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Master Thesis

Analysis of the Feasibility of the Irish Climate Action Plan Using TIMES Modelling Platform and QGIS Geospatial Software

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Streszczenie

W pracy określono potencjał energii słonecznej Irlandii, wcześniej nie publikowany w literaturze. Za pomocą zmodyfikowanego modelu energetycznnego TIMES Ireland (MTIM) opracowano scenariusze energetycznych z założonymi celami klimatycznymi na lata 2030 i 2050. Pozowliło to na zbadanie wykonalności obecnego planu działań na rzecz klimatu (CAP). W wyniku analizy wielokryterialnej (AHP) stwierdzono, że 9672 km^2 (13,8% całkowitej powierzchni gruntów) nadaje się do rozwoju fotowoltaiki. Odpowiada to całkowitej mocy elektrycznej możliwej do wybudowania na takim obszarze równej 603,57 GW i rocznej produkcji energii elektrycznej na poziomie 559,49 TWh. W scenariuszu pełnej elektryfikacji zapewnienie bilansowania zapotrzebowani na energię elektryczną na poziomie 25% w 2050 r . wymagało zainstalowania 32,64 GW mocy elektrycznej w elektrowniach słonecznych (523 km^2, tj. 0,74% powierzchni lądowej) odpowiadającej produkcji równej 121 TWh. Wielkość inwestycji CAPEX umożliwiających osiągnięcie celów neutralności netto do 2050 r., przekładających się na roczną redukcję emisji CO_2 o 97 000 kt wyniosła 134 mld EUR i objęła budowę 10 GW lądowej energii wiatrowej, 37 GW morskiej energii wiatrowej oraz 33 GW fotowoltaiki. Analiza wyników wykazała, że obecny plan CAP jest niewystarczający do osiągnięcia celów klimatycznych. Konieczna jest ponowna jego ocena zwłaszcza w zakresie długoterminowej strategii rozwoju energetyki słonecznej, kwestiami związanymi z planowaniem energetycznym, emisjami niezwiązanymi z energetyką oraz elektryfikacją systemu energetycznego. Przyszłe prace powinny obejmować szczegółową analizę potencjału energii słonecznej i miksu energetycznego oraz winny być prowadzone w oparciu o bardziej dokładne dane wejściowe przy holistycznym podejściu do analizy emisji sektorowych. Wskaźnik LCOE dla dużych systemów fotowoltaicznych w 2025 r. wyniosło 49,75 EUR/MWh. Do 2050 r. przewidywany jest spadek tego wskaźnika o 43,2%, czyli do 28,25 EUR/MWh. Będzie on więc o 11% niższy niż w przypadku elektrowni wiatrowych na lądzie i o 26,5% niższy niż w przypadku elektrowni wiatrowych na morzu, co dodatkowo potwierdza potencjał dla rozwoju energetyki słonecznej w Irlandii.

Abstract

Herein, the solar potential of Ireland was successfully determined, which is previously unpublished in the literature. A modified-TIMES Ireland (MTIM) energy model investigated a future potential energy scenario to reach the 2030 and 2050 climate targets, which also provided insights into the feasibility of the current Climate Action Plan (CAP). Through an Analytic Hierarchy Process (AHP) multi-criterial analysis, 9672 km^2 (13.8% of total land area) was found suitable for solar PP development, equating to a total capacity of 603.57 GW and generation potential of 559.49 TWh. To ensure a reliable future electricity grid, 32.64 GW of solar (523 km^2, 0.74% of land area) will be required to meet 25% of the predicted 2050 electricity demand (under a full electrification scenario – 121 TWh). 10 GW of

onshore wind, 37 GW of offshore wind, and 33 GW of solar PV will be required to reach the 2050 net-neutrality targets, abating 97’000 $ktCO_2$ and having a CAPEX investment of €134 billion. The LCOE of utility-scale solar PV was calculated as 49.75 €/MWh in 2025, decreasing by 43.2% to 28.25 €/MWh in 2050, which is 11% lower than onshore wind and 26.5% lower than offshore wind, respectively, further validating the potential of solar energy in Ireland. Through analysis of the results, the CAP was deemed insufficient to meet climate targets. A re-evaluation is necessary to address the lack of a long-term solar implementation strategy, issues pertaining to planning limitations and non-energy related emissions, and concerns regarding energy sector electrification. Future work should involve a more detailed analysis of the solar potential and future energy mix, including more accurate input data and more a more comprehensive analysis of sectoral emissions.

Acknowledgements

I’d like to offer a special thanks to both Artur Wyrwa and Maciej Raczyński, AGH Department of Energy and Fuels, for assisting in the development of the modified-TIMES Ireland energy model. Further appreciation is extended to Artur for supervising my thesis work and providing invaluable insights throughout the duration of the thesis work. I would also like to thank Andreas Wabbes, formerly PVComplete, for providing industry-specific insights into the utility-scale solar power plant selection process. Finally, I would like to thank Stephen Tracey, ESB Networks, for providing information on the available electrical infrastructure in Ireland, which was a key component of the solar suitability analysis.

1. Introduction

1.1. Background

Climate change has rapidly become a focal point of conversation in both social and political circles over the previous several years. The effects of climate change are becoming more apparent, with adverse weather events and climatic conditions having a direct impact on the livelihoods of others, e.g., droughts in Sub-Saharan countries have led to famine and the increase of lethal diseases [1]. While the developed world is less affected by current climate change, there is expected to be a long-term impact on the economic prosperity of developed nations if it is not controlled. Due to this, there has been an influx of climate-focussed policy aiming to curb greenhouse gas (GHG) emissions and reduce the warming of the planet to below 1.5 C°. However, while many countries have published national climate policies, most are falling short on their obligations. This has the potential to derail the necessary energy transition further the negative effects of climate change. While the European Union (EU) is traditionally a pioneer of climate policy, several countries within the EU bloc are unlikely to meet the proposed targets.

1.2. Thesis Motivation

Ireland, as a member of the EU-27 bloc, is obligated to reduce its emissions and increase renewable energy (RE) implementation in accordance with EU 2030 and 2050 targets. However, despite being one of the most successful economies in the EU, it has failed to make necessary progress in reducing GHG emissions. Ireland missed its 2020 targets, being the second-worst performer in Europe, with an increase in emissions across several sectors [2]. There are now growing concerns that this will be replicated at the end of the current decade [3]. Several factors have influenced this, but it can be partly blamed on mismanagement and uncertainty regarding the actual implementation of goals. The CAP, published by the Government of Ireland in 2021, is a document detailing the steps to achieve the necessary reductions [4]. An amended version was released in 2023 to reflect more ambitious targets. While it is an excellent blueprint, there are few national studies on the RE potential of Ireland, with the CAP lacking clarity on how and where RE systems will be introduced and integrated into the current electric grid. Particularly, there is little information on the solar energy potential in Ireland and how it will contribute to the future Irish energy system. The primary aim of this thesis is to investigate Ireland's solar energy potential from both a financial and technical perspective, and its influence on achieving the 2030 and 2050 RE targets, with a focus on the feasibility of current climate policy. The secondary aim is to use energy models to propose a future energy mix which will help Ireland achieve its long-term net-neutrality targets.

1.3. Current State of Play

To better understand Ireland's current situation and its impact on future climate goals, a background on their failures to meet the 2020 climate targets is provided. Ireland was obligated to reduce its emissions by 20% compared to 2005 levels before 2020. This should have included a 16% and 10% share of renewables in final energy sources and the transport sector, respectively. However, energy related emissions decreased by 16%, agricultural emissions increased by 8%, and total emissions decreased by only 7%, which is a clear failure of enacted policy [2]. To achieve the 2030 targets, Ireland requires a CO2 emission reduction of 4.8% per annum from 2020. In 2021 emissions increased by 5.4%, while there was only a 1.9% reduction in 2022. Ireland are the second-worst performers in the EU regarding GHG emissions reduction, ahead only of Poland, a coal-dominated country, with both countries receiving a very low score for climate performance [5]. Government mismanagement and overambitious targets (second most ambitious targets after Denmark) have been cited as the main reasons for these failures, as well as the unavailability of resources to meet demand.

The current government is positive about their progress regarding climate action. A quarterly report is published which details the completion rate of each respective task for that quarter and/or year [Table I].

TABLE I

ANALYSIS OF THE DELIVERY RATE OF 2023 CAP

Department	Q1 Actions Due	Complete	Delayed	Delivery Rate (%)
DECC	14	10	4	71
DAFM	11	10	1	91
DPER	4	1	3	25
DHLGH	3	2	1	67
DFIN	2	2	0	100
DETE	1	1	0	100
DFA	1	1	0	100
Total	36	27	9	75

CAP Q1,2023 Progress Report [6].

For Q1 2023, 75% of actions were completed. However, many of these measures were planning-orientated, which is characteristic of the failures leading up to the 2020 targets. Further, there is no long-term metric to assess quantitative data related to RE implementation (particularly solar energy), residential buildings, and transport.

To reach the 2030 emissions targets, 80% of electricity sources need to be renewable, which will consist of 9 GW of onshore wind capacity, 8 GW of solar, and at least 5 GW of offshore wind [4].

Regarding residential buildings, the government plans to retrofit 500’000 buildings and install 680’000 renewable heat sources by 2030, which is part of the National Retrofit Plan [7]. Cost is a main barrier, with prices to retrofit homes quoted as between €20–80’000. With the current cost of living crisis, this plan has been branded as impractical. Current estimates are that 27’000 homes were retrofitted in 2022, far below the required targets [8]. Finally, 1’000’000 electric vehicles (EVs) are expected to be present on Irish roads by 2030. In 2022, 15’678 EVs were registered [9], with an estimated total fleet in the tens of thousands. With an average of 100’000 new car registrations per year, it seems increasingly unlikely that Ireland will come even close to the 2030 goal. A lack of public charging infrastructure is a main concern, with 80% of all EV charging done at home. The government have recently announced a new national charging plan, with the hope that this, coupled with higher fossil fuel prices, will increase consumer confidence and cause EV sales to significantly improve [10]. The net-neutrality targets outlined in national policy rely on the full electrification of the Irish energy system, so these delays have large potential knock-on effects for the long-term success of the climate goals.

While the CAP contains detailed information on the capacities required to meet the 2030 targets, it features no long-term plan and doesn’t frame the current targets in the context of a wider net-neutrality strategy, which will impact developer confidence in the industry and the eventual capacity goals. A modified TIMES (The Integrated MARKAL-EFOM System) energy model is presented herein to propose a potential future energy mix. It will also provide insights into the environmental benefits of the future scenario and associated investment costs. To ensure a reliable future electricity grid, and to minimise the need of fossil fuel technologies during low periods of wind resources, solar energy will be necessary to meet Ireland’s net-neutrality targets. Current government publications focus on wind energy, with no official information on the solar capacity to be implemented by 2050. GIS (geographic information system) software will be used to evaluate the potential of solar energy Ireland in Ireland, which will be necessary to achieve the national climate policy targets. The LCOE’s of different Re technologies will also be compared to support the solar energy potential analysis. A multi-criterial AHP analysis will be completed to rank the suitability of different regions for utility-scale solar PPs. This will also provide insights into the feasibility of the current CAP, and whether it is achievable considering past and current progress.

2. Literature Review

2.1. Energy System Models for Climate Policy

Energy system models are crucial to understand the necessary emission abatement steps. TIMES is a bottom-up energy system optimisation model which represents the possible evolution of an energy system on a national, regional, or global level. It is a linear optimisation model using the GAMS (General Algebraic Modelling System) modelling language, which minimises cost according to user constraints [11], and is executed in VEDA 2.0 modelling software. TIMES has been used to map out energy transitions, with respective models created for national energy transition scenarios, e.g., for Ukraine [12] and the United Kingdom [13]. The TIMES Ireland model was created by the Environment Research Institute, University College Cork, for the Environmental Protection Agency of Ireland, to evaluate the progress and feasibility of Ireland’s 2020 climate targets and map out alternative energy pathways [14]. Since then, different iterations have influenced Irish climate policy over the previous decade, e.g., as a foundation for Ireland’s first low-carbon roadmap [15] as well as developing strategies in line with the Paris Climate Agreement [16]. The latest iteration, the TIMES-Ireland model (TIM), was updated to reflect the latest energy goals, technological improvements, and improvements to optimisation model techniques [17]. TIM is used in the CAP to propose energy transition strategies, and so is the preferred model for an assessment of Ireland’s future energy mix. Current literature reveals the versatility of TIM in exploring Ireland’s decarbonisation strategy. Examples are the modelling of agricultural emissions in Ireland [18], exploring decreased energy demand scenarios as a pathway to decarbonisation [19], and even for a regional analysis of the transport sector and the challenges faced by EVs [20]. However, TIM has not considered solar as a main contributor to a future variable energy mix in Ireland, which will be important to achieve the 2050 net-neutrality targets.

2.2. Renewable Energy Site Selection

While TIM successfully models energy sectors, it cannot provide insights into a countries implementation strategy, particularly related to the REG potential of different technologies. Combining energy models with REG potential assessments allows for a more comprehensive analysis of climate policy feasibility. A popular method is using GIS software to run suitability analyses on land areas. GIS software is used to store, visualise, analyse, and interpret geographic/geospatial data. It became a popular site selection tool in the late 90s, where the potential of RE sources from both a practical and financial perspective was evaluated [21]. The location potential for wind farms was also assessed [22], which were poised to experience prolonged growth in the subsequent decades. This naturally progressed to assessing locations for utility-scale solar plants at the advent of the current solar boom [23]. One advantage of GIS software is its flexibility regarding scale, with feasibility studies conducted on both nationwide, e.g., determining optimal locations for solar plants in Croatia [24], and regional levels, e.g., where GIS software was used to find solar plant locations in the Malatya Province of Turkey [25]. GIS software has reduced associated costs with the pre-feasibility stage of RE projects, as it's an easy and inexpensive method to identify locations for implementation as well as providing information on the RE potential of a particular technology.

