Core Scenarios	
BASE/RE%/Carbon Constraint	Medium level of bioenergy supply 50% VRES penetration allowed at annual level, 75% at time slice level
Alternative Constraints	
HighBioImport	Abundant global bioenergy supply
VRES100%	100% VRES penetration allowed in power generation
NoBioImport	Disabled international bioenergy import
NoBiomassPP	Disabled biomass power plants

2.3.2 **Sensitivity Analysis**

In addition to scenario analysis, local sensitivity analysis is carried out on renewable energy targets to explore incremental impact of increasing renewable targets. The sensitivity analysis starts from the base scenario which has 25% renewable share in 2050, each subsequent scenario increases the renewable target by 1%. The resulting set of scenarios range from 25% renewable to 100% renewable resulting in a total of 76 scenarios. The sensitivity analysis is also carried out under alternative constraints.

Sensitivity analysis is also carried out on decarbonization targets to determine the differences between the two policy targets, focusing on the economic implications. For each renewable energy scenario, emission levels for each model year obtained from the model results are applied to a CO2 scenario as exogenous emission constraint. This results in 76 carbon constraint scenarios, each corresponding to a renewable energy scenario.

In this study we use global sensitivity analysis to quantify the impact of critical uncertainty sources on the transition pathways. The principle is to propagate uncertainties by simultaneously perturbing multiple uncertain input parameters represented by probability distributions. The collection of model outputs are then evaluated statistically using the global sensitivity analysis approach [89] to quantify how uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input. The global sensitivity analysis consists of 500 scenarios and is carried out with constraints of 100% renewable energy share and 100% VRES penetration is allowed. The global sensitivity analysis is carried out in the following steps.

1. Triangular probability distributions are assigned to techno-economic parameters including capital costs of renewable technologies, bioenergy import prices and availability. The uncertainty ranges are summarized in Table 2.
2. A sample of random values is generated based on the probability distributions.
3. The randomly generated sample is fed into the model to compute a set of outputs.
4. The procedure is repeated 500 times and 500 samples are generated.
5. The outputs are evaluated using global sensitivity analysis. Standard correlation coefficients are calculated to determine the correlations among input uncertainties and key model results such as system costs, bioenergy consumption and technology penetration

3 Modelling Results

This section presents the cost optimal energy systems configurations of a high renewable energy system in 2050. Modelling results of scenario ensembles consisting of over 1000 scenarios are presented, with a focus on addressing optimal mixes of electrification and bioenergy usage, the relationships among decarbonization and renewable, and the roles of key renewable technologies.

3.1 Energy systems results

3.1.1 Energy supply and demand

Maximum feasible levels of renewable penetration under different assumptions are explored with sensitivity analysis. The results show that under the base scenario assumptions of medium bioenergy projection and VRES limitation of 50%, the maximum feasible renewable level is 94%. Sensitivity scenarios with alternative constraints show that the maximum renewable level reaches 100% if 100% VRES penetration in power generation is allowed. Bioenergy import also has significant impact on the feasible renewable level. 100% renewable can be met under the assumption of high bioenergy import availability and only 75% renewable can be reached when bioenergy import is disabled. When both bioenergy import and high VRES penetration are not allowed, only 75% renewable can be reached. This pathway has a high electrification level, but a large share of the electricity is produced from natural gas, resulting in both high carbon emissions and energy system costs.

Targeting higher renewable penetration is characterized by higher amount of bioenergy consumption. Figure 1 shows the total primary energy required (TPER) in 2050. Figure 2 shows the system wide total final consumption (TFC) in 2050 with shares of renewables shown in Figure 3. In the BASE scenario, the amount bioenergy supply in 2050 is 1700ktoe accounting for 12.7% of TPER. The share of bioenergy in TPER rises to 9360ktoe at 90% renewable level (RE90%-VRES50% scenario), and further to 80.8% TPER at 100% renewable level (RE100%-VRES50%-HighBioImport scenario).