Firstly, limiting factors for deciding suitable locations need to be decided. Insolation data has naturally been identified as a primary factor, e.g., in Saudi Arabia, whereby GIS software was used to identify locations for solar PPs (power plant) on a nationwide scale [26], with 16% of the land area suitable for utility-scale solar. Further, the proximity to modern infrastructure; namely roads, transmission lines, and urban centres, was also identified as important limitations, as the proximity to these features heavily impacts the project cost and therefore the suitability of a prospective location. A review on solar PV PP site selection reaffirmed these influencing factors, with additional insights also highlighting the contribution of land topography and watercourses [27].

In Ireland, literature publications using GIS software to identify solar PP locations are sparse. In County Kilkenny, a region in the South of the country, 0.67% of the land area was found suitable for utility-scale solar plants [28]. Like previous findings, topography was the main influencing factor. However, this study overestimated the influence of insolation data on the suitability of locations, which is impractical given the small variation in irradiance throughout Ireland. Likewise, it did not consider electrical infrastructure, which has been identified as one of the main contributors to the success of a solar PP development. Finally, it focussed on one region in Ireland, failing to address the nationwide potential for utility-scale solar PPs. To better assess the influence of solar energy on the future Irish energy system, a more robust, in-depth nationwide analysis into the potential of utility-scale solar PV will be conducted.

3. TIMES Model Description

To frame the results of the energy model and solar PP potential, the architecture of the TIMES energy model is described herein. The TIM was developed by researchers in UCC, Ireland for the purpose of climate policy creation. User inputs are required for each section of the model and are submitted as tables in Excel documents, with specific tags used by the model to identify the desired input data. A reference energy system establishes the relationships between the processes and energy flows in the Irish energy system and a national energy balance is used to calibrate the model. Fig. 1 below describes the TIM model architecture used herein.

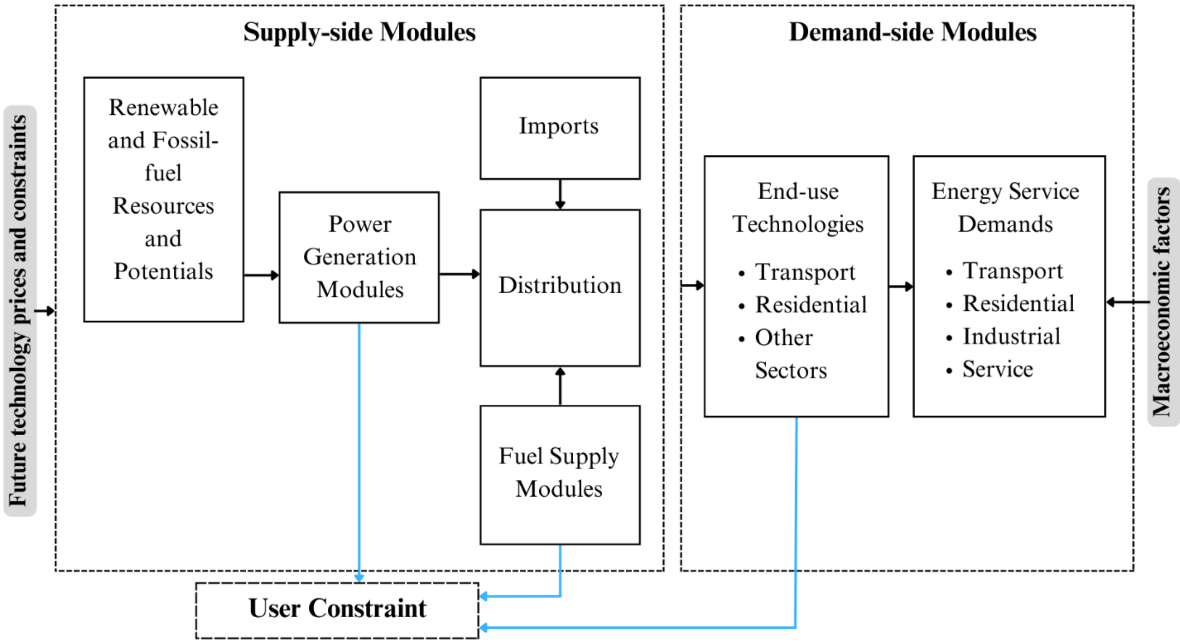


Fig. 1. TIM model structure, adapted from [29].

3.1. Supply-side Modules

Energy supply curves provide information on the availability of energy, both primary energy resources (e.g., solar and wind energy) and processed imported energy (fossil fuels). The supply-side modules consist of energy suppliers, i.e., fossil fuel and RE technologies, which are used for both power generation and other fuel-based products. Both fossil fuels and renewable resources are used to produce oil products, natural gas, biogas, liquid biofuels, and hydrogen gas, which are used in non-power generation end-use sectors e.g., heating and transport. Further, the model accounts for energy imports: electricity through undersea cables and solid fuels. The latter is a crucial consideration as Ireland is heavily dependent on fossil fuel imports for heating and transport. Electricity and solid fuel products are categorised in the distribution system as electricity, oil products, biofuels, and natural gas. These supply-side modules are then fed into the demand-side modules, which are explained below.

3.2. Demand-side Modules

The demand-side modules consist of both end-use technologies and energy service demands. End-use technologies utilise end-user energy (electricity, natural gas, oil, etc.,) to create useful work. In the TIM model, these are categorised into three sectors: transport, residential, and other. Each sector uses a combination of electricity and fossil fuel energy. Energy service demands use final energy to provide a service. These are categorised into four sectors: transport, residential, industrial, and service.

3.3. Techno-economic Parameters

The techno-economic parameters of both current and future energy production technologies are also required. The technical parameters are the transformation efficiencies of different technologies, availability and capacity factors, and emission factors. Economic parameters relate to the current cost, projected future cost decreases, fixed and variable costs (fuel, etc.,), decommissioning costs, and efficiencies. Costs relating to energy system infrastructure (distribution and transmission) are also included. The techno-economic parameters will allow for insights into the investment costs of different RE technologies in Ireland.

3.4. User Constraints

Both the supply-side modules and demand-side modules require inputs and limitations (user constraints) to dictate their function. Constraints are related to technology capacity, emissions, or fuels. For example, the implementation of offshore wind energy may be constrained due to certain allowed capacities dictated by government PPA auctions. Importantly, constraints allow the model to adhere to climate policy, which will be necessary to propose a future Irish energy mix.

3.5. Time & Regional Resolution

The model time resolution and regions must be defined. TIM is both a single-region (national) and multi-region (26 counties) model. The time resolution is the consecutive period whereby the model will run and execute the objective function. These are split into seasonal, weekly, day/nighttime, or hourly time slices. For example, at a seasonal resolution, the model will be executed at each season, for a total of four time slices. The TIM model offers full flexibility regarding region/time resolution combinations, e.g., from the lowest resolution (single-region and annual) to the highest possible resolution (26 county multi-region and hourly).

Higher resolutions are desired for long-term energy models, particularly for energy systems with high RE penetration. Due to RE's intermittency, a lower resolution would not accurately represent natural resource variability throughout the year, and therefore impact the model's accuracy. As a focus of this work is to propose a long-term solar implementation strategy to increase grid reliability of the future

Irish electricity mix, a higher time resolution is preferred. Similarly, a multi-regional resolution generally allows for greater accuracy. However, it is not required for the power generation sector in Ireland as there is no regional policy in place. Therefore, the resolutions used within the modified-TIM (MTIM) will depend on time constraints.

To model the RE implementation strategy from 2025–2050, defining time periods for reporting data are required. Shorter time periods (annually) are used for short-term modelling, while longer time periods (usually 5-year terms) are used for long-term. As this work is focused on two distinct climate goals, i.e., the 2030 emission reduction targets and the 2050 net neutrality targets, a combination of both short-term (until 2030) and long-term (until 2050) time periods are used for the model described herein.

3.6. Commodities and Processes

Fig. 2 displays the core relationships between the base components of the TIM model, using solar energy generation as an example.

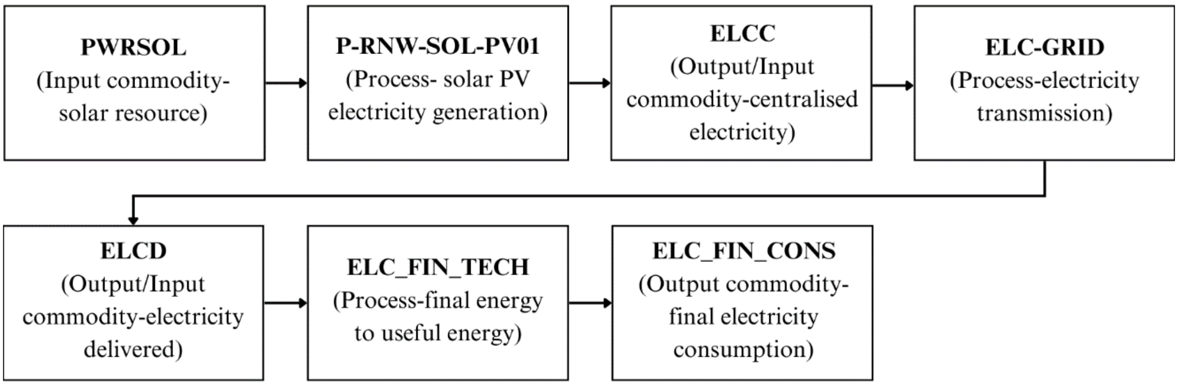


Fig. 2. Relationship between commodities, processes, and commodity flows.

Commodities are the main data inputs and outputs of the model, e.g., energy carriers and monetary flows. As seen in Fig. 2, the input commodity PWRSOL is the solar resource input into the model chain. Commodities are transformed into other commodities using processes, i.e., P-RNW-SOL-PV01 converts the natural solar resource into electricity using a solar PV plant. A combination of further processes and inputs/outputs result in a final output (ELC_FIN_CONS) which relates to the specified electricity demand. Multiple processes are combined to create the overall model structure. In the MTIM, all processes involve energy transformations due to the focus on the power generation sector.

3.7. Discount Rate and Objective Function

Discount rates are used to estimate the worth of a project's future cashflows in the present. Discounting is a key feature of the TIMES architecture due to the cost optimisation structure of

TIMES; whereby only profitable (positive NPV) projects are implemented. The social discount rate describes projects beneficial to society, e.g., government-funded projects. Financial discount rates are employed by corporations when making investment decisions. The latter is traditionally higher due to increased importance on overall profitability and a favourable return for investors. In the TIM model, a 4% social discount rate is used, which is based on a government-published document that considers public expenditure and labour statistics [30].

TIMES is a linear optimisation model that optimises the total cost of an energy system. It assumes perfect competition and perfect foresight. The former describes an economic system whereby there are many suppliers and producers and there is no entry or exit barrier. Perfect foresight describes the assumption that accurate predictions can be made regarding future market trends. These assumptions form the basis of the objective function, which can be described by Fig. 3 below.

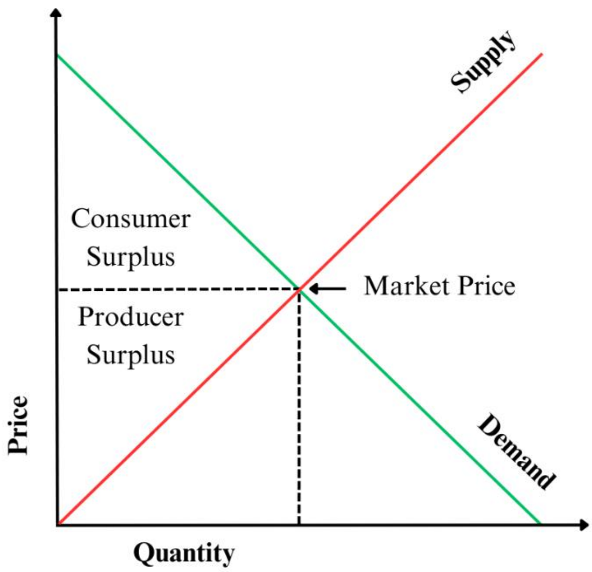


Fig. 3. Objective function result for TIMES model.

The objective function's aim is to maximise the total surplus, which is the sum of the consumer and producer surplus. This maximises the NPV, and thereby models the most socially efficient and cost-effective energy system over the desired time horizon.

3.8. Renewable Energy Generation and the Power Sector

The MTIM focusses on the power sector. Each REG unit is aggregated into one energy producer, which provides a total capacity result. Battery storage systems (BESS) will not be accounted for in the model due to time constraints. To model future expansion of REG in Ireland, the CAP's KPI's and government-publicised long-term climate goals are used as constraints. Costing data and expected future costing data, as well as transmission losses and grid connection costs are obtained from online resources. There are no grid expansion costs included due to Ireland's highly developed electrical infrastructure. Scenario files are used to introduce constraints to TIMES models, which will allow for manipulation of the model to propose the future Irish energy mix.

4. Methodology

4.1. Modified-TIM

To see if the CAP is sufficient to achieve the future climate targets, a MTIM model was created to propose a future energy mix for Ireland under a full-electrification scenario.

4.1.1. Future Electricity Demand

As the power sector was the focus of this study, each sector's demands were aggregated into one final electricity demand, which was the driving factor of the optimisation. The 2025–2050 future electricity demands were used based off predictions related to the electrification of the Irish energy grid [Table II]. The upper limit of the 2050 electricity demand was used for the MTIM. Demand data was input in PJ and then converted to TWh for the results analysis. This demand data was separated into 224 time slices to account for the variability of demand throughout the year [Appendix I].

TABLE II

PREDICTED FUTURE ELECTRICITY DEMAND OF THE IRISH ENERGY SYSTEM

	2025	2030	2035	2040	2045	2050
Final Electricity Demand (PJ)	140	162	220	300	350	439

IWEA future energy mix report [31].

4.1.2. Model Resolution

To account for RE intermittency, a temporal resolution was implemented to ensure greater accuracy. Availability factors for solar and onshore/offshore wind energy were used from the TIMES Poland model (provided by AGH Department of Energy and Fuels), as climatic conditions are similar to Ireland [Appendix II].

All costing and technical data, including the CAPEX, future costing data, system lifetimes, and future availability factors, were used from the TIM model for each electricity generation technology. An example is included in Appendix III. This data was unmodified for the purpose of this study.

A total of 224 time slices were used, each representing a period of ~40 hours. Each time slice represents a 40-hour time during a particular day of each week of each season, allowing for a relatively comprehensive representation of the annual time periods.

4.1.3. Model Limitations

As the TIMES model optimises by cost, if no limitations were introduced to the model, it would favour cheaper fossil-fuel technologies and neglect the implementation of the required RE systems.

Therefore, limitations (in GW) were introduced to force the model to adhere to Ireland's national 2030 and 2050 net neutrality targets, which were inserted to the MTIM as a scenario file [Table III]

TABLE III

FUTURE CAPACITIES OF REG TECHNOLOGIES INTRODUCED AS A SCENARIO FILE

Renewable Technology	2025	2030	2035	2040	2045	2050
Solar PV	4	8	14.3	20.5	26.8	33
Offshore Wind Energy	2	5	13	21	29	37
Onshore Wind Energy	6	9	10	10	10	10

The onshore wind capacity figure was based off the predicted onshore wind potential of Ireland of between 8.5–10 GW [32]. The offshore wind capacity of 37 GW was based off official government publications regarding minimum 2050 targets for offshore wind, with it expected to become Ireland's main energy source [33]. The solar PV capacity allowed for a 25% contribution to Ireland's electricity demand in 2050, which is an assumption allowing for a more variable energy generation profile and more reliable future electricity grid.

4.1.4. Economic Analysis

A primary factor towards Ireland's inactions regarding a long-term implementation strategy for utility-scale solar is the perceived lack of solar resources in the country in comparison to wind. This directly impacts the ROI of the project, thereby influencing investors and developers' decisions to pursue a solar PP from a purely financial perspective. However, solar energy has some of the lowest investment and operational costs, which when coupled with a low construction time, makes it financially viable in varying climates. To validate this, the LCOE of utility-scale solar in Ireland was calculated using the below formula.

$$LCOE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ electrical\ energy\ produced\ over\ lifetime}$$

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

The LCOE's of other RE technologies according to the MTIM results were also calculated for comparison.

Once the capacity datasets were added as scenario files, two separate MTIM cases were created: one with REG targets and the other without REG targets. These two files were run using VEDA 2.0 and the results for technology capacity, CAPEX investment, LCOE, and carbon emissions were compared.

4.2. Solar Site Suitability Using QGIS

To validate the results of the MTIM and identify the solar energy potential of Ireland, QGIS (Quantum Geographic Information System) was used for the location suitability analysis. Both vector and raster datasets were used. Vector datasets represent features, e.g., rivers, roadways, and points of interest, whereas raster datasets contain pixels that represent a range of values projected over geographical regions, e.g., irradiance data and slope data.

4.2.1. QGIS and Projection System

Project coordinate reference systems (CRS) are used in QGIS to associate numerical coordinates with a position on the earth's surface. As the earth is an irregularly shaped ellipsoid, it is important to choose the appropriate reference system to ensure that each data point is projected onto a flat surface, which is required for accurate map analysis. The TM65 Irish Grid (ESPG:29902) CRS was used for this project. As QGIS projects on the fly, new datasets were automatically assigned this CRS when loaded into the project. The TM65 CRS details are included in Appendix IV.

4.2.2. Data Sources

To obtain the optimal locations for solar PP development in Ireland, various limiting factors were introduced via datasets implemented into QGIS. Two main dataset sources were used. The GeoHIVE/Tailte Éireann Open Data Portal [34] and the EPA database [35] are online repositories of map files by OSI (Ordnance Survey Ireland). OSM is a built-in QGIS plugin that identifies requested features using the OSM Maps database. Combining the OSI and OSM datasets ensured that most desired features were represented. The digital elevation map (DEM), which is necessary for topographical analysis, was obtained from the NASA Earthdata AppEEARS platform [36]. Irradiance data was obtained from SolarGIS. The vector datasets and their sources are in Appendix V, while the raster datasets are described below.

4.2.3. Modification of Datasets

The modified vector datasets are explained here, with their images included in Appendix VI.

Watercourses, Lakes, and Roadways: A limitation of these GeoHIVE datasets were that they didn't contain secondary roadways and watercourses/water bodies, i.e., rural roads, ponds, and streams. Therefore, OSM data was obtained for each of the 26 regions in Ireland and then combined with the GeoHIVE dataset to produce a final master file.

Settlements: The GeoHIVE dataset only included larger urban areas and disregarded small villages, which are numerous throughout Ireland. Therefore, a point layer was created using the OSM plugin for each small village, buffered to account for the approximate total village area, and then combined with the GeoHIVE dataset.

Land Use: According to solar plant implementation best practices [28], only pasture or natural grassland is suitable for construction. The Corine land-use dataset was modified to only contain these two land-use categories.

4.2.4. Setback Distances & Buffering

Once the datasets were acquired, setback distances and buffers were applied to each feature. As there are no national guidelines for utility-scale PV development in Ireland, with each application treated on a case-by-case basis, assumptions were made from currently approved/rejected projects.

Regarding settlements and roadways and railways, planning permission inspector's reports for solar plants in Ireland were consulted [37]. The setback distances ranged from 30–700 m and were dependent on the mitigation of glare effects by local vegetation. Rural Ireland is characterised by hedgerows that would negate these effects, and so a setback distance of 30 m was applied to all secondary roads, while a 50 m distance was applied to primary roads and railways. A distance of 500 m was imposed on all settlements and 1000 m for conservation areas and heritage sites, based on the literature [38].

A minimum 10 m setback distance is required for construction near watercourses, which is often increased during the appeal process. However, as all solar plants require boundary fences located several metres from the panels, a setback distance of 25 m was applied to watercourses. This corroborates with non-binding solar plant development guidelines [39].

4.2.5. Classification of Vector Datasets

TABLE IV

LAYERS AND BUFFER DISTANCES FOR VECTOR DATASETS

Feature	Buffer distance (m)
Primary roads & railways	50
Secondary roads	30
Conservation and heritage sites	1000
Settlements	500
Watercourses and Water bodies	25

Table IV displays the respective setback distances for each vector dataset, which were subsequently applied as surrounding buffers in QGIS. The overlap between the country map and vector datasets was removed, which resulted in available land for solar PV development [Fig. 4].

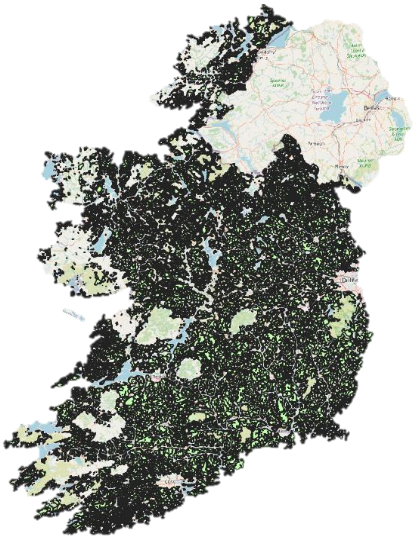


Fig. 4. Suitable land for PV plant development, countrywide (left) and zoomed in (right).

The raster datasets were then classified to allow the execution of the multi-criteria analysis over the suitable land area shown in Fig. 4.

4.2.6. Digital Elevation Map: Calculating the Slope and Aspect

To calculate the slope, DEMs were obtained from the NASA Earthdata AppEEARS platform, created using a combination of shuttle technology and other topographical analysis techniques. The resultant files (. Geo tiff raster) were converted into ESRI format and merged within QGIS. The merged file was then projected onto the TM65 Irish Grid CRS and clipped in QGIS to the country area. The slope was then calculated using a native QGIS process using the $\frac{rise}{run}$ equation. The lighter areas represent higher altitudes (left) and therefore more severe slopes (right) [Fig. 5].

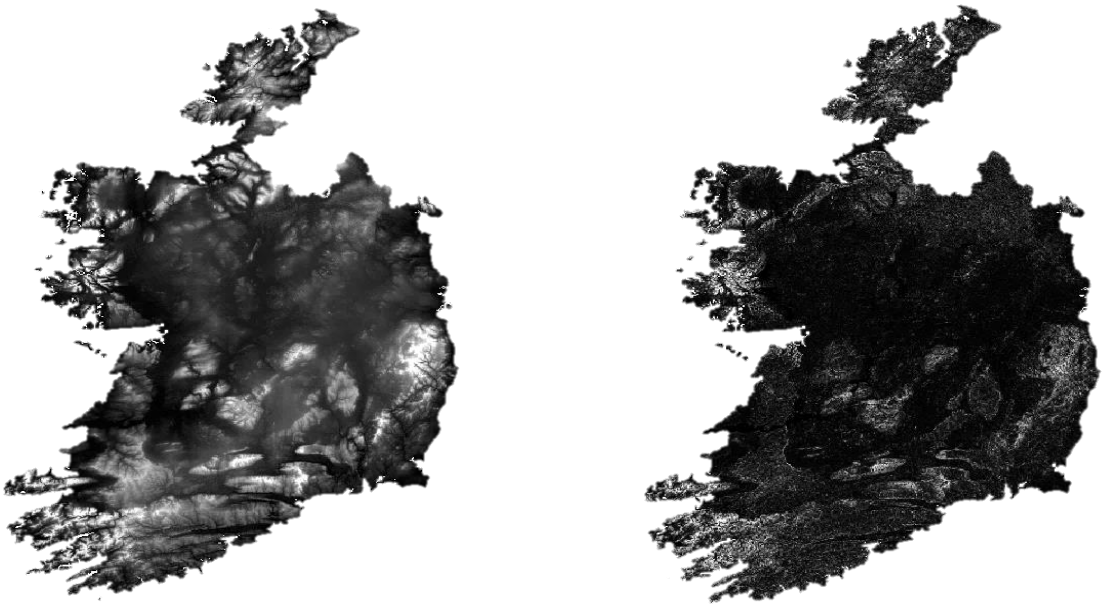


Fig. 5. DEM map (left) and calculated slopes (right).

The aspect was created from the same DEM raster file by executing a native QGIS process that expressed the slope direction by assigning a degree value between 0–360° [Fig. 6].

Fig. 6. Aspect calculated from the DEM file.

4.2.7. Classifying the Slope and Aspect

From literature, a slope of 0–2% is most suitable for module placement, as shadowing effects, and therefore reduced PV performance, occurs above this [40]. Various sources cite ~6–8% as the upper limit, and so the slope was ranked based on this range, whereby 1 (green) is most suitable and 4 (red) is least suitable [Table V]. The resultant layer can be seen in Fig. 7.

TABLE V

RELATION OF SLOPE SEVERITY TO PV PP SUITABILITY

PV PP Suitability	Slope (%)	Colour Label
1 (most suitable)	0–2	Green
2	2–4	Orange
3 (least suitable)	4–6	Red
4 (not suitable)	>6	Purple

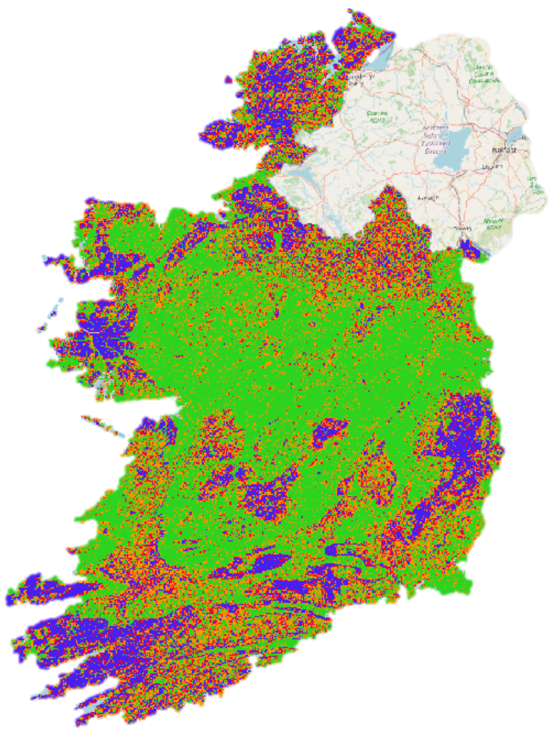


Fig. 7. Suitability of slope for PP construction in Ireland.

Similarly, the aspect was found using another native QGIS process. Due to Ireland's presence in the northern hemisphere, SE to SW are the optimal slope aspects, with due south being the most suitable. Following consultation with an expert in solar system plant sizing (Andreas Wabbes, formerly PVComplete), areas with slopes < 2° were not considered when applying the aspect and were therefore assigned a suitability ranking of 1. Table VI displays the suitability ranking of the aspect, while Fig. 8 shows the results of the analysis.

TABLE VI

CLASSIFICATION OF ASPECT

PV PP Suitability	Aspect (°)	Colour Label
1 (most suitable)	<2, 157.5–202.5	Green

2	202.5–247.5	Orange
3	112.5–157.5	Red
4 (least suitable)	Other	Purple

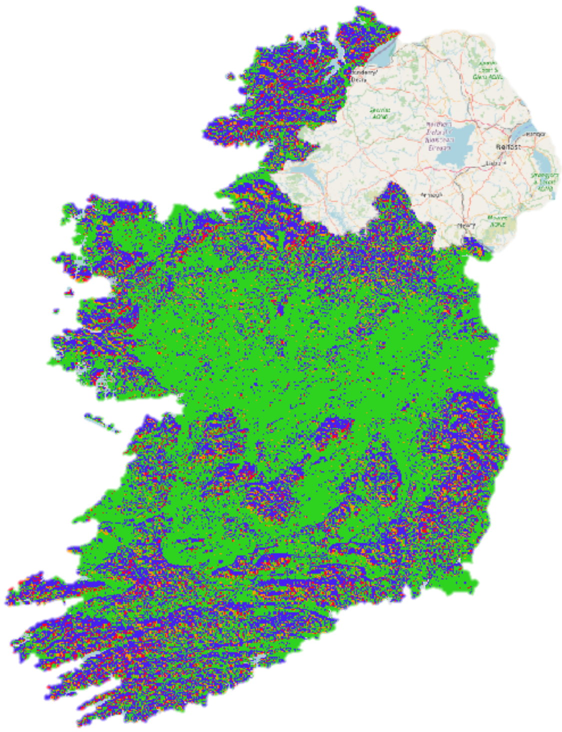


Fig. 8. Aspect dataset of Ireland.