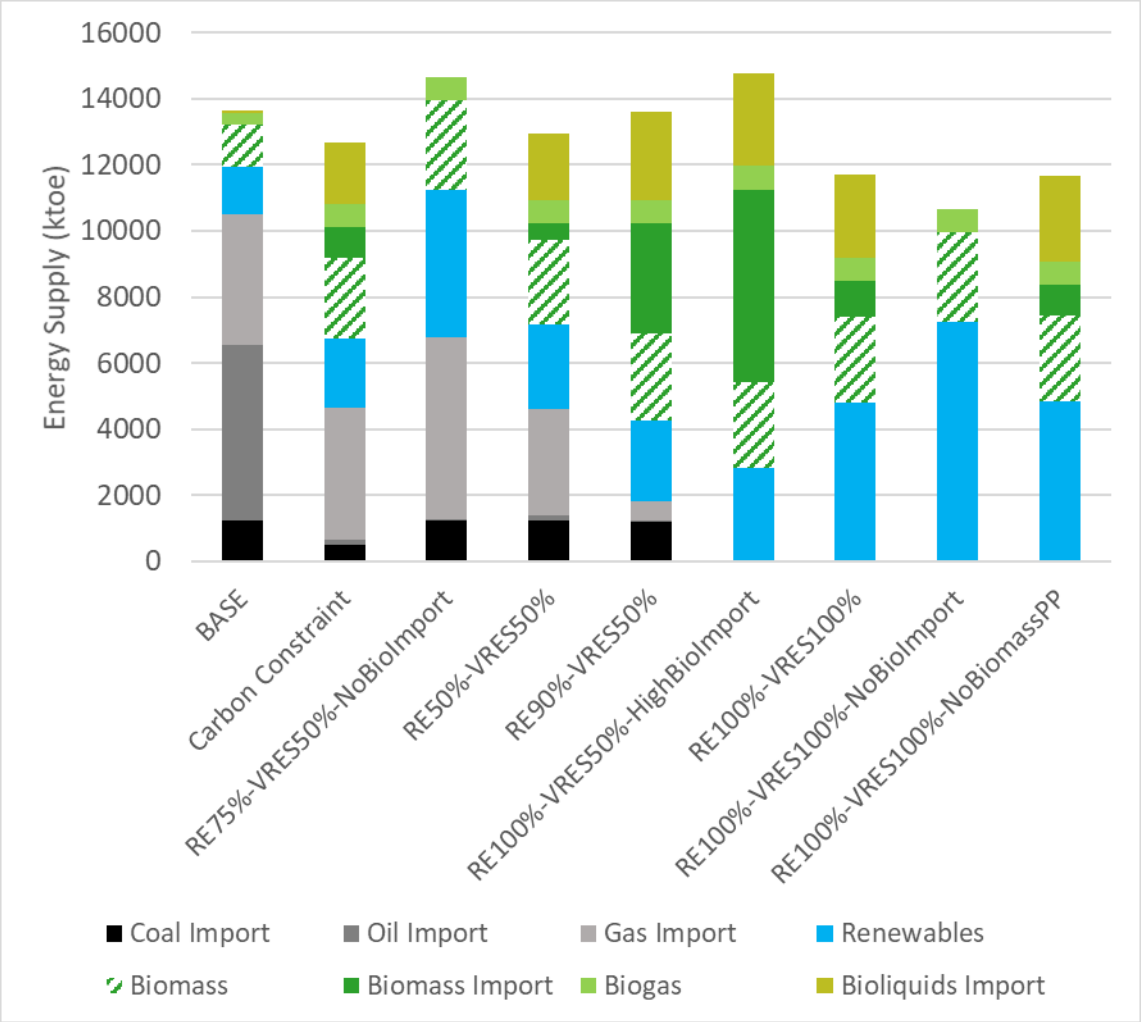

Figure 1 Total primary energy required (TPER) in 2050

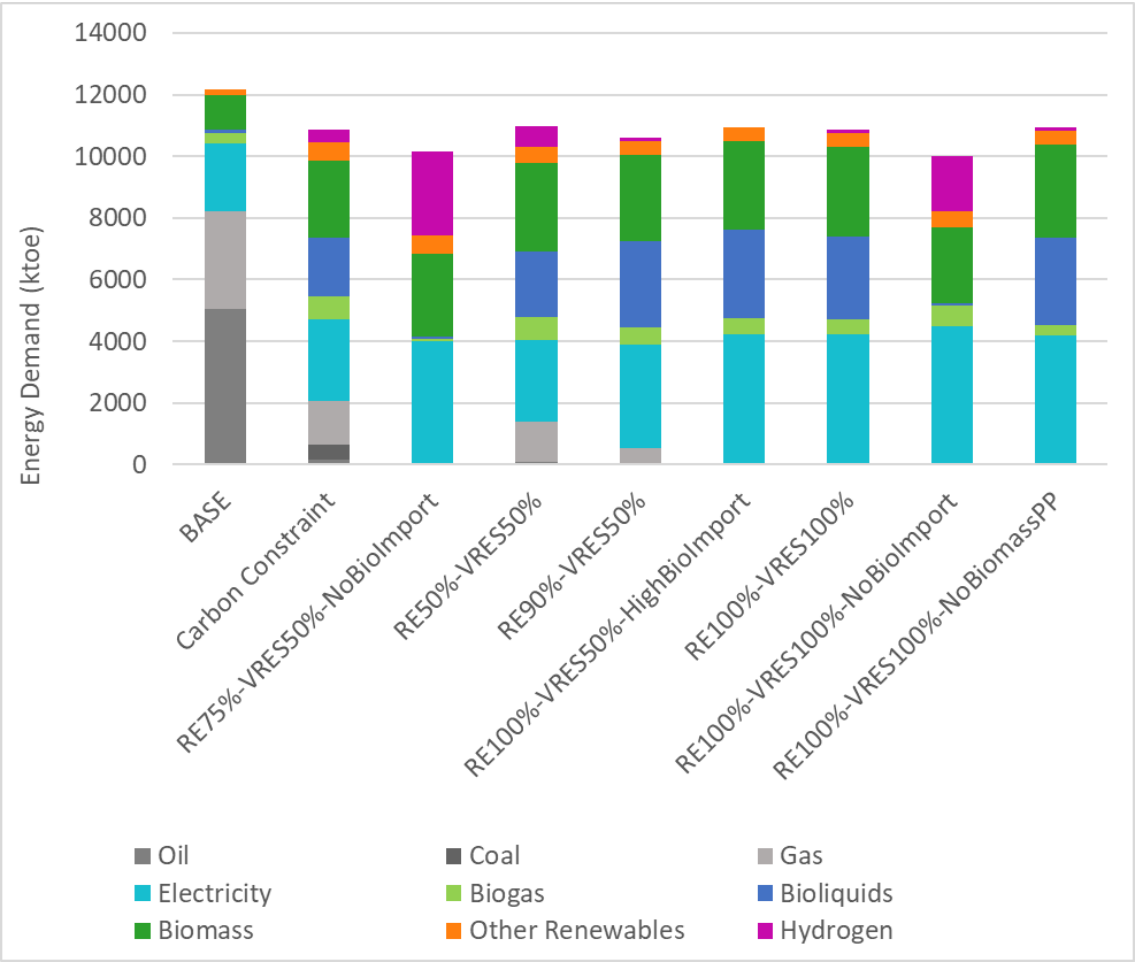

Figure 2 Total final energy consumption (TFC) in 2050

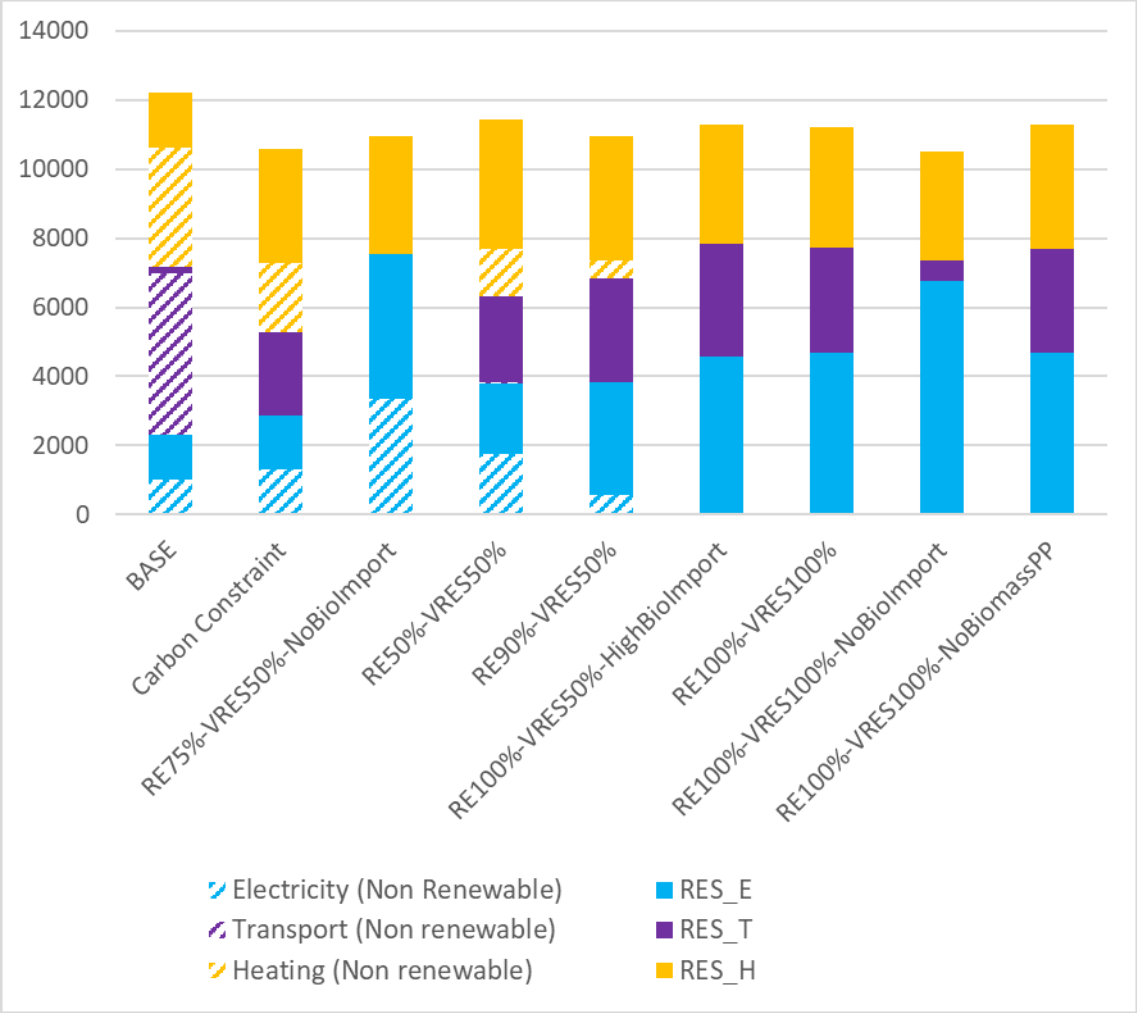

Figure 3 Renewable share by mode of application in 2050. It should be noted that RES-E includes electricity production and hydrogen production from power-to-gas. Electricity and hydrogen consumption in transport and heat sectors are therefore not reflected in RES-T and RES-H.

Another important source of renewables is electricity from wind, solar and ocean energy. Figure 4 shows electricity production by source and Figure 5 presents overall electrification level, which is calculated by percentage share of electricity consumption in total final energy consumption. It should be noted that the electricity input into power-to-x processes is included in the calculation of total electricity consumption. This should be distinguished from hydrogen consumption presented in the TFC graph, which presents final hydrogen consumption by end-use technologies. Under the BASE scenario where no policy constraints are applied, the electricity consumption in 2050 remains similar and is projected to 27.2TWh with an overall electrification level of 18.4%. The electricity demand increases significantly from BASE scenario to 43.1TWh (25.8%) at 50% renewable target, and further increases to 53.3TWh (38.8%) in RE100%-VRES50%-HighBioImport scenario.

Comparison between RE100%-VRES50%-HighBioImport and RE100%-VRES100% scenarios show that increasing VRES levels has little impacts on overall electrification levels. Allowing more VRES penetration in power generation causes a switch from dispatchable biomass plants towards intermittent renewable generation such as wind and ocean energy. This results in reduction of bioenergy consumption from 80.9% to 58.8% share in TPER. Electricity consumption significantly increases when bioenergy import is not available, which drives up the demand in hydrogen to replace biofuel consumption in transport sector. Under the RE100%-VRES100%-NoBioImport scenario, electricity consumption increases to 78.5TWh and the overall electrification level increases to 64.1% and bioenergy share reduces to 32.1% TPER.

In the residential and commercial sectors (Figure 6), transition towards 100% renewables is characterized by a switch from gas to higher biomass and electricity consumption for heating. Electricity consumption for lighting, appliances, and energy saving from insulation remain relatively the same in renewable energy scenarios compared to the BASE scenario. The increase in electricity consumption is driven by high penetration of electric heaters and radiators. Compared to electric heaters and radiators, penetration of heat pumps is relatively low due to their high investment costs.

In the transport sector (Figure 7), freight and navigation cannot be electrified and require energy-dense fuels such as oil, hydrogen and biofuels. The transition towards high renewable energy in the transport sector is achieved through electrifying the private cars and replacing fossil fuels with biofuels for freight transport and navigation. Allowing higher penetration of VRES does not have much impact on the transport sector (RE100%-VRES50%-HighBioImport scenario). Limited biofuel supply (RE100%-VRES100%-NoBioImport scenario) drastically increases the electrification level in the transport sector, and consumption in electricity and hydrogen accounts for over 80% of total final consumption.

The industry sector in Ireland is small and has a relatively simple representation in Irish TIMES model compared to other sectors. To reach higher renewable targets, biomass replaces gas in producing industrial heat. The sectoral emissions (Figure 8) shows that the production of cement and lime in industry sector is the major source of residual emissions in 100% renewable energy scenarios. Comparison between renewable energy scenarios and the carbon constraint scenario shows that the residual emissions from cement and lime production need to be mitigated with carbon sequestration processes.

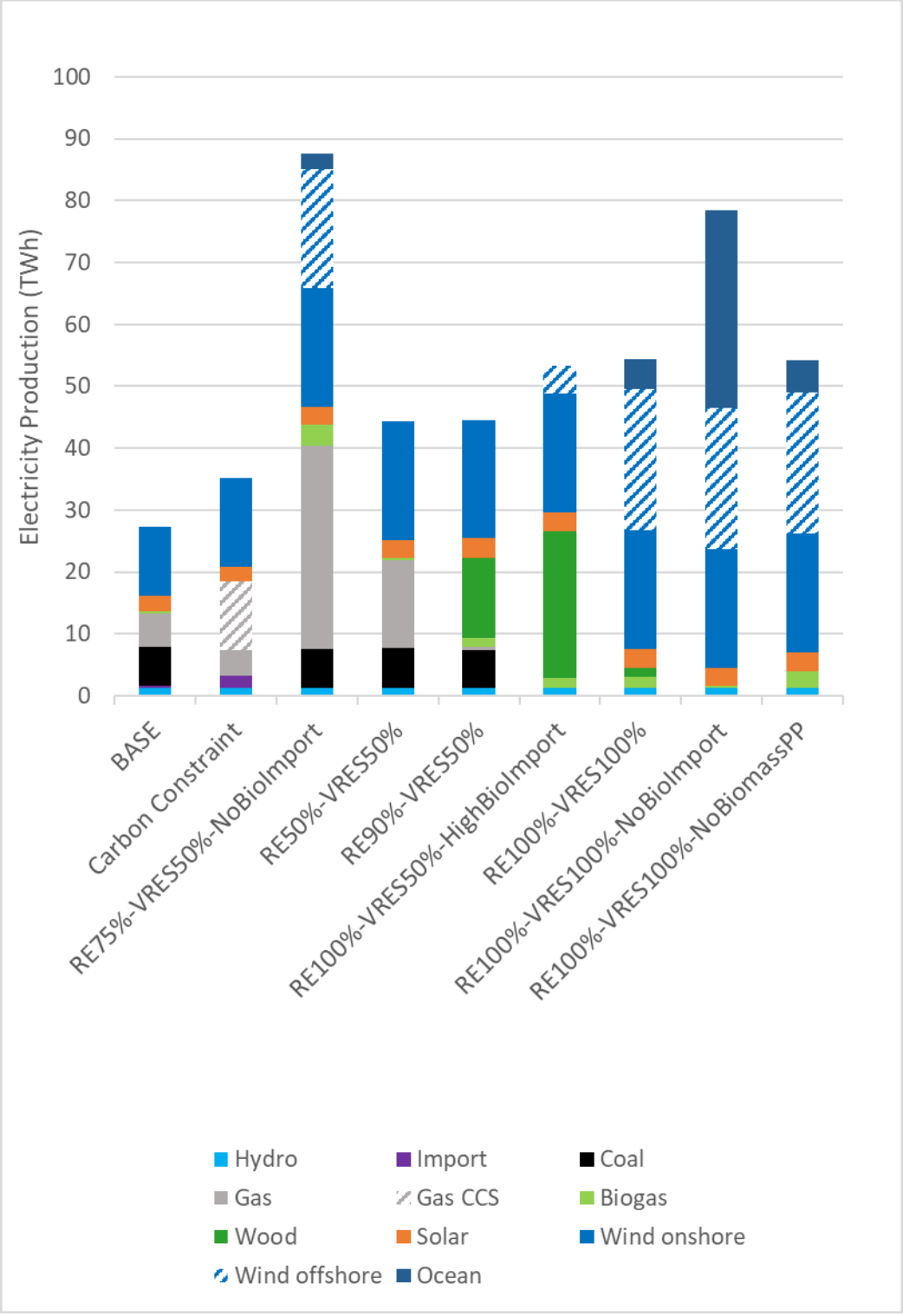

Figure 4 Electricity production by fuel use in 2050

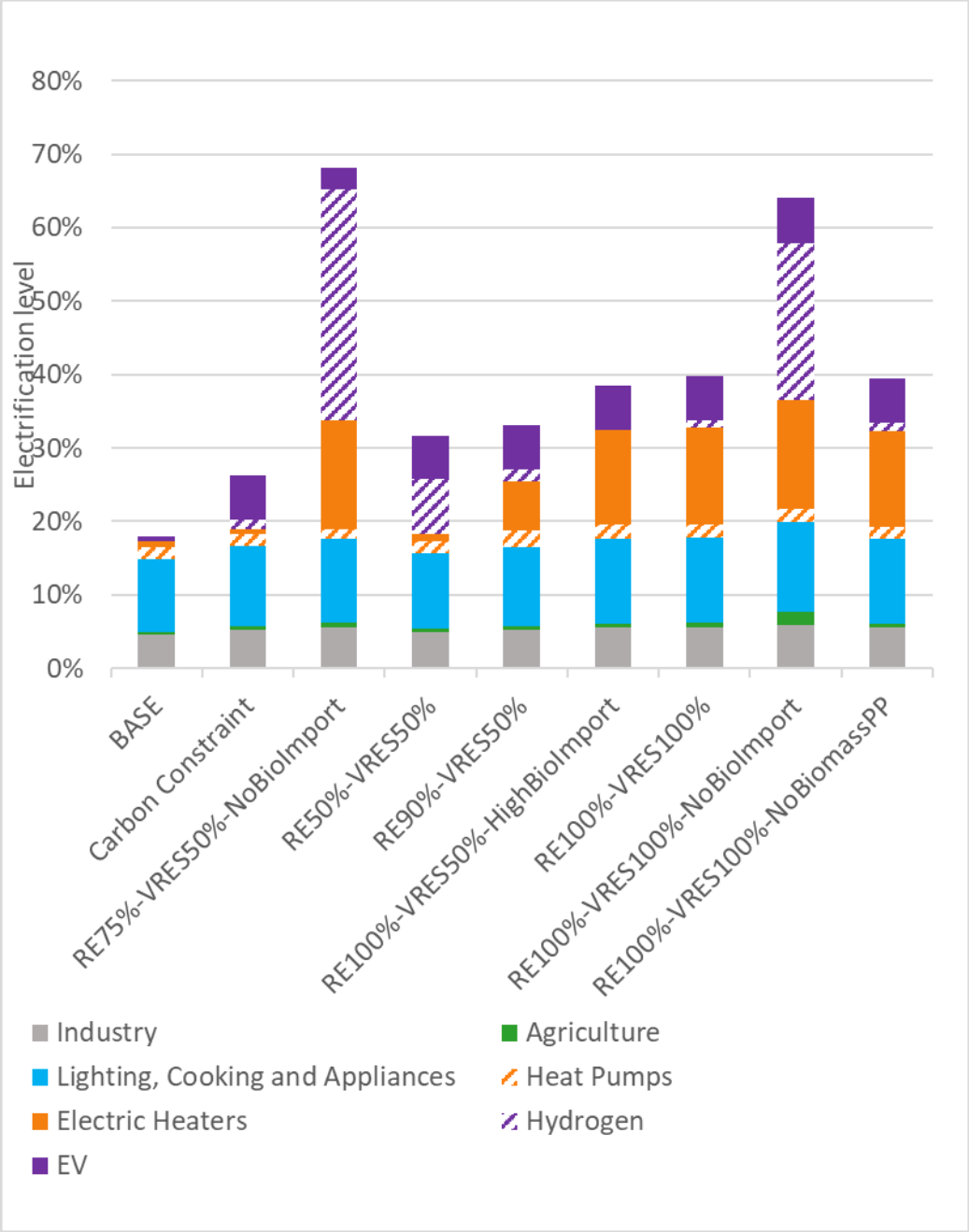

Figure 5 Electrification level by applications in 2050

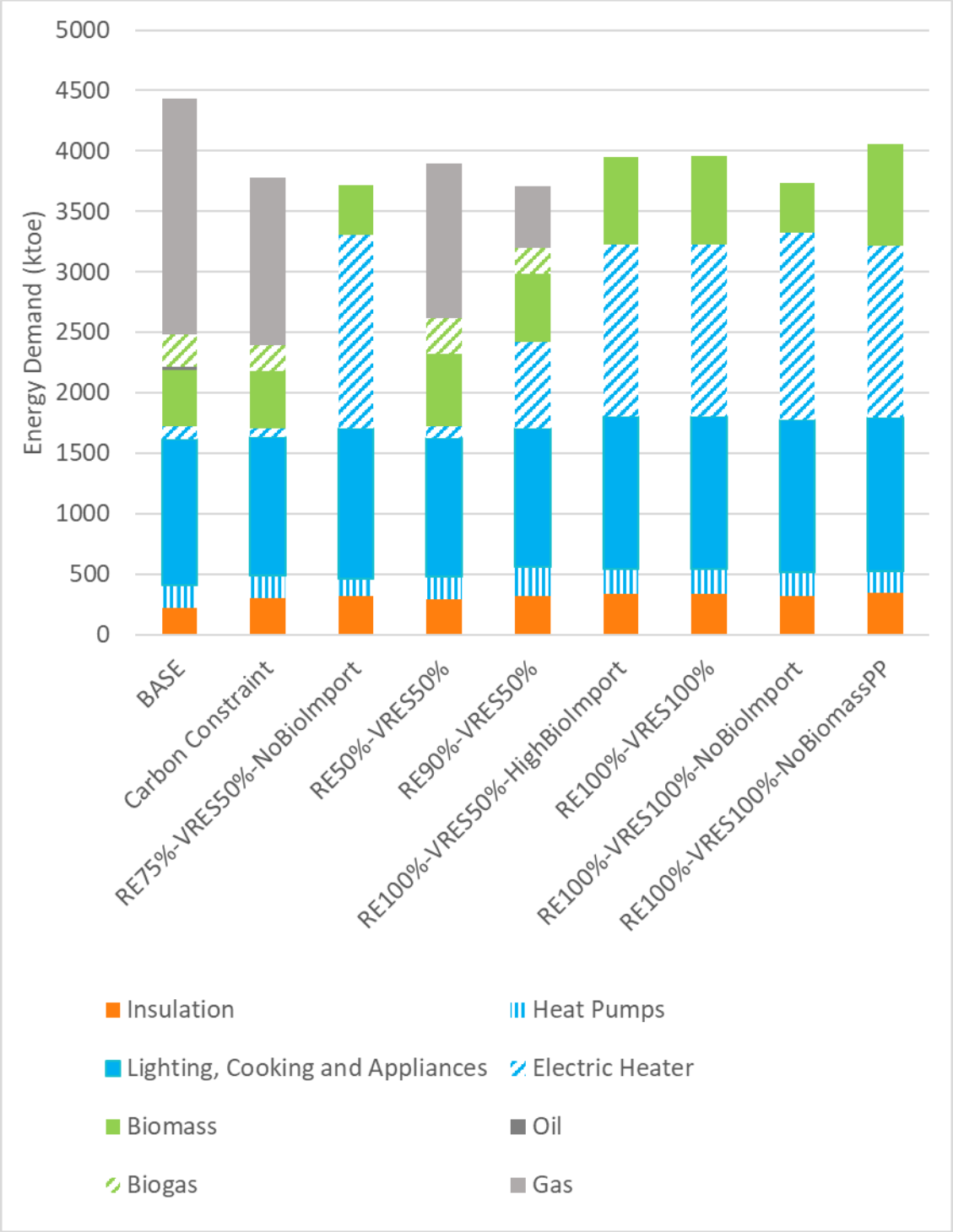

Figure 6 Final energy demand in building sector in 2050

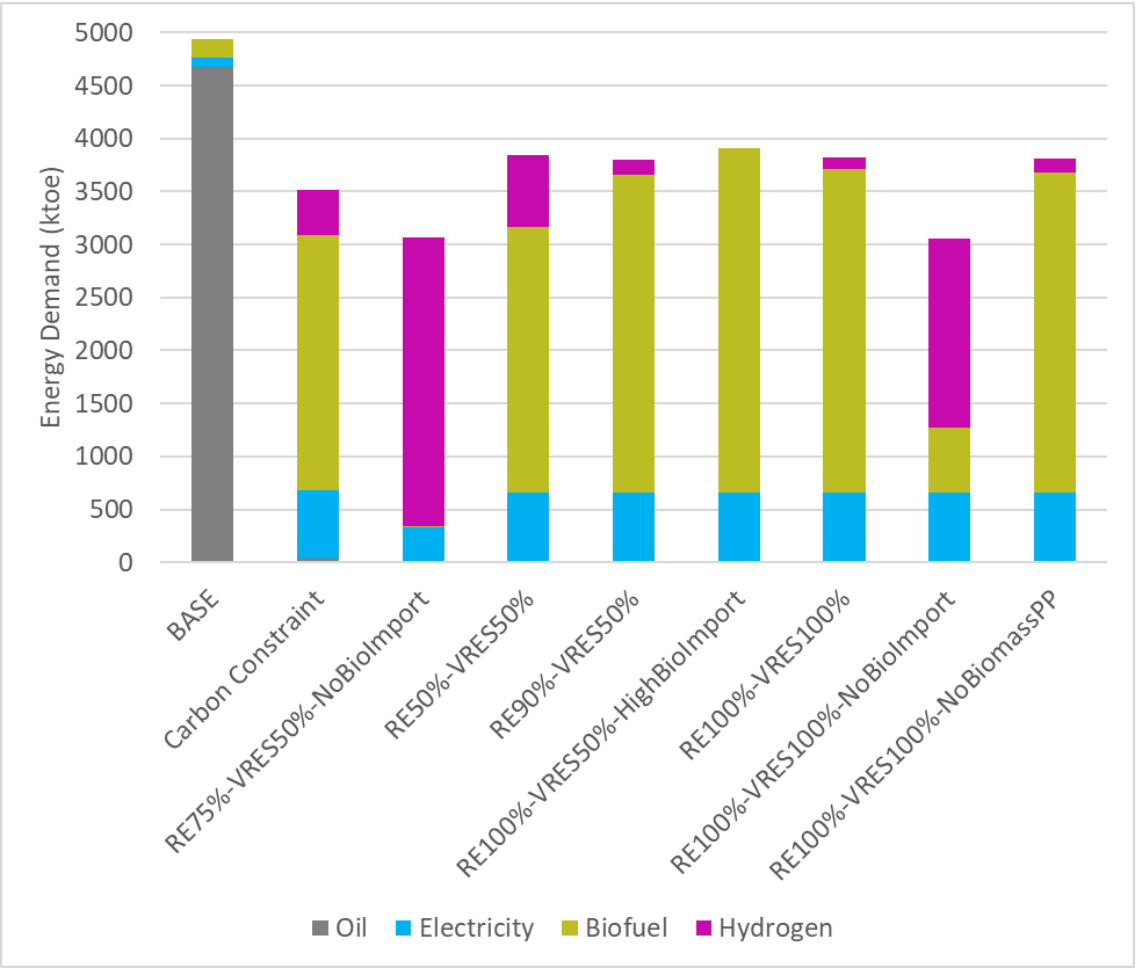

Figure 7 final energy demand in transport sector in 2050

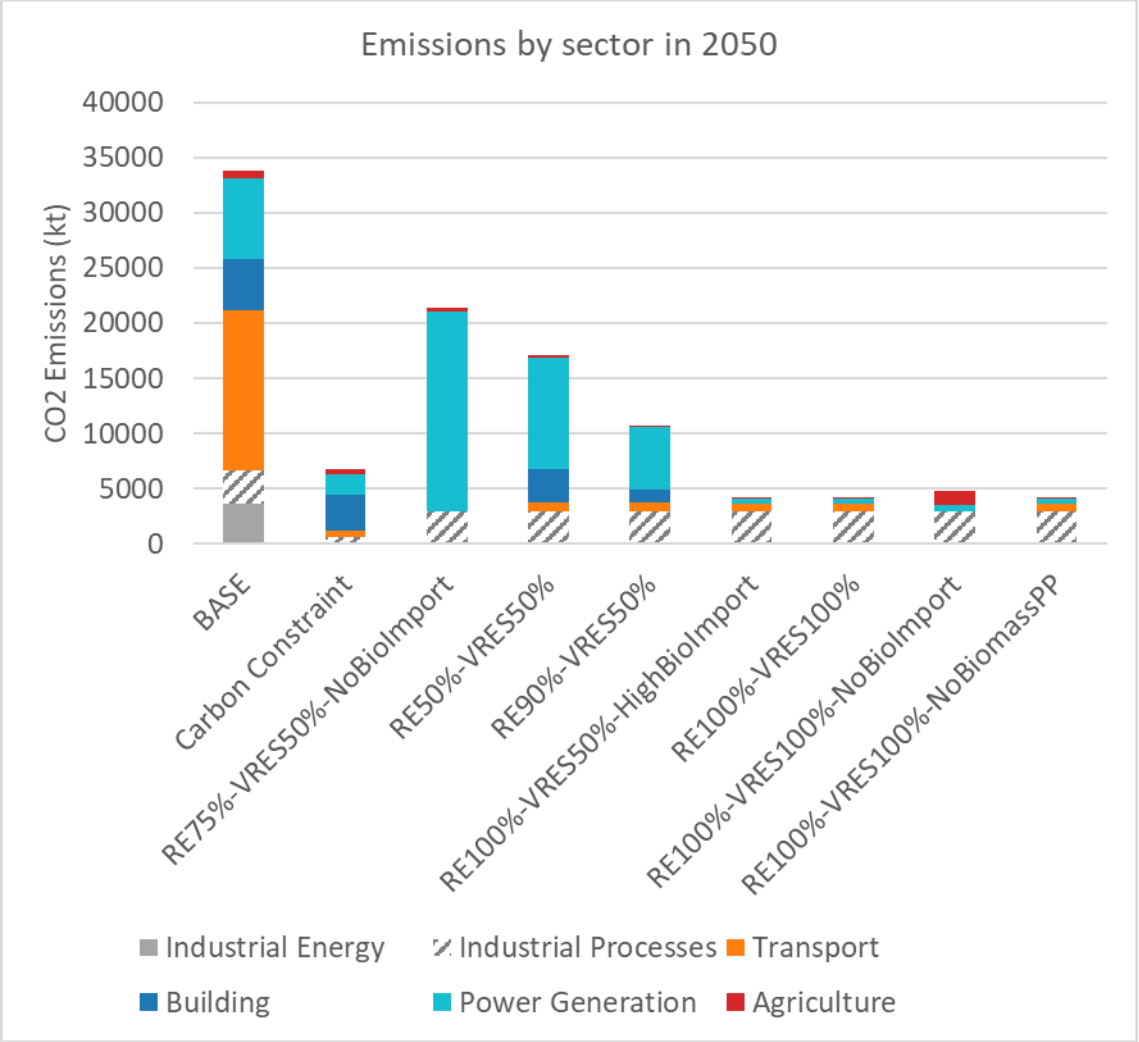

Figure 8 Emissions by sector in 2050

3.1.2 **Economic Implications**

The level of difficulties in achieving renewable energy targets can be measured by the total energy system cost. As explained in Section 3.1, the principle of the TIMES model is to minimize the total discounted energy system cost over the entire time horizon. The total system cost includes energy import costs, capital investments and operation and maintenance costs. A higher total system cost indicates more efforts required to achieve more ambitious renewable energy targets. Figure 9 shows total systems cost in 2050 expressed in terms of percentage of projected GDP in 2050. The cost curve is nonlinear and the marginal efforts at high renewable penetration levels are significantly higher. Increasing renewable penetration from 25% to 50% requires additional total system cost equivalent to less than 0.3% of total GDP in 2050. Further pushing renewable penetration to 90% requires 1.7% GDP in total system cost.

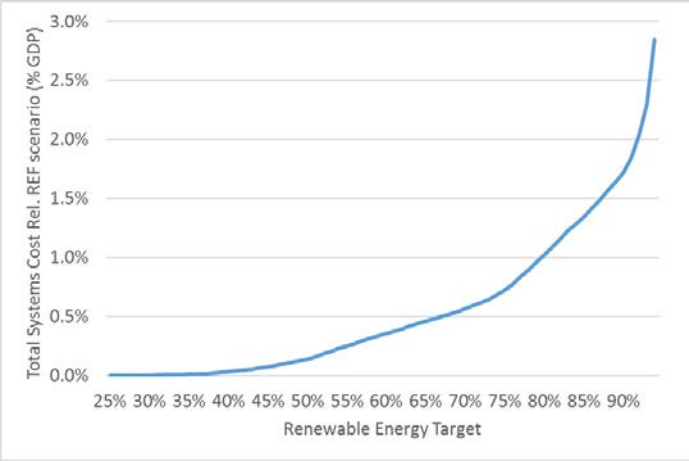

Figure 9 Total system cost in 2050 over different renewable energy penetration targets. The cost is measured in additional total energy system cost compared to BASE scenario in terms of GDP. The total energy system cost of BASE scenario is equivalent to 8% GDP.

3.2 Comparison between renewable and decarbonization targets