4.2.8. Classifying the Solar Potential

Potential solar output raster files were obtained from SolarGIS. The chosen file conveyed the annual output in kWh/kW. There are more detailed methodologies to obtain the solar potential, however, due to Ireland's relatively small land mass and therefore, low solar radiation variation, this method was deemed sufficient. The resultant raster file can be seen in Fig. 9 below.

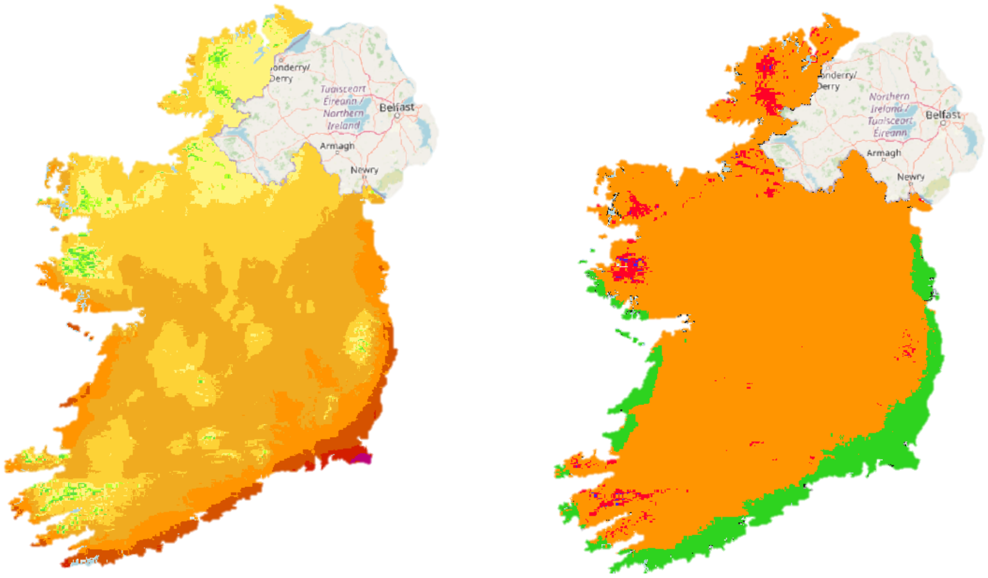


Fig. 9. PVOut solar potential in Ireland: unclassified (left) and classified (right).

The potential was ranked for suitability according to Table VII below.

TABLE VII

CLASSIFICATION OF SOLAR POTENTIAL DATASET

PV PP Suitability	kWh/kWp	Colour Label
1 (most suitable)	960–1075	Green
2	845–960	Orange
3	730–845	Red
4 (least suitable)	615–730	Purple

4.2.9. Classifying Electrical Infrastructure

It is favourable to develop solar plants close to existing high-voltage (HV) transmission and substation infrastructure, as solar PP's high energy generation cannot be connected to the medium-voltage distribution system. In Ireland, the transmission system consists of 400, 220, and 110 kV HV lines and substations [41]. Currently, most solar plants undergoing development are near 110 kV substations to facilitate their connection to the grid, however, they can also connect to higher voltage substations. Therefore, a dataset of these transmission-level substations and the connected transmission lines was created from the QGIS OSM plugin and cross referencing with maps obtained from EirGrid (national grid regulator) [42], with the results displayed in Fig. 10 below.

Current literature varies with distance recommendations for site suitability, however, anything greater than 10 km is generally deemed as financially infeasible [40], [43], and so the ranking in Table VIII was structured around this. Naturally, sites closest to the substation (within 1 km) are the most suitable, given the high cost of transmission lines and infrastructure upgrades associated with connections further from the grid connection site.

TABLE VIII

RANKING OF DISTANCE TO SUBSTATION FOR SOLAR SITE SUITABILITY

PV PP Suitability	Distance from substation (km)	Colour Label
1 (most suitable)	< 1	Green
2	1–2	Orange
3	2–10	Red
4 (least suitable)	> 10	Purple

Obtained from online literature and consultations with solar energy experts.

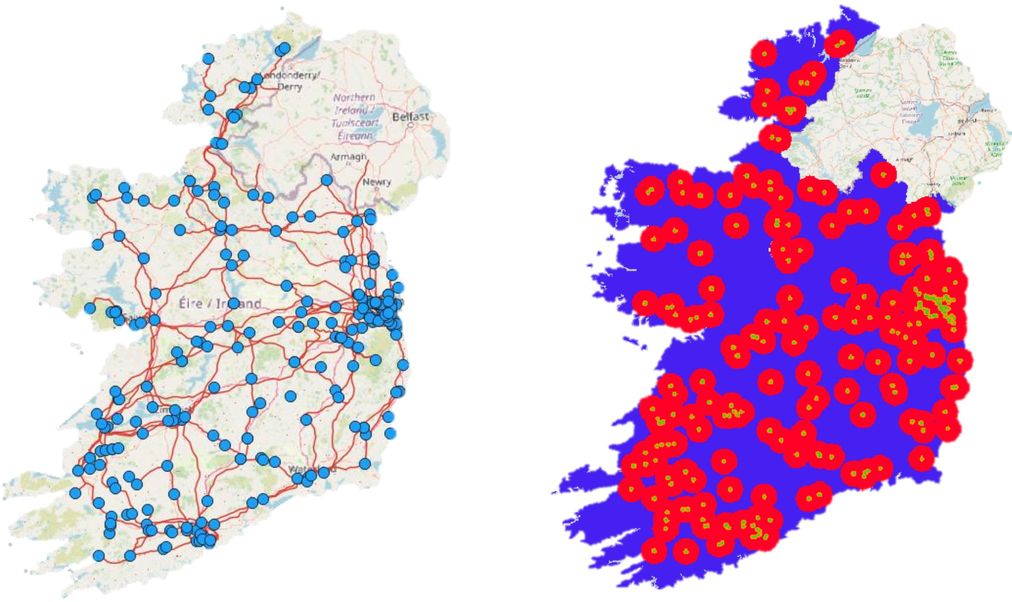


Fig. 10. HV substations (point layer) and transmissions lines (polyline layer) in Ireland (left) and ranked substations (right).

The available capacity map from ESB displays the transformer capacity at each nationalised substation. This dataset was downloaded as an Excel document, modified, and then converted to a point layer within QGIS. ESB ranks the available transformer capacity as green (>15 MVA), orange (0–15 MVA) and red (no capacity available). These substations were then ranked according to Table IX. As any substation can be upgraded (at a high cost to the project developer), no substations were disregarded from the analysis. Areas without substations were ranked as least suitable for project development.

TABLE IX

RANKING OF AVAILABLE CAPACITY CONTRIBUTING TO SOLAR SITE SUITABILITY

PV PP Suitability	Available Capacity (MVA)	Colour Label

1 (most suitable)	> 15	Green
2	0–15	Orange
3	0	Red
4 (least suitable)	No substation	Purple

Obtained from EirGrid capacity map website.

Not all HV substation transformers were represented in the capacity map. Many substations are built specifically for large industrial operators or large wind and solar farms. However, it's likely that these have limited capacity as they are already connected to large generators, therefore, they were assumed to be between 0–15 MVA. The final available capacity results are included in Fig. 11 below.

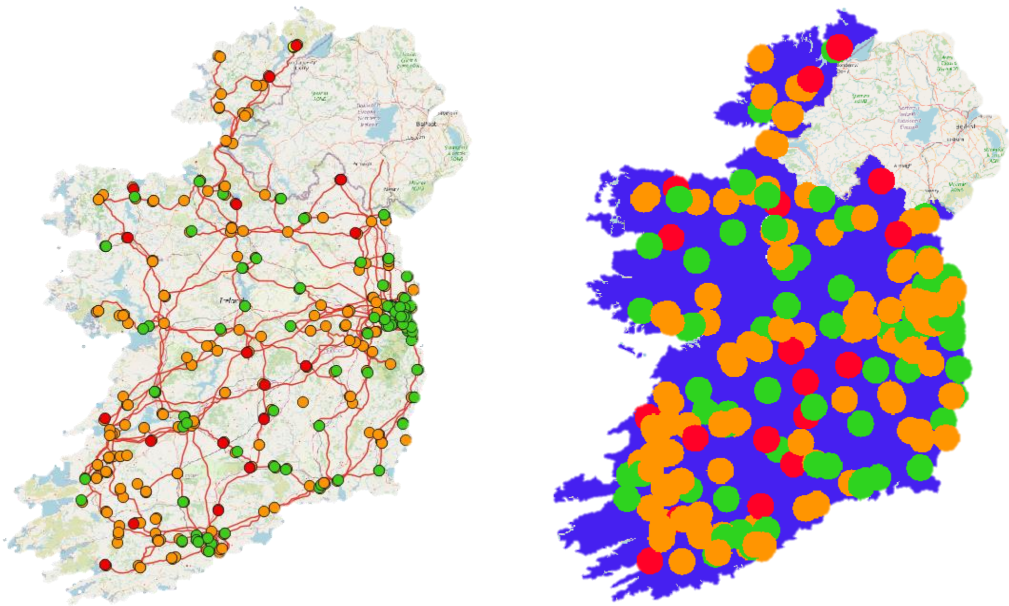


Fig. 11. Available transformer capacity map for each substation in Ireland.

4.2.10. Datasets Weighting using Multi-criterial Analysis

Once the datasets were compiled and classified, their contribution to the overall site suitability was determined to conduct the multi-criteria analysis. Several weighting methods for multi-criteria decision making (MCDM) techniques were examined: Weighted Sum Method (WSM), AHP, Elimination and Choice Translating Reality (ELETRE), amongst others. The AHP technique was chosen due to its ease-of-use and suitability for a low number of criteria.

The AHP uses pairwise comparisons to determine the relative importance of each contributing factor. The importance of each factor on a scale of 1 to 10 when compared to its pair was recorded, and these results were used to construct a comparison matrix [Table X] and therefore the weighted importance of each [Table XI].

TABLE X

AHP PAIRWISE COMPARISON MATRIX

	Slope	Aspect	Solar Potential	Substation Proximity	Available Capacity
Slope	1	1	5	2	2
Aspect	1	1	6	2	2
Solar Potential	1/5	1/6	1	1/3	1/3
Substation Proximity	1/2	1/2	3	1	1/2
Available Capacity	1/2	1/2	3	2	1

TABLE XI

CONTRIBUTION OF EACH RASTER DATASET TO OVERALL SOLAR SITE SUITABILITY

Dataset	Weight (%)
Slope	30.4
Aspect	31.5
Solar Potential	5.5
Proximity to Substations	14.0
Available Substation Capacity	18.5

Weighting obtained through consultation with a utility-scale solar design expert (Andreas Wabbes, PVComplete)

To ensure accurate results, the AHP requires consistent pairwise comparisons. The Consistency Index (CI) and the Consistency Ratio (CR) are used to determine the inconsistencies present in the comparison process, and therefore the validity of the resultant weights. If CR ≥ 0.10, the relative importance of each factor must be revised until a suitable tolerance is achieved. For the above comparison, the CR = 0.014, which is indicative of a very high consistency and, therefore, valid weights.

A weighted multi-criteria analysis was then conducted within QGIS to rank the suitability of the land area in Ireland for solar generation.

5. Results

5.1. TIMES Energy Model

5.1.1. Comparing RE and No-RE Scenarios

Two scenarios were executed in TIMES; one adhering to national RE targets and the other with no RE targets set. This provides insights into the energy makeup of the future net-neutrality scenario.

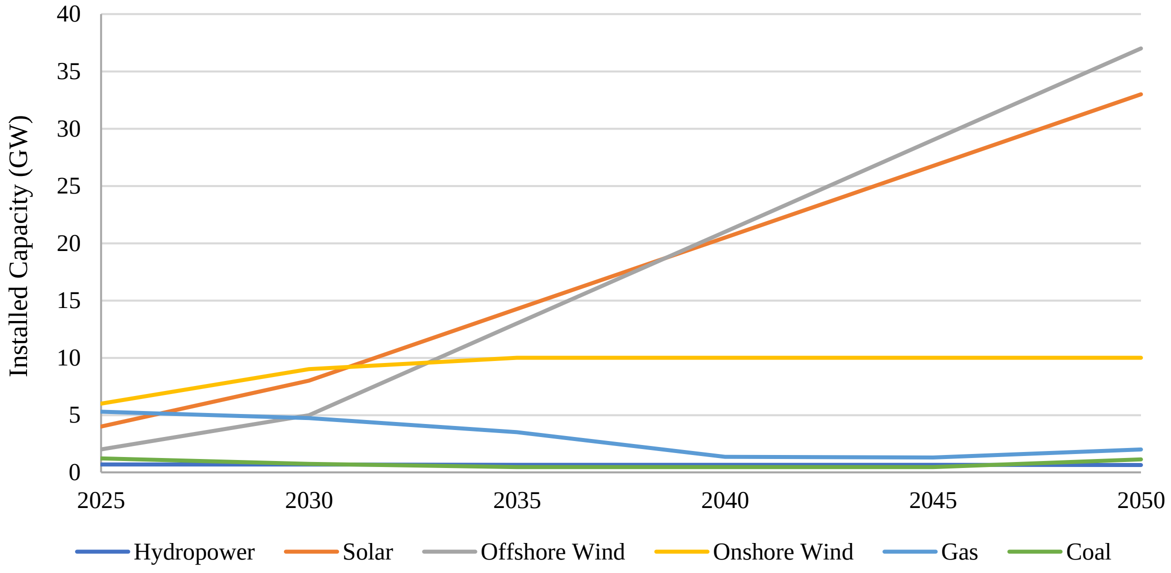


Fig. 12. Total installed capacity in Ireland according to government targets.