Sensitivity analysis is carried out on the renewable energy targets to explore their economic implications in carbon mitigation. The sensitivity analysis is carried out under the assumptions of medium level of bioenergy import supply and 50% maximum VRES penetration. As described in Section 2.3.2, for each renewable scenario, a corresponding carbon constraint scenario is developed with the same amount of carbon emissions in each model year.

The total systems costs in 2050 across renewable and decarbonization scenarios are graphically related and presented as cost curves in Figure 10. The Y-axis measures the additional total systems cost in 2050 compared to the BASE scenario measured in percentage of GDP. The X-axis measures the carbon reduction in 2050 relative to 1990 levels. For example, achieving 50% renewable target corresponds to an emission reduction of 49%, and 90% renewable energy target corresponds to 69% emission reduction.

The differences between the two cost curves demonstrate that focusing on renewable energy penetration is less cost effective in carbon mitigation compared to focusing solely on decarbonization. The gap between the cost curves widens as carbon reduction levels increases. Focusing solely on renewable energy targets is over 20% less cost effective in carbon mitigation compared to focusing on carbon reduction targets at high ambition levels. With an additional energy system cost equivalent to 1% GDP, emission reduces by 73% under CO_2 targets, but only reduces by 55% when focusing on renewable energy targets. Similarly, the energy system cost of 80% carbon reduction scenario only reduces emissions by 60% when focusing on renewable targets.

It should be noted that carbon prices cannot be compared directly between renewable scenarios and decarbonization scenarios. In linear programming models like TIMES models, the marginal abatement costs in carbon reduction are determined by the shadow price of CO_2. Under renewable scenarios, CO_2 emissions are model outputs rather than applied constraints, which makes the shadow prices under renewable scenarios 0.