Fig. 12 displays the installed capacities of each power generation technology according to national RE targets. By 2050, 10 GW of onshore wind (potential national capacity), 37 GW of offshore wind, and 33 GW of solar PV should be implemented to fully decarbonise the power generation sector and achieve net neutrality. Negligible amounts of fossil fuel-technologies will also be present to account for REG variability.

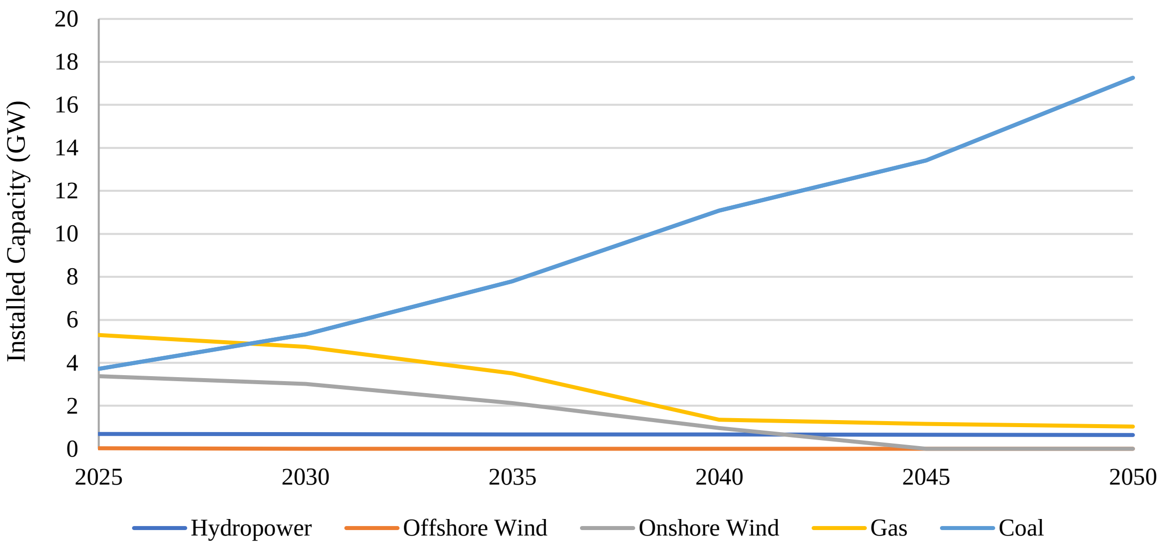


Fig. 13. Total installed capacity in Ireland with no RE targets.

Fig. 13 displays the installed capacities of each power generation technology under the scenario with no RE targets. Fossil fuel technologies are favoured, as the MTIM optimises cost by maximising total surplus, and so cheaper coal technology is implemented. By 2050, 17 GW of coal and 1 GW of gas should be implemented, with no REG technologies present as they are not cost optimal.

5.1.2. Analysis of CO_2 Abatement and CAPEX Investment Costs

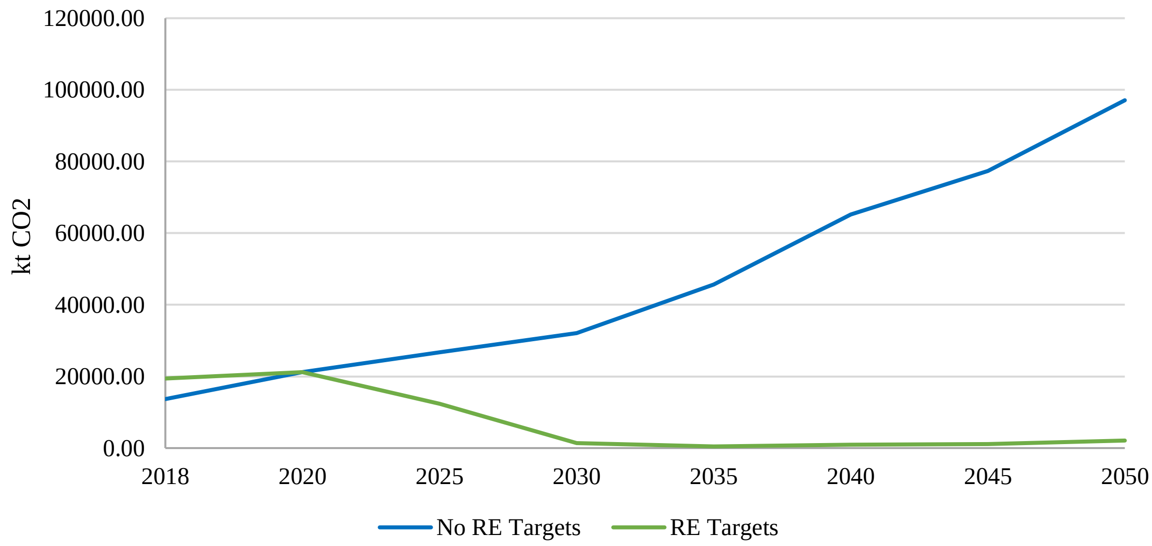


Fig. 14. Comparison of CO_2 emissions in the power sector for two alternate scenarios.

Fig. 14 exhibits the CO_2 emissions in the power sector for each scenario. Under the no RE targets scenario, the total emissions increase significantly due to the high increase in electricity demand because of the electrification of Ireland's energy sector. This equates to 97'000 ktCO_2 by 2050. Under the RE Targets scenario, the power generation sector is decarbonised by 2030, with the high increase in REG to 2050 meeting the increase in electricity demand, which allows Ireland to become carbon neutral by 2050 in line with the CAP targets.

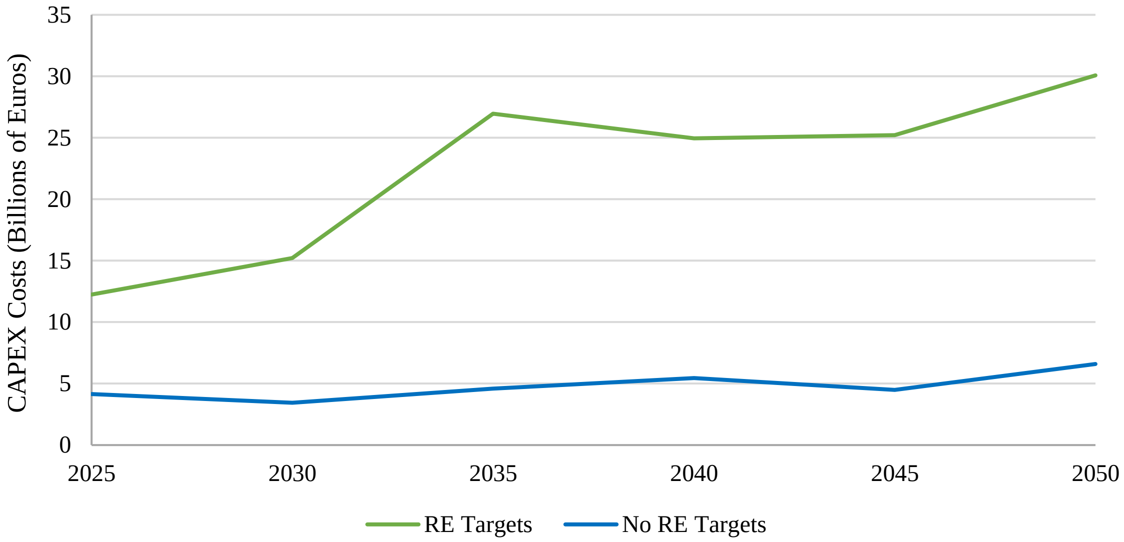


Fig. 15. Total investment cost of the two executed scenarios.

Fig 15. displays the CAPEX investment costs under both scenarios. To achieve net neutrality by 2050, €134 billion is required to install the required capacity. Under the no RE Targets scenario, €28.7 billion is required, which highlights the large cost associated with the planned energy transition. These figures were used to calculate the LCOE of different RE technologies.

5.1.3. LCOE Calculation for Different RE Technologies

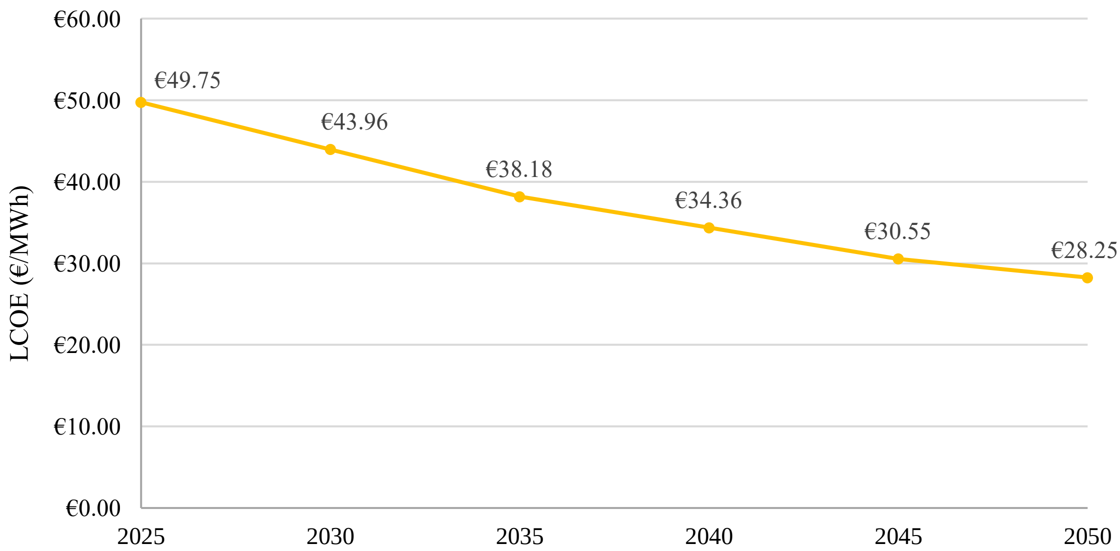
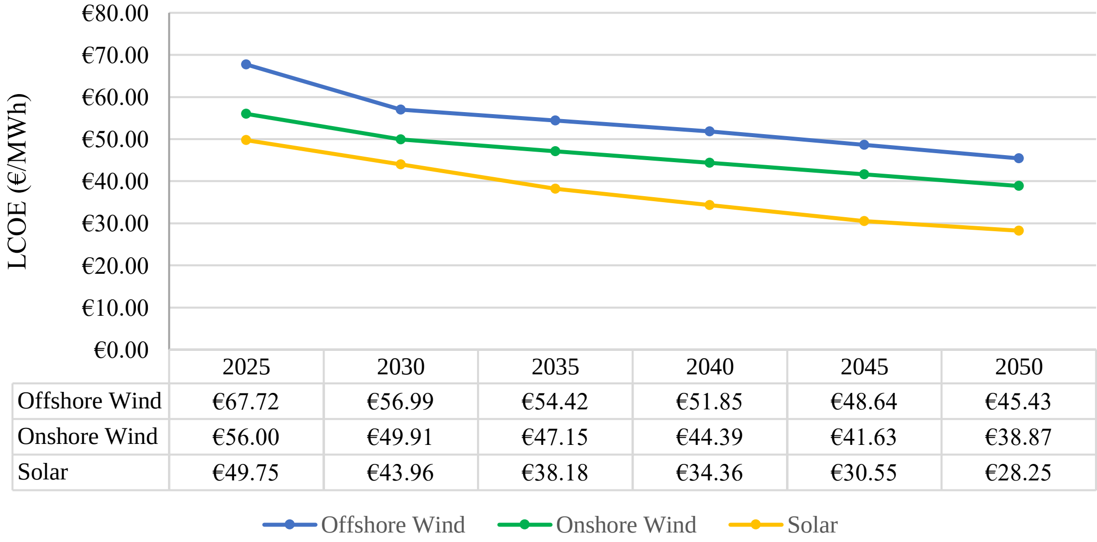


Fig. 16. LCOE of utility-scale solar in Ireland.

Fig. 16 displays the LCOE of utility-scale solar in Ireland from 2020–2050. The values were calculated based off existing costing data (CAPEX and OPEX) from the MTIM model. A 4% discount rate was used as per the MTIM model. Energy production was calculated from MTIM, and the system lifetimes ranged from between 20–30 years.

There was a 43.2% decrease in LCOE (€49.75/MWh in 2020 to €28.25/MWh in 2050) of utility-scale solar energy in Ireland. To analyse the above results, they were compared to the LCOE's of other RE technologies, which were created using the respective MTIM input [Fig. 17].



	2025	2030	2035	2040	2045	2050
Offshore Wind	€67.72	€56.99	€54.42	€51.85	€48.64	€45.43
Onshore Wind	€56.00	€49.91	€47.15	€44.39	€41.63	€38.87
Solar	€49.75	€43.96	€38.18	€34.36	€30.55	€28.25

Fig. 17. LCOE Comparison of different RE technologies from 2025–2050.

5.2. Solar Location Selection

5.2.1. Solar PP Suitability Map and Regional Analysis

A suitability map for solar PPs was generated using the described methodology, which is the first example of a nationwide suitability study of solar energy in the country. This was overlaid with the potential area map from Fig. 4 to produce a final solar suitability map for Ireland, which can be seen in Fig. 18 below.

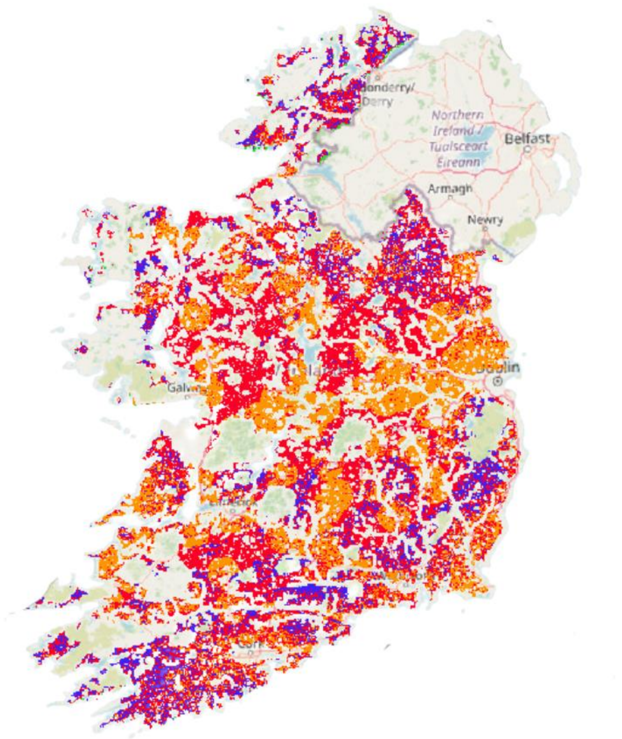


Fig. 18. Final solar suitability map for Ireland.

TABLE XIIII

RANKING OF AREA BY SUITABILITY FOR SOLAR PPS

PV PP Suitability	Colour Label
1 (most suitable)	Green
2	Orange
3	Red
4 (least suitable)	Purple

Table XII describes the colour ranking of area suitability, with green being the most suitable and purple being the least suitable. The resultant map was analysed for each of the 26 counties included in this study. Fig. 19 exhibits these results, with the 26 counties ranked in order of decreasing available area.

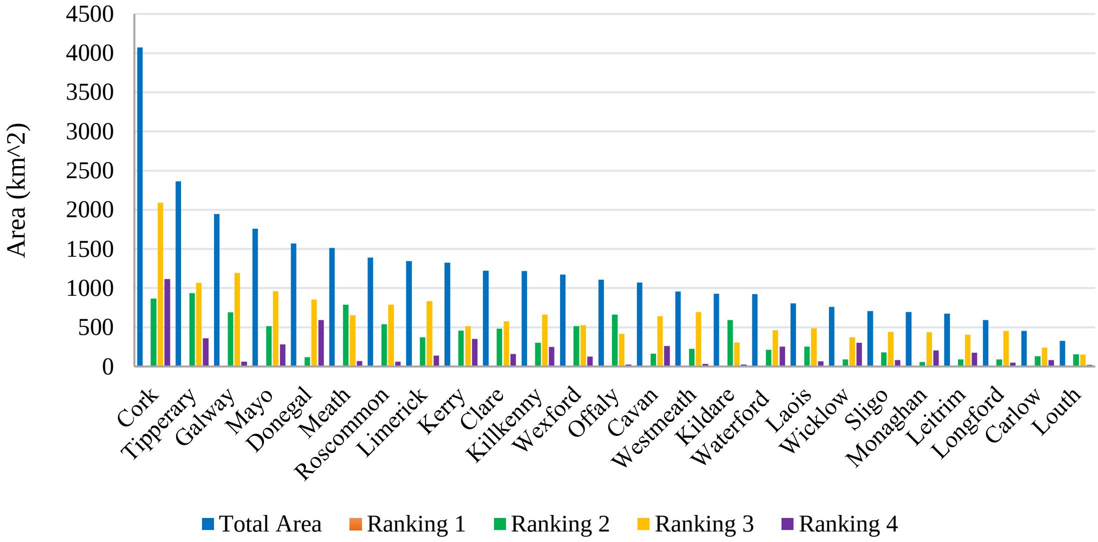


Fig. 19. Results of suitable area for solar development in each county in Ireland.

The most suitable land for solar development is naturally the higher-ranking areas, as higher suitability will lead to lower investment costs for the developer. The higher ranked areas will be developed first, and so the lower ranked areas (ranking 3 and 4) were disregarded. Therefore, Fig. 20 displays the suitable land area for each county of suitability ranking 1 or 2.

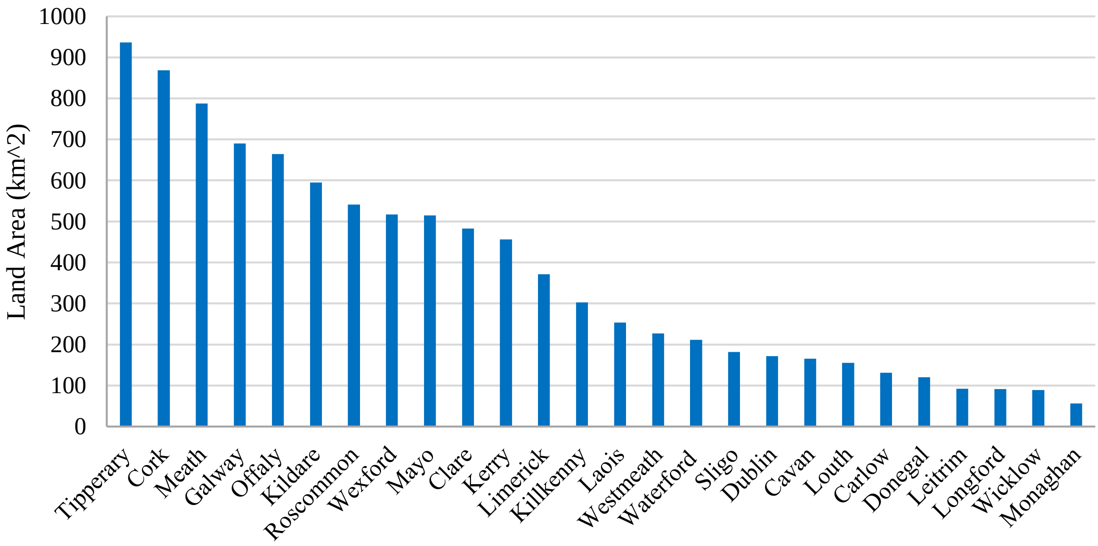


Fig. 20. Total land area with 1 and 2 suitability ranking.

A total land area of 9’672 km^2 (13.8% of the national landmass) was identified as suitable for solar PP development. Tipperary, Cork, and Meath are the three most suitable counties to develop utility-scale solar plants whereas Monaghan, Wicklow, and Longford are the three least suitable counties.

5.2.2. Solar Capacity and Generation Potential

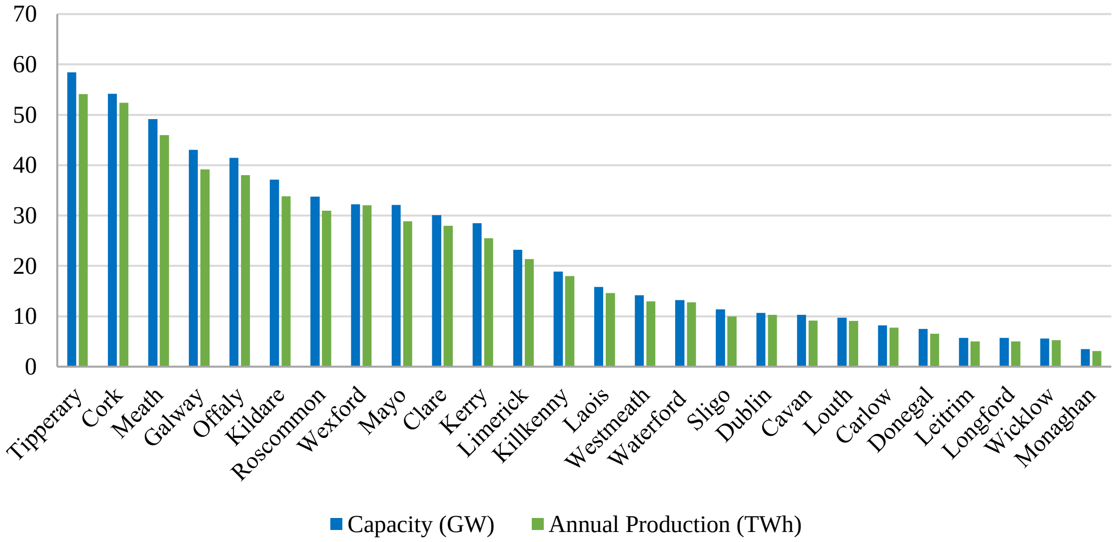


Fig. 21. Potential capacity (GW) and annual production (TWh) of each county in Ireland.

Fig. 21 exhibits the potential capacity and annual production of the proposed locations for utility-scale solar PPs. To calculate the potential capacity from the produced results, the average capacity per land area in Ireland was first determined. Ten Inspector's reports from An Bord Pleanála related to utility-scale solar farms were consulted, with an average capacity of 0.624 MW/ha or 62.4 MW/km^2. To calculate the generation potential, 5 points (N, S, E, W, and central) were chosen using QGIS and the average of these 5 points was used as the PV Potential of a utility-scale solar PP in each respective county. The total potential capacity was calculated as 603.57 GW while the total annual production from this capacity was calculated as 559.49 TWh.

6. Discussion

6.1. Ireland's Solar Energy Potential

To better visualise the solar energy potential of Ireland, a country map displaying the data in Fig. 20 was created, which shows the total area of suitable land in each of the 26 counties [Fig. 22].

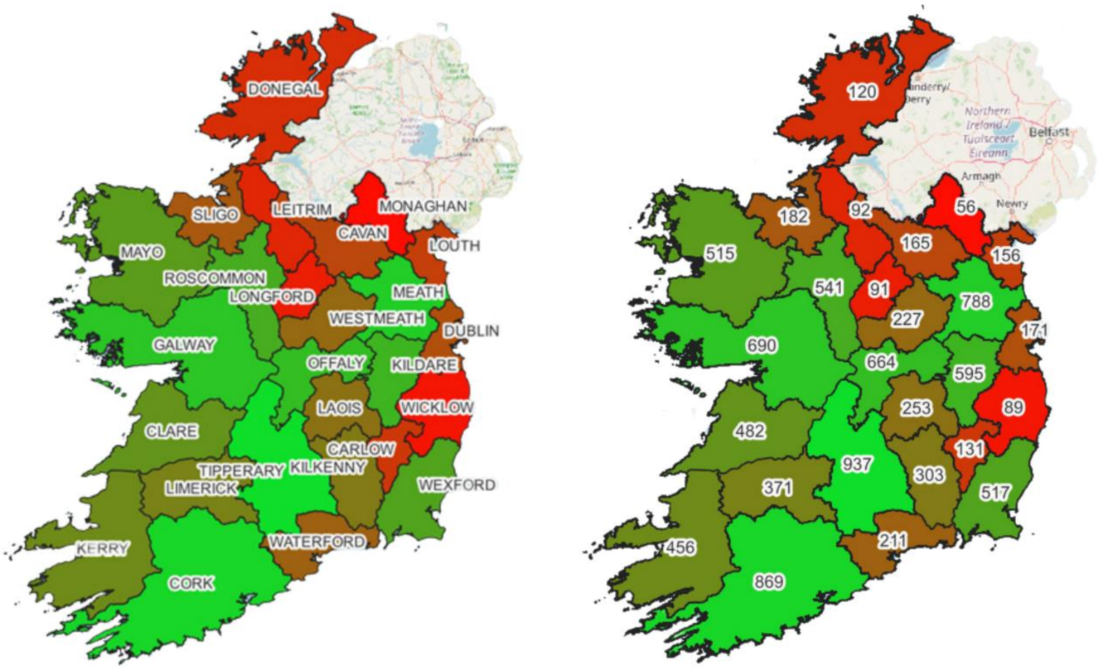


Fig. 22. Total suitable area for solar PP development in km^2 (ranking 1 & 2).

The midlands are flat, which is favourable for solar plant development. The west and south of Ireland are remoter than other parts of the country. They also contain more land area than other counties, and so this, combined with the low populations make them suitable for development. Likewise, several large population centres (Cork, Galway, and Limerick City) exist in these areas which require large substations and developed electrical infrastructure, which increases their overall suitability.

As expected, the main population centre, i.e., Dublin, does not have a lot of suitable land due to its high population density. However, it does have the most favourable electrical infrastructure in the country, as well as the highest demand, which means that its neighbouring counties (Meath and Kildare) are very suitable areas. This is validated by the results presented herein. Wicklow is one of the least suitable due to the presence of a large national park.

The northern counties (Donegal, Leitrim, Cavan, Monaghan) are characterised by unfavourable slopes and smaller land masses, and therefore, are the least suitable areas for solar plant development. They are also influenced by less developed electrical infrastructure, i.e., suitable substations, as they have few large population centres in comparison to other major counties in Ireland, as well as a lower irradiance due to their more northern position.

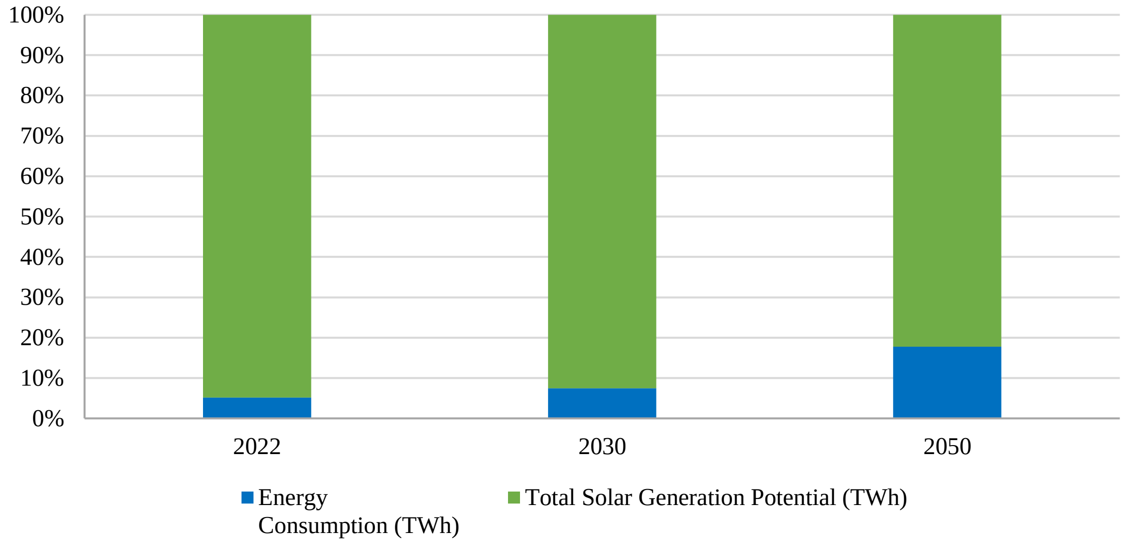


Fig. 23. Comparison of total potential solar generation and expected electricity consumption in Ireland through 2050.