Energy system analysis on the underlying scenarios of the two cost curves show that transition pathways with renewable energy targets and decarbonization targets differ significantly at less ambitious policy targets. For example, when focusing on CO_2 reduction, carbon intensive coal power plants phase out rapidly at 20% reduction target. On the other hand, when focusing on renewable penetration, coal plants are not phased out by 2050 at 70% renewable targets. At more ambitious policy targets, pathways towards renewable and decarbonization targets are broadly aligned as many of renewable technologies are carbon free. The key difference is that carbon sequestration technologies are ignored when focusing solely on renewables. Only 88% carbon reduction is reached in 100% renewable scenarios due to residual emissions from industrial processes.

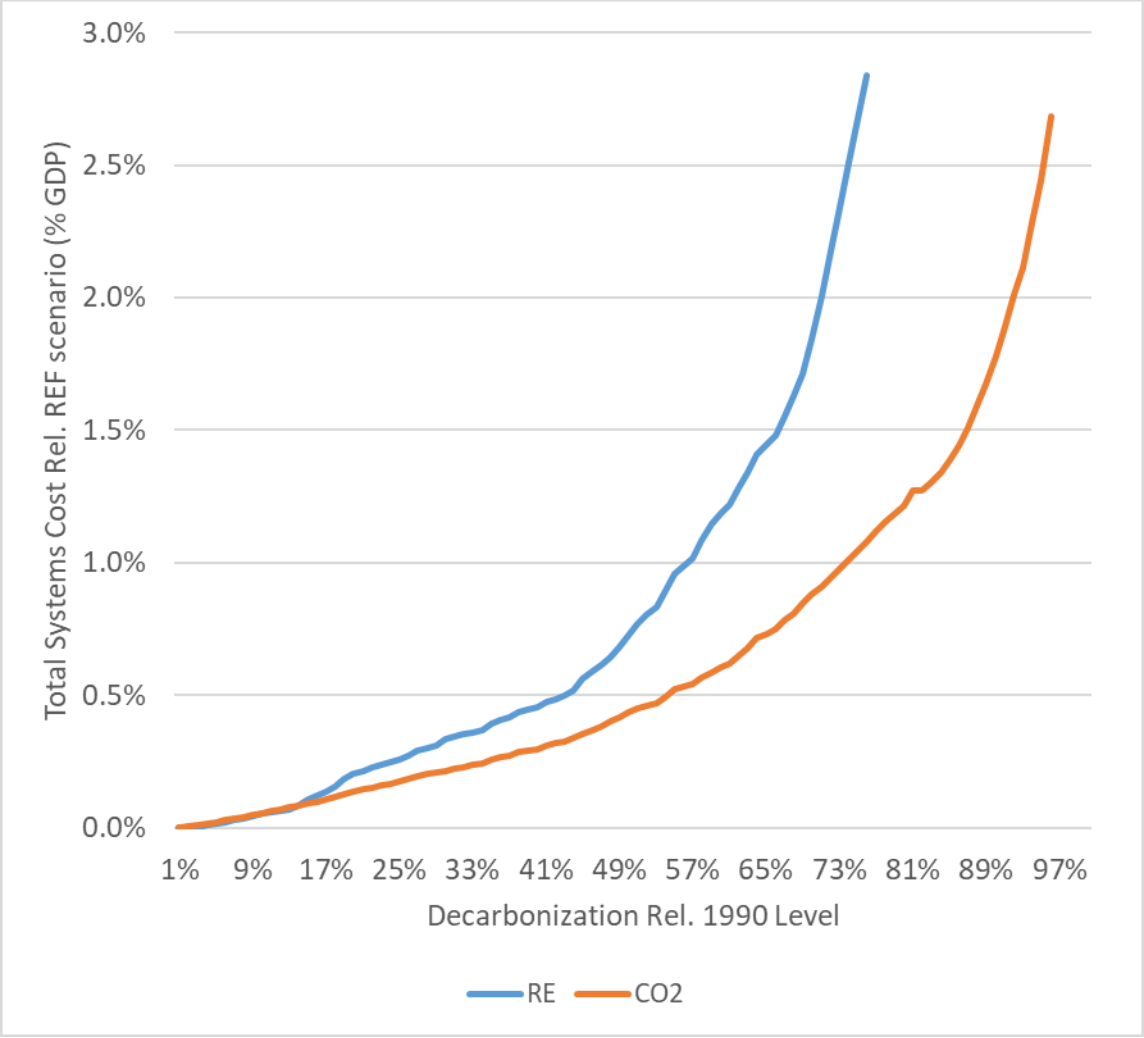

Figure 10 Cost curves in 2050 for renewable energy (RE) scenarios and their corresponding carbon constraint scenarios (CO2) with the same emission levels in each model year. The RE curve includes scenarios from the BASE scenario to the maximally feasible renewable energy level (94%), which corresponds to a 76% CO_2 reduction. For comparison purposes, the CO2 cost curve also includes scenarios with CO_2 reduction targets beyond 76%. In these scenarios, emissions in intermediate model years are linearly interpolated.

3.3 Global Sensitivity Analysis

While a range of deterministic scenario runs is useful in exploring the impacts of certain alternative model assumptions, a more systematic approach to address uncertainties for a broader range of input assumptions is through global sensitivity analysis. In this section we capture uncertainties for a large set of model inputs related to bioenergy and renewable technologies and analyse their impact on model results including energy consumption and capacity of renewable technologies. Global sensitivity analysis using 500 scenarios with stochastic input assumptions are used to quantify the relationships between model inputs and outputs.

A statistical measurement that quantifies the relationship between variables is the correlation coefficient. Table 4 presents the standardized correlation coefficients between input parameters and model results. A higher value indicates stronger impacts from input uncertainties on the model results. Parameters with p value greater than 0.05 are considered lack of statistical evidence in any relations between inputs and outputs. The correlation coefficients with high p values are left blank in Table 4. A positive correlation coefficient indicates that increasing the input parameter is likely to cause increases on the corresponding output. Similarly, a negative value indicates that the increase in input value is likely to cause decreases on the output.

The correlation coefficients show that uncertainties in bioenergy imports have strongest impacts on 100% renewable pathways. Table 4 shows that bioenergy import price and availability have the highest correlation coefficients with most of the model output. Compared to uncertainties in the investment costs of renewable technologies, uncertainties in bioenergy import has greater impact on the total system costs and capacity of renewable generation technologies. Uncertainties in technology costs mainly affect their own capacity expansion and have relatively weak impacts on other model outputs. For example, the cost of offshore wind has a strong negative correlation (-0.56) with its own capacity and much weaker correlations with the capacity of ocean energy (0.22) and biomass power plants (0.21).

Figure 11 presents the pathways from 2015 to 2050 of key renewable options under uncertainties, demonstrating optimal investment timings and robustness against uncertainties. The graph shows that the pathways of hydrogen consumption in transport sector have a wide span over time and are therefore susceptible to uncertainties. On the other hand, onshore wind has a much narrow span and reaches maximum resource potential by 2050 across all scenarios and can therefore be considered as “no-regret” options. This is consistent with the statistical results in Table 4. High correlation coefficients indicate that hydrogen consumption is very sensitive towards assumptions in bioenergy import price and availability, whereas none of the model inputs have significant correlations with onshore wind capacity.

Table 4 Standard Correlation Coefficient of global sensitivity analysis

Model Inputs \ Model Outputs	System Cost	Level of Electrification	Bioenergy Consumption	Offshore Wind	Solar Plant	Ocean Energy	Biomass Plants	Electric Vehicles	Transport Biofuel	Transport Hydrogen	Heat Pumps	Biomass Heating	Solar heating
Bioenergy Import Availability	-0.33	-0.44	-0.15	-0.18	-0.17	-0.30	0.44	-0.30	0.31		-0.37	0.44	
Bioenergy Import Price	0.88	0.69	-0.66	0.27	0.25	0.37	-0.58	0.60	-0.66	0.76	0.38	-0.39	
Onshore Wind Cost	0.06												
Offshore Wind Cost	0.23		0.28	-0.57		0.22	0.21		-0.06	-0.07			
Electrolysis Cost	0.01	-0.06								-0.14			
Wave Energy Cost	0.05	-0.20	0.38	0.36	0.25	-0.57	0.35			-0.18			0.08
Heat Pump Cost	0.03										-0.10	0.15	
Commercial Solar Cost		-0.06									-0.17	0.19	
Residential Solar Cost	0.06	0.25	0.19		-0.08		0.26				-0.09		-0.83
Solar Power Plant Cost	0.03				-0.51								