Fig. 23 displays the total potential energy production from the identified suitable sites as well as the predicted electricity consumption in Ireland from 2022–2050. Ireland's electricity consumption is expected to increase ~395% to 121 TWh under a maximum growth scenario. This large increase is due to the eventual electrification of the Irish energy system, which is in line with EU-wide net-neutrality goals.

As reported, Ireland has a potential solar energy production of 559.49 TWh. To ensure a reliable future electricity grid, solar energy needs to become a key contributor to the future energy mix. For 25% of the future electricity demand (30.25 TWh) to be met by solar energy, 32.64 GW of solar energy and 523 km^2 (0.74% of total land area) will be required. The CAP aims to implement 8 GW of solar energy by 2030, which means that a four-fold increase in solar capacity will be required (if the 2030 target is achieved) to ensure net-neutrality. However, both residential and utility-scale solar can contribute to this figure. Currently, Ireland has ~680 MW of installed solar capacity, consisting of 371 MW of utility-scale solar and 309 MW of rooftop and commercial ground-mounted solar systems (on 60'000 homes). The total solar capacity is expected to increase to 1 GW by the end of 2023, therefore requiring an 8-fold increase to reach the 2030 capacity goal of 8 GW. Residential systems are unaccounted for in the MTIM as they will likely be dwarfed in comparison to future utility-scale solar systems. However, they should be included in a more detailed future modification of MTIM.

It is clear from these results that even though Ireland is traditionally a wind-energy dominated country, there is a huge potential to develop solar PPs. This will help to stabilise the grid, reduce curtailment, and reduce the need for fossil fuel technologies. The above results validate the potential of Ireland to become a large solar energy producer in Europe. The lack of national utility-scale solar PP guidelines exemplifies the need to renew conversations on the impact of solar energy in Ireland. To achieve the goal of 33 GW of solar capacity by 2050, the Irish government needs to reassess their commitment to solar energy and modify current policy to ensure that the net-neutrality targets are met.

6.2. Is Solar Energy Economically Viable in Ireland?

As discussed herein, Ireland has one of the lowest solar capacities in Europe, with the first utility-scale solar PP only connected in June 2022. National policy has favoured wind energy due to the countries abundant wind resources, which has led to the solar energy market in Ireland being neglected. However, as solar energy is one of the most mature RE technologies worldwide, Ireland can benefit from the lower costs despite a lower-than-average solar resource. Table XIII displays the LCOE calculation results for each of the RE technologies contributing to the future proposed energy mix.

TABLE XIII

LCOE (€/MWh) OF RE TECHNOLOGIES IN IRELAND 2025–2050

Technology	2025	2030	2035	2040	2046	2050
Offshore Wind	67.72	56.99	54.42	51.85	48.64	45.43
Onshore Wind	56.00	49.91	47.15	44.39	41.63	38.87
Solar PV	49.75	43.96	38.18	34.36	30.55	28.25

As seen above, utility-scale solar has the lowest LCOE of the three investigated RE technologies, ~26.5% lower than offshore wind, and ~11% lower than onshore wind, respectively. This trend continues to 2050 as the CAPEX and OPEX decrease, while system lifetimes increase. These results mirror similar studies that solidify large-scale utility-scale solar energy as the cheapest form of RE.

Not only would utility-scale solar PPs ensure a more reliable electricity grid, but they would also achieve this at a lower cost for consumers, and therefore a higher ROI for investors and developers. Further, solar energy has a much lower construction time than competing technologies, which is beneficial considering Ireland's tendency to miss climate targets. This result further validates the potential of solar energy to become a major component of a future Irish energy system and shows that it can compete with wind energy despite the difference in natural resource availability. It also reaffirms the need for the implementation of a national solar energy strategy, which would allow the country to benefit from a lower LCOE on the path to 2050 net-neutrality.

6.3. Potential Future Irish Energy System

To achieve the 2050 net-neutrality targets, a 4-fold increase in solar PV (from 2030), a 5-fold increase in offshore wind, and a 2-fold increase in onshore wind energy is required. However, this is only one example of a potential future Irish energy system. Solar and wind energy are the focus of this study as they are the two most mature technologies and have been shown from literature review and the work herein that there is a lot of potential for these sources in Ireland.

However, other renewable sources and storage solutions will likely be a component of a future energy system. Ireland possesses excellent ocean energy resources, due to its location in the Atlantic Ocean, and so wave and tidal technology is proposed as a potential key contributor to the overall energy mix. However, like solar energy in Ireland, there is no official timeline for the implementation of ocean energy. Likewise, the MTIM does not account for battery storage technologies. While pumped hydro is included (due to a single pumped hydro plant in Ireland), BESS needs to become part of a wider RE implementation strategy. As seen in Fig. 16, CO^2 emissions increase as the electrification of the Irish energy system proceeds. This is due to the installation of new fossil-fuel PP technology to account for the intermittency of RE resources. Likewise, energy curtailment is likely, which results in higher overall investment costs and a less efficient energy system.

Currently, the CAP contains limited information on storage technologies. Hydrogen storage will likely become a key component of the future energy system, with 2 GW of offshore wind hydrogen storage expected by 2035. However, it does not provide more detailed information on the implementation strategy, instead opting for a later date to discuss it. To account for the need of a more comprehensive solar energy implementation strategy, a realistic strategy on ocean energy implementation, and a more detailed framework on the future role of BESS in the Irish energy system, the current CAP needs to be reevaluated and framed in the context of the wider net-neutrality targets.

6.4. Is the CAP Sufficient?

While the CAP at first appears to be a comprehensive document outlining the steps to achieve Ireland's climate goals, it is insufficient in providing more comprehensive planning decisions regarding RE implantation, instead providing a general overview of the strategy. While some may consider this appropriate given the length of time to achieve this goal, Ireland has traditionally not taken climate policy seriously, instead missing all climate change objectives.

Furthermore, Ireland has a stringent and lengthy planning process, with the Irish Solar Energy Association (ISEA) warning that planning bottlenecks are hindering solar PP developers' ability to meet the 2030 targets [44]. Several key projects have waited more than a year for approval. They cited an average 37 week waiting period rather than the legally mandated 18 weeks. The main limitation is the lack of staff at An Bord Pleanála to expedite these cases, which has been a common occurrence in all aspects of Irish national strategy. One benefit of solar energy is the reduced implementation time compared to wind energy technologies, so these delays are eliminating the main advantage of solar PP development in the country, thereby highly reducing the chances of achieving the 2030 and 2050 capacity targets of 8 GW and 33 GW, respectively. There is also severe local opposition to RE development throughout the country, as they are often located in more remote and scenic areas. Anecdotally, the Irish populace in rural areas is against the energy transition. Failures by the government on other important issues, e.g., the current housing crisis, have instilled distrust in government policy which has a knock-on effect for the proposed energy transition. The ISEA recommends new legislation to protect solar PP development from these often-misaligned appeals, which will be necessary to achieve the ambitious solar energy and other REG targets.

Compounding these problems are the potential issues associated with the electrification of the Irish energy system and the influence of other non-energy related sectors to national emissions. As explained in the background of this work, there has been a lack of progress in achieving current goals, and although these aren’t displayed in the MTIM model, this directly impacts the future electricity demand and therefore the implementation of more REG systems. The progress towards electrification of the transport and housing sectors has been insufficient so far, due to mismanagement by the government, a lack of sufficient labour and infrastructure to meet these goals, and a misjudgement of the priorities of the Irish populace. For example, one barrier to the implantation of more EVs is the high cost of electricity in Ireland, which had the third-highest electricity price in the EU in the second half of 2022 [45]. Consumer confidence in the financial benefits of EVs is low, which needs to be addressed if the EV goals are to be completed.

Furthermore, the agricultural sector in Ireland has the potential to completely derail Ireland’s long-term climate goals. As a traditionally agricultural-dominated economy, this industry is usually overlooked in terms of climate policy. It was responsible for 38.4% of emissions in 2022. Of this, 62.6% was produced by enteric fermentation, which is a direct result of the increasing livestock numbers in the country [46]. This is on the back of an abolishment of the milk quota in Ireland, which led to an increase in dairy cow numbers of 42.5% between 2012 and 2022, which was legislation spearheaded by agricultural lobby groups. However, the CAP does not advocate the reduction of herd sizes, instead opting for policies such as improving the genetics of livestock to reduce their methane gas production. Instead of directly addressing the main issues and holding the agricultural industry accountable for its emissions, other industries are expected to compensate for the lack of emission reductions. This is a primary example of how the CAP fails to address key issues concerning the energy transition and is further proof of its insufficiency to achieve Ireland’s climate targets.

To ensure that the climate goals are met, the CAP needs to be reevaluated. A more detailed RE implementation strategy is required, which should focus on more variable energy sources (including solar energy) and storage technologies. Current legislation regarding planning applications and the compounding failures to ensure grid electrification need to be addressed. Currently, the Irish government is not doing enough to ensure the CAP is successfully implemented, putting the country in danger of falling behind the rest of the EU.

6.5. Limitations and Future Work

Several limitations existed for both the solar site selection and the MTIM. Concerning the model, the costing data did not include operational costs. While this doesn't hugely affect REG, the fossil-fuel generators have a much higher operational cost due to fuel, and so this is likely the main reason why fossil fuels were favoured in the no RE targets scenario. If operational costs were correctly implemented, there would be higher RE generation, but still not to the extent of the RE target scenario. Further, future work should include Ireland-specific demand profiles and availability factors for wind and solar energy, to allow for a more accurate model.

Likewise, the MTIM was limited due to time constraints. To form more concrete conclusions concerning the feasibility of the CAP, each sector should be modelled, rather than just the power generation sector. This would allow an analysis into the electrification of the energy sector, which is likely the main barrier to Ireland's climate targets, as discussed throughout this study. Further, the agricultural industry needs to be modelled in detail as it's a huge contributor to total GHG emissions. Including more accurate costing data as well as modelling each energy sector within Ireland should be a focus of future research. Finally, the LCOE calculation did not consider certain contributing factors, e.g., decommissioning costs. This results in less accurate figures which would be consolidated in future work by using a more advanced calculation.

Regarding solar site selection, the main limitations were related to the accuracy of the input data. As there are no national utility-scale PV guidelines, and several assumptions had to be made, it's likely that the calculated areas are not fully realistic. It's also possible that certain smaller features, i.e., secondary roads and waterways were not fully modelled. However, time constraints meant that this could not be achieved, as it would take several months to ensure complete accuracy of data. Further, the lack of a national solar PP development plant hindered accurate analysis, as each solar PP is decided on a case-by-case basis, and therefore the associated buffer distances vary. Future work on the suitability of land for solar PV development should consist of a larger government-funded study which could be used as a tool by REG developers to simplify the development process in Ireland.

7. Conclusions

Herein, a solar PP site suitability map was successfully created, which is currently unpublished in the literature. This provides invaluable insights into the potential solar capacity of Ireland, but also the suitability of certain regions based off limiting factors, including physical features, irradiation and topographical data, and electrical infrastructure. The total potential capacity was calculated as 603.57 GW while the total annual production from this capacity was calculated as 559.49 TWh, with a total suitable land area of 9’672 km^2 (13.8% of the national landmass). This work can be used by solar PP to streamline the development process and reduce their development costs. A government-funded solar energy feasibility study should be conducted to increase investor confidence in the industry which will be crucial in achieving the required capacity increases.

The MTIM successfully modelled the future energy mix of a net-neutral Ireland, by accounting for future expected capacities of RE technologies. This will drastically reduce emissions and the reliance on fossil fuels. The required 33 GW of solar capacity is of particular importance, as there is no government-published figure for large-scale solar development in the country. LCOE calculations revealed a lower solar energy LCOE than competing renewable technologies, which further validates the feasibility of solar energy as a key component of a future Irish energy mix. The MTIM also highlighted the importance of transparent energy policy and legislation, as without this the model favoured cheaper fossil-fuel technologies, due to the cost optimisation objective function. The MTIM results can be used to influence a national solar energy development plan for Ireland, which will be useful for both government and private organisations who are seeking to develop solar PPs in the country.

The investigation into current literature and the CAP showcased the reliance on wind energy resources in Ireland, which will cause issues in the future concerning grid reliability due to the reliance on a single natural resource. While solar energy resources are not as favourable as wind resources in Ireland, the results show that Ireland has significant solar potential, far exceeding the 33 GW of installed capacity required to reach the 2050 net-neutrality targets. However, the CAP does not outline steps to achieve this figure, and so it needs to be reevaluated with a focus on securing the reliability of the future electricity-dominant grid through the diversification of energy sources, i.e., wind and solar resources.

While there were some limitations concerning the accuracy of input data, both for the solar potential site assessment and the MTIM, this work should serve as a starting point to reassess Ireland’s climate strategy. More focus is necessary on the potential failure to electrify the energy grid, and the contribution of the agricultural industry to national GHG emissions. Without this, it is unlikely that Ireland can achieve its emissions reduction targets using the CAP, demonstrating its insufficiency as a national climate policy. However, by pre-emptively addressing these issues, Ireland can achieve its long-term climate goals and solidify its reputation as a ‘green’ country under more optimistic circumstances.