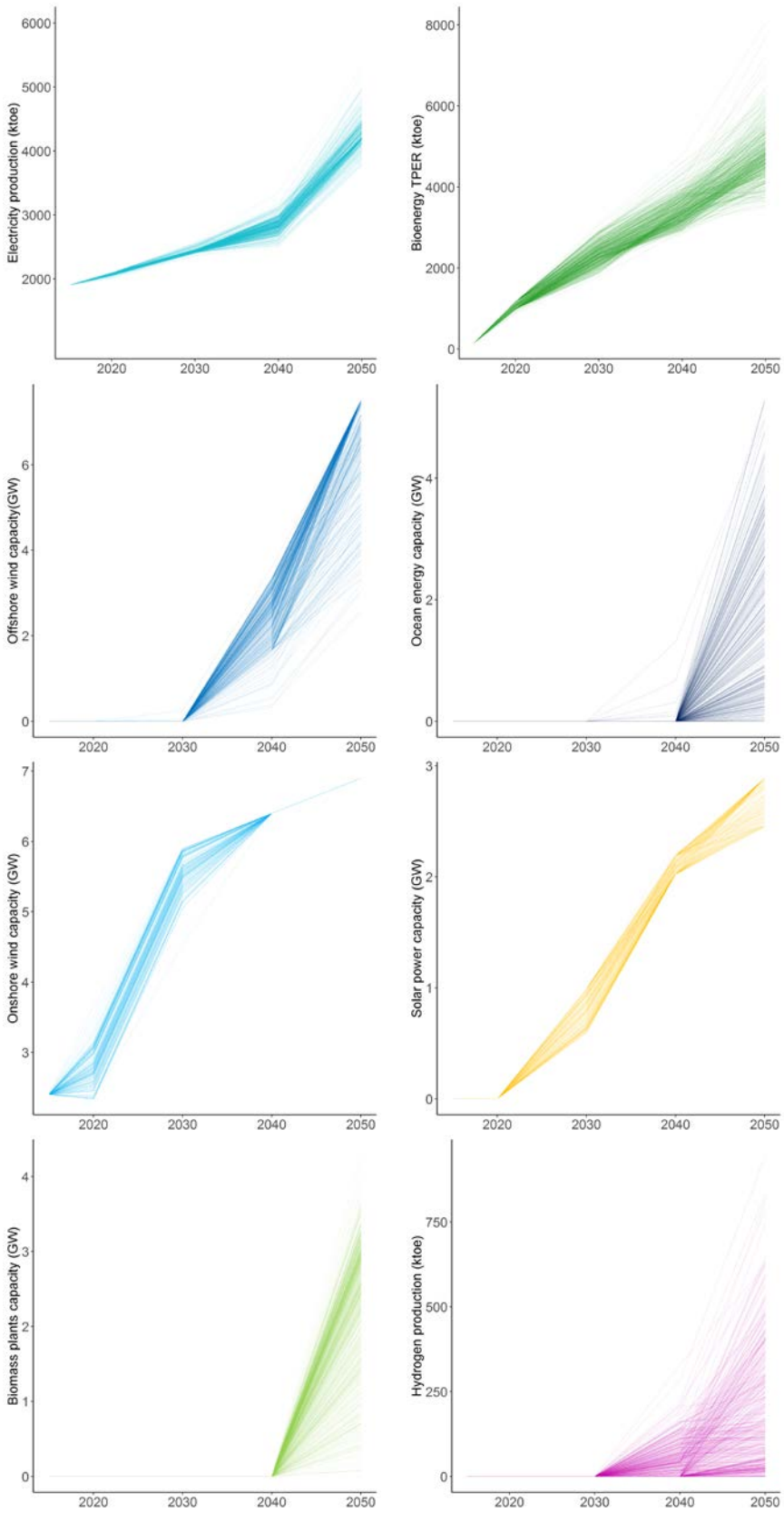

Figure 11 Pathways of renewable technology penetrations and fuel consumption under uncertainties

4 Discussions

Compared to using simulation models to analyse 100% renewable energy systems, the major advantage of using TIMES model is optimizing the bioenergy consumption and electrification level while considering power generation, heat and transport sectors in an integrated manner. Bioenergy and renewable electricity are the primary energy supplies under 100% renewable pathways. Decision making should strike a balance between the use of bioenergy and electrification with considerations in feasibilities, uncertainties and technical challenges. The roles of bioenergy and electrification under 100% renewables can be demonstrated by comparing advantages and challenges between the bioenergy dependent pathway represented by the RE100%-VRES50%-HighBioImport scenario and the electrification pathway represented by the RE100%-VRES100%-NoBioImport scenario.

The bioenergy and electrification pathways have similar total energy system costs. Total system costs in 2050 of both pathways are 29% higher relative to the BASE scenario and the difference in total system cost between these pathways is less than 1%. However, the cost composition of the system costs in these scenarios differ significantly. Bioenergy dependent pathways rely heavily on the bioenergy import. Ireland's import dependency remained around 85% to 90% until 2016. It fell to 69% in 2016 and 66% in 2017 due to the new gas field and increases in wind energy. The total import cost in 2017 was €4 billion accounting for 1.2% total GDP. The import dependency under the bioenergy pathway is 58% by 2050. The import cost rises to €9.9 billion import cost accounting for 26.3% of the system cost. This amount is higher than the fossil fuel import cost of €9.3 billion in 2050 projected by the BASE scenario.

High dependency on bioenergy import poses significant challenges in energy security. A review study by [90] suggests that under different technical and sustainability assumptions the estimate in global bioenergy supply ranges widely from 100EJ per year to over 1200EJ per year [90] and estimate of over 600EJ is based on extreme assumptions and should not be considered as socially acceptable or environmentally responsible. The current world population share of Ireland is 0.06% and the share of primary energy demand is about 0.1% [91]. If the share of global bioenergy supply for Ireland (12700ktoe) remains at the similar level to its current share of primary energy demand, the world bioenergy supply should exceed 530EJ, which is roughly similar to the current global primary energy supply (550EJ). As shown in Section 3.3, the global sensitivity analysis indicates that the uncertainties in bioenergy import has strongest impacts on the energy pathways. Therefore, locking into a bioenergy dependent pathway is susceptible to uncertainties and poses risks for energy security.

When the bioenergy import is disabled, the 100% renewable pathways rely on renewable electricity and electro-fuels. Under the electrification dependent pathway, all energy supply is from indigenous sources including indigenous bioenergy production and renewable electricity. Even though this electrification pathway is robust against uncertainties in energy import, technical challenges of high intermittency is a source of risks and high installation rate of renewable power generation technologies also pose challenges in acquiring investment, materials and labour. By 2050, electricity accounts for 64.1% of final energy demand and the VRES penetration in power generation reaches 97.9%. The annual investment cost requirements in new generation is €8.4 billion, which is significantly higher than the €1.3 billion under the BASE scenario and €3.4 billion under the bioenergy pathway. The capacity of renewable generation is projected to 30.8GW under the electrification pathway implying annual average installation rate over 800MW in onshore and offshore wind, solar and ocean energy, which is more than 50% higher compared to the installation rate of 532MW in wind energy as of 2017.

The key challenge of the electrification pathway is the integration of 100% intermittent generation in power sector. As a relatively small isolated Ireland country, integrating high VRES into the power system could be particularly challenging for Ireland due to lack of interconnection [92]. From the literature review we find that the technical feasibility of power systems with 100% renewable electricity remains controversial. As discussed in Section 2.1, many studies indicate that 100% renewable energy systems are feasible at reasonable costs while other studies conclude differently. An EU project in exploring solutions and costs for high VRES power system is currently underway[93]. While this analysis is not intended to address the feasibilities and costs associated with integrating 100% VRES into the power system, the modelling results point to significant potentials in applying demand side management techniques to improve system flexibility. Under the electrification pathway, electricity consumption from electric vehicles and power-to-gas account for over 40% share of total electricity consumption.

It should be noted that the cost estimate related to energy storage within the current modelling frame is underestimated. Long term energy systems models are best suited in projecting long term optimal pathways and may not properly validate feasibility of power system under 100% VRES or determine the associated costs. In the Irish TIMES model, each milestone year contains 12 time slices (seasonal, day, nights and peak for four seasons). Using a small number of time slices cannot properly capture variation in intermittent generation and may result in underestimate in the capacity of hydrogen storage required [86] [62]. Our model results show that energy storage mainly capture day/night variabilities in power generation and does not sufficiently account for variation in wind energy. To address this underestimate in storage capacity and usage, in this analysis we leave some reserve for energy storage by crudely increasing the assumption in capital cost of power to gas by 20%. Future work on Irish TIMES model will focus on improving integration of short-term variations of the power system to provide a more accurate projection of energy storage. Possible methods include incorporating high temporal resolution, dispatching features and soft linking with power systems models [94].

Another important area related to 100% renewable energy that requires further research is the estimates in renewable source potential, which vary significantly within the current literatures. For example, Estimates from SEAI [95] projects onshore wind potential between 11GW – 16GW and 30GW of offshore wind by 2050, which is more than twice as much as our assumptions (6.9GW on onshore wind and 7.5GW offshore wind). In our model the constraints applied on renewable resource potentials are based on relatively conservative assumptions. Compared to analysis assuming wind and solar power can provide all renewable electricity [22], the generation portfolio from our modelling results is more diversified with combinations of wind, solar, offshore wind, wave and tidal energy, which is also more energy secure compared to 100% WWS power system as ocean energy is more predictable than wind and solar. This diversified generation portfolio requires much higher investment cost as the costs for wave, tidal and offshore wind are significantly higher, which could somehow account for the underestimate in the cost for integrating high VRES into the power system.

5 Conclusions

The use of renewable energy is a critical decarbonization option with co-benefits in environment, economics, and energy security. In this analysis, we carry out the first assessment of 100% renewable energy system in 2050 for Ireland using the Irish TIMES energy system optimization model. Scenario ensembles under a broad scope of assumptions are used to explore technical and economic feasibilities towards 100% renewables while assessing the roles of electrification, bioenergy, and key renewable technology options.

The results show that under current technology assumptions and resource potentials with an annual limit of 50% on VRES generation, a maximum of 94% renewable can be reached, where electricity accounts for one third of energy consumption with over 85% from renewables. Without bioenergy import, maximum feasible renewable reduces to 75%. 100% renewables can be reached with more ambitious bioenergy supply or integrating higher shares of variable renewable energy. Scenarios with 100% renewables requires additional system cost equivalent to more than 2% GDP relative to the BASE scenario. Incremental cost in targeting for higher ambitious renewable penetration levels is non-linear. Extra system cost from 25% to 50% renewable level is less than 0.3% of total GDP and reaching 90% RES requires 1.3% of total GDP.

The policy target of 100% renewable energy should not be confused with a net zero emission target. Focusing on renewable penetration is less cost effective in achieving carbon mitigation compared to focusing only on carbon mitigation. The energy system cost required for 80% carbon reduction targets will only deliver a 60% reduction in when achieved focusing on renewables. It is critical to set renewable energy targets in line with carbon reduction targets and avoid overlooking cost effective carbon mitigation measures and residual emissions that require negative emission technologies.

Bioenergy and renewable electricity from wind, solar, ocean and offshore wind are the main sources of renewable energy. Indigenous bioenergy consumption is close to maximal resource potentials in all 100% renewable pathways, indicating that efforts in maximizing indigenous bioenergy resources should be made. The overall electrification level ranges from 39% to 61%. Given that the current electrification level is less than 20%, much stronger efforts and faster progresses are required than the current renewable energy plan [96].

Pathways relying on high bioenergy imports are less costly and require less upfront investment and infrastructural transformation. However, under these pathways up to 58% of TPER comes from imported biofuels. Global sensitivity analysis with 500 scenarios has been used to address critical uncertainties in bioenergy availability, import prices and investment costs of renewable technologies. The results indicate that bioenergy import has much greater impacts compared to uncertainties in investment costs. Given the current view of the world, more caution is required when setting policy targets with high shares of bioenergy. Some of the recent incidents such as Amazon wildfires and COVID-19 may have negative impacts on international trade and global bioenergy supply in the future. Relying on bioenergy imports therefore presents challenges in securing energy supply.

It is recommended that further policy consideration should be given to pathways with higher electrification levels. Renewable electricity plays a critical role when bioenergy imports are disabled. Compared to pathways relying on bioenergy, pathways with high electrification levels are more robust to uncertainties and can help improve energy security. However, it should be noted that these pathways require integrating high shares of variable renewable electricity combined with high penetration of power-to-gas technologies, which may confront challenges in high upfront

investment costs and integration of intermittent generation. If the strategy of incorporating a higher share of electrification levels while reducing bioenergy import dependency is desired, the development of renewable electricity should speed up, with additional efforts made on electrifying heat and transport sectors through heat pumps, EVs and power to gas.

While a broad range of uncertainty sources related to renewable energy are considered in this analysis through scenario ensembles, it is impossible to exhaustively capture all uncertainty sources. Future analysis could explore uncertainties from other aspects. One possible area of research is developing scenarios that envisage no growth in GDP or energy consumption with energy service demands projected using macro-economic modelling approaches.

Acknowledgements

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6 Reference

[1] UNFCCC. Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010. 2011.

[2] UNFCCC. Adoption of the Paris Agreement. Report No. FCCC/CP/2015/L.9/Rev.1. 2015.

[3] Rogelj J, Schaeffer M, Friedlingstein P, Gillett NP, van Vuuren DP, Riahi K, et al. Differences between carbon budget estimates unravelled. Nat Clim Chang 2016;6:245–52. https://doi.org/10.1038/nclimate2868.

[4] Millar RJ, Fuglestvedt JS, Friedlingstein P, Rogelj J, Grubb MJ, Matthews HD, et al. Emission budgets and pathways consistent with limiting warming to 1.5 °c. Nat Geosci 2017;10:741–7. https://doi.org/10.1038/NGEO3031.

[5] Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichefet T, Friedlingstein P, et al. Long-term climate change: Projections, commitments and irreversibility. Clim Chang 2013 Phys Sci Basis Work Gr I Contrib to Fifth Assess Rep Intergov Panel Clim Chang 2013:1029–136. https://doi.org/10.1017/CBO9781107415324.024.

[6] European Council. Presidency Conclusions: Brussels European Council 29/30 October 2009, 15265/1/09. 2009.

[7] Rankin J. EU leaders to spar over zero-carbon pledge for 2050. Guard 2019. https://www.theguardian.com/environment/2019/jun/20/eu-leaders-to-spar-over-zero-carbon-pledge-for-2050 (accessed June 20, 2019).

[8] Ocasio Cortez A. H.Res.109 - 116th Congress (2019-2020): Recognizing the duty of the Federal Government to create a Green New Deal. vol. 000000. 2019.

[9] Walker P, Mason R, Carrington D. Theresa May commits to net zero UK carbon emissions by 2050. Guard 2019. https://www.theguardian.com/environment/2019/jun/11/theresa-may-commits-to-net-zero-uk-carbon-emissions-by-2050 (accessed June 19, 2019).

[10] Motyka M, Slaughter A, Amon C. Global renewable energy trends. Deloitte Insights Sept 2018;13.

[11] Rogelj J, Jiang K, Fifita S. Mitigation pathways compatible with 1.5° C in the context of sustainable development. Glob. Warm. 1.5°C. An IPCC Spec. Rep. impacts Glob. Warm. 1.5°C above pre-industrial levels Relat. Glob. Greenh. gas Emiss. pathways, Context Strength. Glob. response to Threat Clim. Chang., 2018.

[12] IRENA. Global Energy Transformation: A Roadmap to 2050. 2018. https://doi.org/Doi 10.1002/(Sici)1097-0029(19990915)46:6<398::Aid-Jemt8>3.0.Co;2-H.

[13] Höök M, Tang X. Depletion of fossil fuels and anthropogenic climate change-A review. Energy Policy 2013;52:797–809. https://doi.org/10.1016/j.enpol.2012.10.046.

[14] International Energy Agency. Energy Technology Perspectives 2017 - Catalysing Energy Technology Transformations. 2017. https://doi.org/10.1787/energy_tech-2017-en.

[15] UN Climate Change. NDC Registry 2019. https://www4.unfccc.int/sites/NDCStaging/Pages/Home.aspx (accessed June 21, 2019).

[16] Wuester H, Strinati C. Untapped Potential for Climate Action: Renewable Energy in Nationally Determined Contributions. 2017.

[17] European Commission. STATEMENT/18/4155 2018.

[18] REN21. Renewables 2019 global status report. 2019.

[19] IEA. Energy Technology Perspectives 2017. OECD; 2017. https://doi.org/10.1787/energy_tech-2017-en.

[20] Hansen K, Breyer C, Lund H. Status and perspectives on 100% renewable energy systems. Energy 2019;175:471–80. https://doi.org/10.1016/j.energy.2019.03.092.

[21] Jacobson MZ, Delucchi MA, Bazouin G, Bauer ZAF, Heavey CC, Fisher E, et al. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. Energy Environ Sci 2015;8:2093–117. https://doi.org/10.1039/c5ee01283j.

[22] Jacobson MZ, Delucchi MA, Bauer ZAF, Goodman SC, Chapman WE, Cameron MA, et al. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. Joule 2017;1:108–21. https://doi.org/10.1016/j.joule.2017.07.005.

[23] Clack CTM, Qvist SA, Apt J, Bazilian M, Brandt AR, Caldeira K, et al. Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. Proc Natl Acad Sci U S A 2017;114:6722–7. https://doi.org/10.1073/pnas.1610381114.

[24] Connolly D, Lund H, Mathiesen B V. Smart Energy Europe : The technical and economic impact of one potential 100 % renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. https://doi.org/10.1016/j.rser.2016.02.025.

[25] Zakeri B, Syri S, Rinne S. Higher renewable energy integration into the existing energy system of Finland – Is there any maximum limit? Energy 2015;92:244–59. https://doi.org/10.1016/J.ENERGY.2015.01.007.

[26] Child M, Breyer C. The Role of Energy Storage Solutions in a 100% Renewable Finnish Energy System. Energy Procedia 2016;99:25–34. https://doi.org/10.1016/J.EGYPRO.2016.10.094.

[27] Ćosić B, Krajačić G, Duić N. A 100% renewable energy system in the year 2050: The case of Macedonia. Energy 2012;48:80–7. https://doi.org/10.1016/j.energy.2012.06.078.

[28] Lund H, Connolly D. Limiting biomass consumption for heating in 100% renewable energy systems. Energy 2012;48:160–8. https://doi.org/10.1016/J.ENERGY.2012.07.063.

[29] Lund HÃ, Mathiesen B V. Energy system analysis of 100 % renewable energy systems — The case of Denmark in years 2030 and 2050 2009;34:524–31. https://doi.org/10.1016/j.energy.2008.04.003.

[30] Vad B, Lund H, Karlsson K. 100 % Renewable energy systems , climate mitigation and economic growth. Appl Energy 2015;88:488–501. https://doi.org/10.1016/j.apenergy.2010.03.001.

[31] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Appl Energy 2011;88:502–7. https://doi.org/10.1016/J.APENERGY.2010.03.006.

[32] Pursiheimo E, Holttinen H, Koljonen T. Path toward 100% renewable energy future and feasibility of power-to-gas technology in Nordic countries. IET Renew Power Gener 2017;11:1695–706. https://doi.org/10.1049/iet-rpg.2017.0021.

[33] Pursiheimo E, Holttinen H, Koljonen T. Inter-sectoral effects of high renewable energy share in global energy system. Renew Energy 2019;136:1119–29. https://doi.org/10.1016/j.renene.2018.09.082.

[34] Löffler K, Hainsch K, Burandt T, Oei P-Y, Kemfert C, Von Hirschhausen C. Designing a model for the global energy system—GENeSYS-MOD: An application of the open-source energy modeling system (OSeMOSYS). Energies 2017;10:1468.

[35] Yue X, Pye S, DeCarolis J, Li FGN, Rogan F, Gallachóir BÓ. A review of approaches to uncertainty assessment in energy system optimization models. Energy Strateg Rev 2018;21:204–17.

[36] Rogelj J, Popp A, Calvin K V, Luderer G, Emmerling J, Gernaat D, et al. Scenarios towards limiting global mean temperature increase below 1.5 °c. Nat Clim Chang 2018;8:325–32. https://doi.org/10.1038/s41558-018-0091-3.

[37] Hourcade J-C, Jaccard M, Bataille C, Ghersi F. Hybrid Modeling: New Answers to Old Challenges Introduction to the Special Issue of" The Energy Journal". Energy J 2006:1–11.

[38] Bhattacharyya SC, Timilsina GR. A review of energy system models. Int J Energy Sect Manag 2010;4:494–518. https://doi.org/10.1108/17506221011092742.

[39] Bazmi AA, Zahedi G. Sustainable energy systems: Role of optimization modeling techniques in power generation and supply - A review. Renew Sustain Energy Rev 2011;15:3480–500. https://doi.org/10.1016/j.rser.2011.05.003.

[40] Loulou R, Remme U, Kanudia A, Lehtila A, Goldstein G. Documentation for the TIMES Model Part II. 2016.

[41] Müller-Merbach H. The energy supply model MESSAGE. Eur J Oper Res 1983;12:408. https://doi.org/10.1016/0377-2217(83)90165-0.

[42] Heaton C. Modelling low-carbon energy system designs with the ETI ESME model. Energy Technologies Institute: 2014.

[43] Howells M, Rogner H, Strachan N, Heaps C, Huntington H, Kypreos S, et al. OSeMOSYS: the open source energy modeling system: an introduction to its ethos, structure and development. Energy Policy 2011;39:5850–70.

[44] Hunter K, Sreepathi S, DeCarolis JF. Modeling for insight using Tools for Energy Model Optimization and Analysis (Temoa). Energy Econ 2013;40:339–49. https://doi.org/10.1016/j.eneco.2013.07.014.

[45] European Council. Decision No. 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020. vol. 5. 2009.

[46] European Union. Intended Nationally Determined Contribution of the EU and its Member States 2015:1–7. https://doi.org/10.1613/jair.301.

[47] Government of Ireland. Climate Action Plan to Tackle Climate Breakdown. 2019.

[48] Chiodi A, Gargiulo M, Rogan F, Deane JP, Lavigne D, Rout UK, et al. Modelling the impacts of challenging 2050 European climate mitigation targets on Ireland's energy system. Energy Policy 2013;53:169–89. https://doi.org/10.1016/j.enpol.2012.10.045.

[49] Chiodi A, Gargiulo M, Deane JP, Lavigne D, Rout UK, Ó Gallachóir BP. Modelling the impacts of challenging 2020 non-ETS GHG emissions reduction targets on Ireland's energy system. Energy Policy 2013;62:1438–52. https://doi.org/10.1016/j.enpol.2013.07.129.

[50] Yue X, Rogan F, Glynn J, Gallachóir BÓ. From 2° C to 1.5° C: How Ambitious Can Ireland Be? Limiting Glob. Warm. to Well Below 2 °C Energy Syst. Model. Policy Dev., Springer; 2018, p. 191–205.

[51] Glynn J, Chiodi A, Gallachóir BÓ. Energy security assessment methods: Quantifying the security co-benefits of decarbonising the Irish Energy System. Energy Strateg Rev 2017;15:72–88.

[52] Chiodi A, Deane P, Gargiulo M, Ó Gallachóir B. The Role of Bioenergy in Ireland's Low Carbon Future – Is it Sustainable? J Sustain Dev Energy, Water Environ Syst 2015;3:196–216. https://doi.org/10.13044/j.sdewes.2015.03.0016.

[53] Deane P, Curtis J, Chiodi A, Gargiulo M, Rogan F, Dineen D, et al. Technical support on developing low carbon sector roadmaps for IrelandLow Carbon Energy Roadmap for Ireland 2013:1–125.

[54] DCCAE. Climate Action and Low Carbon Development Act 2015. 2015.

[55] DCENR. Ireland's Transition to a Low Carbon Energy Future 2015-2030. Gov Pap 2015:122.

[56] Curtin J, Bruin K de, Hanley E, Gallachóir BÓ. Energy Modelling to Inform the National Mitigation Plan 2017:1–36.

[57] Department of Communications Climate Action & Environment. National Mitigation Plan 2017:1–198.

[58] SEAI. Energy in Ireland 2018.

[59] Lund H, Arler F, Østergaard PA, Hvelplund F, Connolly D, Mathiesen BV, et al. Simulation versus optimisation: Theoretical positions in energy system modelling. Energies 2017;10:1–17. https://doi.org/10.3390/en10070840.

[60] Esteban M, Portugal-pereira J, Mclellan BC, Bricker J, Farzaneh H, Djalilova N, et al. 100 % renewable energy system in Japan : Smoothening and ancillary services. Appl Energy 2018;224:698–707. https://doi.org/10.1016/j.apenergy.2018.04.067.

[61] Mai T, Wiser R, Sandor D, Brinkman G, Heath G, Denholm P, et al. Exploration of High-Penetration Renewable Electricity Futures. vol. 1. 2012. https://doi.org/NREL/TP-6A20-52409-1.

[62] Krakowski V, Assoumou E, Mazauric V, Maïzi N. Reprint of Feasible path toward 40–100% renewable energy shares for power supply in France by 2050: A prospective analysis. Appl Energy 2016;184:1529–50. https://doi.org/10.1016/j.apenergy.2016.11.003.

[63] Ye B, Zhang K, Jiang JJ, Miao L, Li J. Towards a 90% renewable energy future: A case study of an island in the South China Sea. Energy Convers Manag 2017;142:28–41. https://doi.org/10.1016/j.enconman.2017.03.038.

[64] Akuru UB, Onukwube IE, Okoro OI, Obe ES. Towards 100 % renewable energy in Nigeria. Renew Sustain Energy Rev 2017;71:943–53. https://doi.org/10.1016/j.rser.2016.12.123.

[65] Bussar C, Moos M, Alvarez R, Wolf P, Thien T, Chen H, et al. Optimal allocation and capacity of energy storage systems in a future European power system with 100 % renewable energy generation 2014;46:40–7. https://doi.org/10.1016/j.egypro.2014.01.156.

[66] Aghahosseini A, Bogdanov D, Ghorbani N, Breyer C. Analysis of 100% renewable energy for Iran in 2030: integrating solar PV, wind energy and storage. Int J Environ Sci Technol 2018;15:17–36. https://doi.org/10.1007/s13762-017-1373-4.

[67] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. https://doi.org/10.1016/j.rser.2015.01.057.

[68] Deason W. Comparison of 100% renewable a system scenarios with a focus on flexibility and cost. Renew Sustain Energy Rev 2018;82:3168–78. https://doi.org/10.1016/j.rser.2017.10.026.

[69] Reedman LJ. High Penetration Renewables Studies : A Review of the Literature 2012.

[70] Lazkano I, Nøstbakken L, Pelli M. From fossil fuels to renewables : The role of electricity storage R 2017;99:113–29. https://doi.org/10.1016/j.euroecorev.2017.03.013.

[71] Pean E, Pirouti M, Qadrdan M. Role of the GB-France electricity interconnectors in integration of variable renewable generation. Renew Energy 2016;99:307–14. https://doi.org/10.1016/j.renene.2016.06.057.

[72] Kaundinya DP, Balachandra P, Ravindranath NH. Grid-connected versus stand-alone energy systems for decentralized power — A review of literature 2009;13:2041–50. https://doi.org/10.1016/j.rser.2009.02.002.

[73] Lilliestam J, Hanger S. Energy Research & Social Science Shades of green : Centralisation , decentralisation and controversy among European renewable electricity visions. Chem Phys Lett 2016;17:20–9. https://doi.org/10.1016/j.erss.2016.03.011.

[74] Mclellan B, Florin N, Giurco D, Kishita Y, Itaoka K. Decentralised energy futures : the changing emissions reduction landscape. Procedia CIRP 2015;29:138–43. https://doi.org/10.1016/j.procir.2015.02.052.

[75] Diesendorf M, Elliston B. The feasibility of 100 % renewable electricity systems : A response to critics ☆. Renew Sustain Energy Rev 2018;93:318–30. https://doi.org/10.1016/j.rser.2018.05.042.

[76] Heard BP, Brook BW, Wigley TML, Bradshaw CJA. Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. Renew Sustain Energy Rev 2017;76:1122–33. https://doi.org/10.1016/j.rser.2017.03.114.

[77] Brown TW, Bischof-Niemz T, Blok K, Breyer C, Lund H, Mathiesen B V. Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems.' Renew Sustain Energy Rev 2018;92:834–47. https://doi.org/10.1016/j.rser.2018.04.113.

[78] Bergin A, Conroy N, Rodriguez AG, Holland D, McInerney N, Morgenroth ELW, et al. COSMO: A new COre Structural MOdel for Ireland. ESRI Working Paper; 2017.

[79] ESBI E. Total renewable energy resource in Ireland. Final Report Eur Comm ALTENER Program Contract 1997;17:t4.

[80] Chiodi A. Characterization of wind energy within the Irish TIMES energy systems model in. Politec Di Torino 2010:167.

[81] Boemer J, Burges K, Nabe C, Pöller M. All island TSO facilitation of renewables studies. 2010.

[82] Clancy M, Bates J, Barker N, Edberg O, Fitzgerald J, Narkeviciute R, et al. BioEnergy Supply Curves for Ireland: 2010 - 2030. 2012.

[83] Tarvydas I. Cost development of low carbon energy technologies. 2018. https://doi.org/10.2760/23266.

[84] Hofmeister M, Guddat M. Techno-economic projections until 2050 for smaller heating and cooling technologies in the residential and tertiary sectors in the EU. 2017. https://doi.org/10.2760/110433.

[85] McDonagh S, O'Shea R, Wall DM, Deane JP, Murphy JD. Modelling of a power-to-gas system to predict the levelised cost of energy of an advanced renewable gaseous transport fuel. Appl Energy 2018;215:444–56. https://doi.org/10.1016/j.apenergy.2018.02.019.

[86] Sgobbi A, Nijs W, De Miglio R, Chiodi A, Gargiulo M, Thiel C. How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. Int J Hydrogen Energy 2016;41:19–35. https://doi.org/10.1016/j.ijhydene.2015.09.004.

[87] Ó Gallachóir BP, O'Leary F, Bazilian M, Howley M, McKeogh EJ. Comparing primary energy attributed to renewable energy with primary energy equivalent to determine carbon abatement in a national context. J Environ Sci Heal - Part A Toxic/Hazardous Subst Environ Eng 2006;41:923–37. https://doi.org/10.1080/10934520600614561.

[88] European Parliament. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009. Off J Eur Union 2009;140:16–62. https://doi.org/10.3000/17252555.L_2009.140.eng.

[89] Saltelli A, Ratto M, Andres T. Global sensitivity analysis: the primer. John Wiley; 2008.

[90] Slade R, Bauen A, Gross R. Global bioenergy resources. Nat Publ Gr 2014;4:99–105. https://doi.org/10.1038/nclimate2097.

[91] Birol F. Key World energy statistics 2017.

[92] Collins S, Deane JP, Ó Gallachóir B. Adding value to EU energy policy analysis using a multi-model approach with an EU-28 electricity dispatch model. Energy 2017;130:433–47. https://doi.org/10.1016/j.energy.2017.05.010.

[93] Hillberg E, Zegers A, Herndler B, Wong S, Pompee J, Bourmaud J-Y, et al. Flexibility needs in the future power system 2019.

[94] Deane JP, Chiodi A, Gargiulo M, Ó Gallachóir BP. Soft-linking of a power systems model to an energy systems model. Energy 2012;42:303–12. https://doi.org/10.1016/j.energy.2012.03.052.

[95] SEAI. Wind Energy Roadmap. 2011.

[96] DCCAE. National Renewable Energy Action Plan - Fourth Progress Report 2017:1–67.