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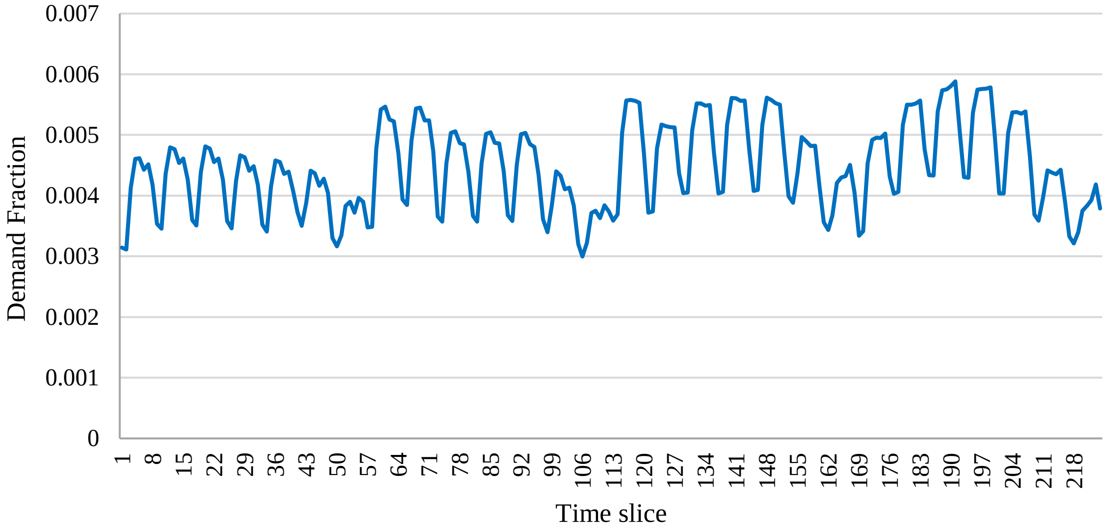
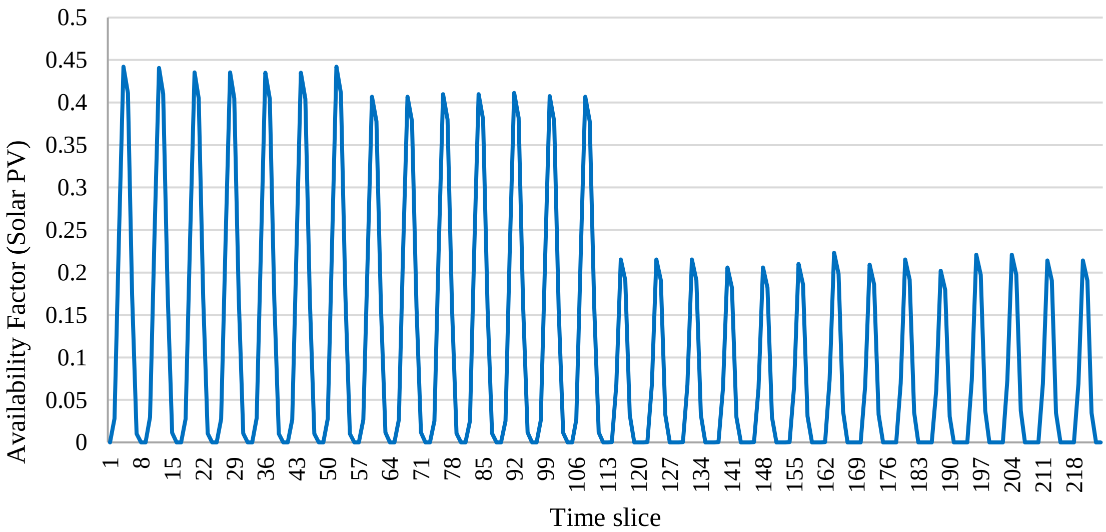
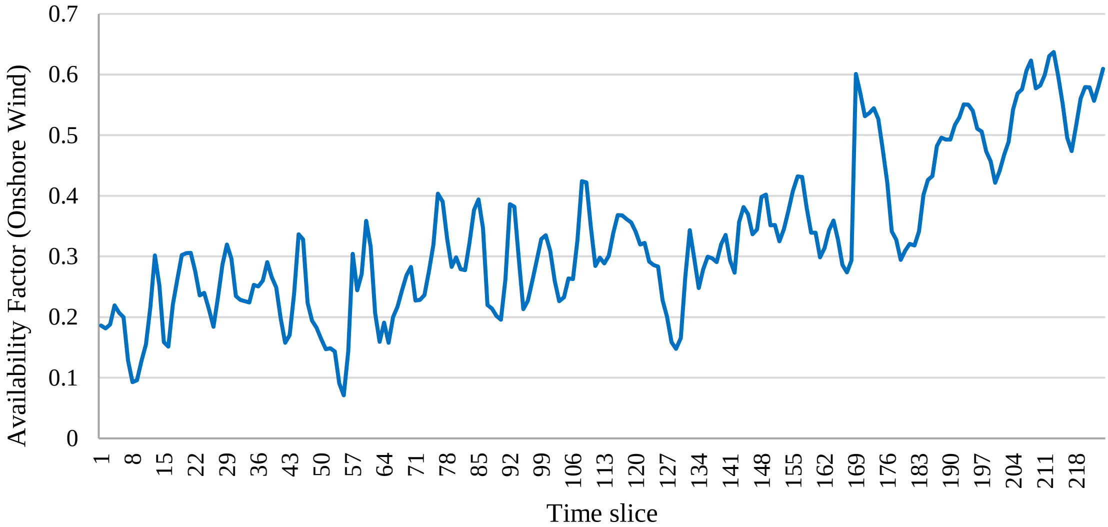
9. Appendices

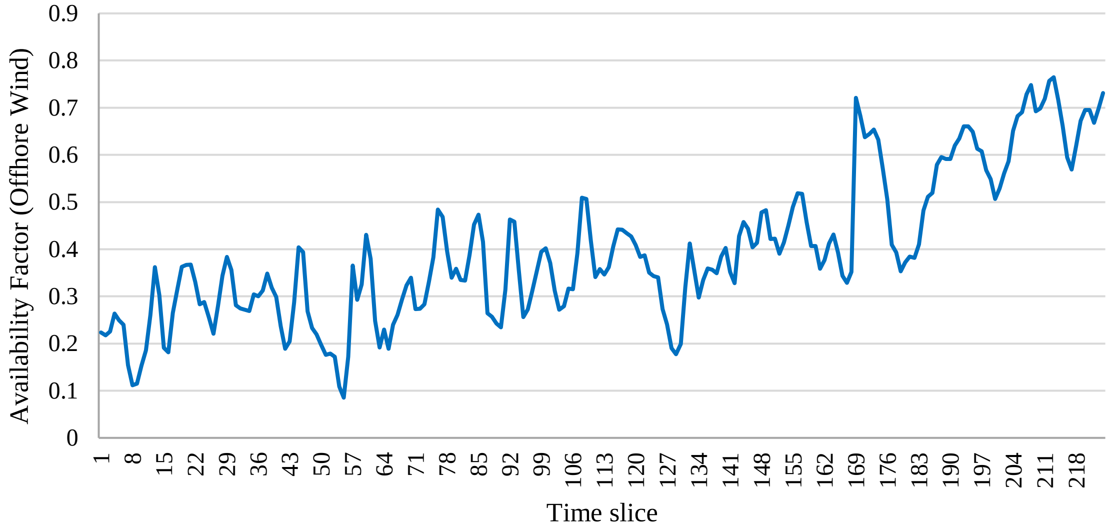
Appendix I: Fraction of final electricity demand distributed over the time slices.



Appendix II: Availability factors of solar PV, onshore, and offshore wind energy introduced as scenario files into the MTIM.







Appendix III: Example of the data provided for each electricity generation technology modelled in MTIM.

Technology Name	P-RNW-WIN-OF02
Input Commodity	PWRWIN
Output Commodity	ELCC
Efficiency (Input to Output)	100%
Start Year	2019
Investment Cost – 2015 (€/kW)	3500
Investment Cost – 2020 (€/kW)	2870
Investment Cost – 2030 (€/kW)	2570
Investment Cost – 2040 (€/kW)	2430
Investment Cost – 2050 (€/kW)	2330
Lifetime	20
Lifetime – 2020	25

Lifetime – 2030	30
Cap2Act	31.356
AFA	50%
AFA - 2020	55%
AFA - 2040	60%
AFA - 2050	65%

Appendix IV: TM65 CRS Information

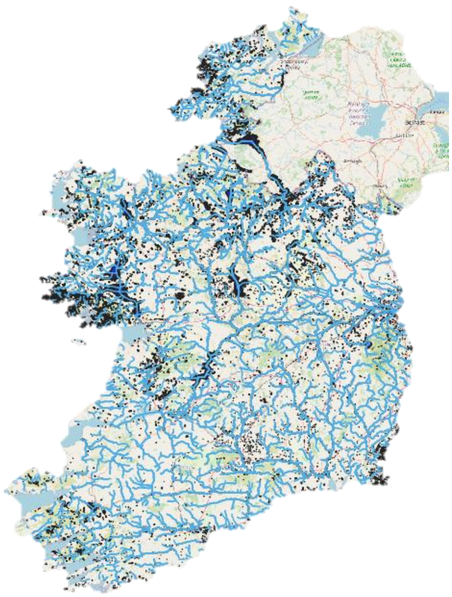
Reference System	TM65 Irish Grid (ESPG:29902)
Reference Ellipsoid	Airy Modified
Geodetic Datum	1965 Datum
Vertical Datum	Malin Head
Map Projection	Transverse Mercator
Measurement Unit	International Metre
True Origin	Latitude 53° 30′ 00” N Longitude 8° 00′ 00” W
False Origin	200 kms west of true origin 250 kms south of true origin
Plane Co-ordinates of True Origin	200 000 E 250 000 N
Scale Factor on Central Meridian	1.000 035

Appendix V: Datasets and sources used for the solar PP location selection.

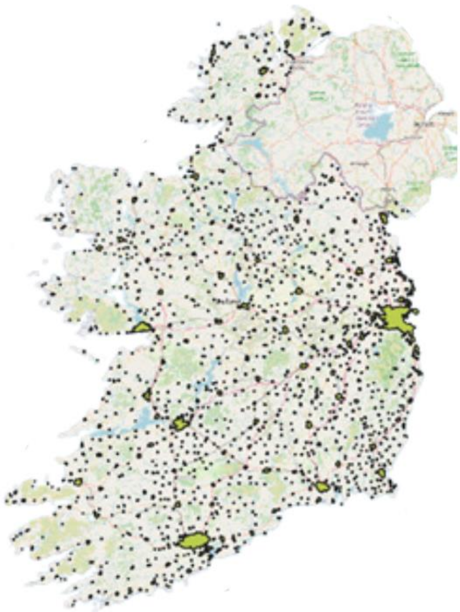
Dataset Name	**Dataset Description**	**Dataset Source**
1. Water - National 250k Map of Ireland 2. Lakes & Reservoirs - National 250k Map of Ireland 3. Water/Water/River & Water/Water/Stream OSM Query Search	All waterways and waterbodies throughout the country	Tailte Éireann Open Data Portal and OSM QGIS plugin
1. Settlements Ungeneralised - National Statistical Boundaries 2015 2. Geography/Places/Village OSM Query Search	All urban areas, including larger cities and smaller villages	Tailte Éireann Open Data Portal and OSM QGIS plugin
1. Corine Landcover 2018	Categorises the land cover by each respective land use	EPA GIS database
1. Roads - National 250k Map of Ireland 2. Highways/Streets/Minor Roads & Highways/Streets/Road (Unknown Type) OSM Query Search	All primary and secondary roads contained within the study area	Tailte Éireann Open Data Portal and OSM QGIS plugin

1. Rail Network - National 250k Map of Ireland	Map of current rail infrastructure	Tailte Éireann Open Data Portal
1. Heritage - National 250K Map of Ireland	Map of important heritage sites present throughout the country	Tailte Éireann Open Data Portal
1. Natural Heritage Area (NHA) 2. proposed Natural Heritage Areas (pNHA) 3. Special Area of Conservation (SAC) 4. Special Protection Area (SPA)	Map of all the current and future proposed conservation areas of significant biological interest,	National Parks and Wildlife Service
1. SRTMGL3_DEM (SRTMGL3_NC.003)	Digital Elevation Map used to determine the slope and aspect of the land	NASA AppEEARS Platform
1. PVOut GIS Dataset	Map of the solar potential of Ireland with respect to solar module performance	Solar GIS
1. Man Made/Power/Power Substation OSM Query Search	Map of all the substations present in Ireland	OSM QGIS plugin
1. Network Capacity Map	Map showcasing the available transformer capacity at each substation	ESB Networks

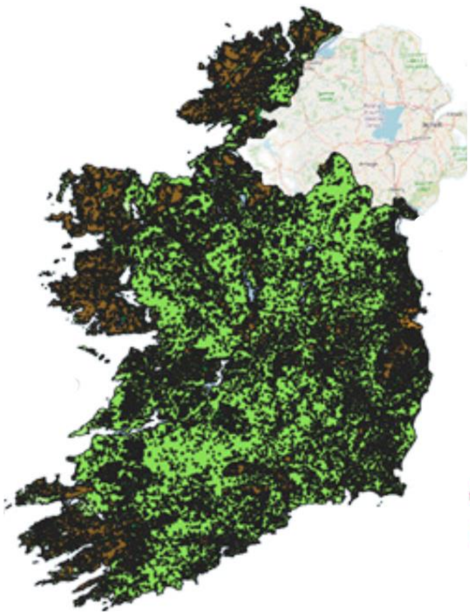
Appendix VI: Images of finalised datasets used for solar PP site selection.



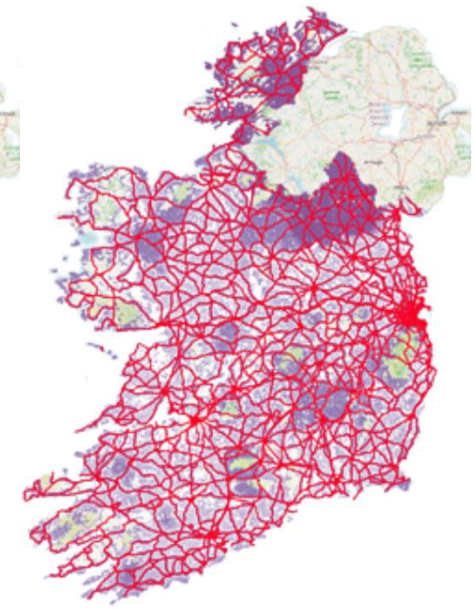
Waterbodies



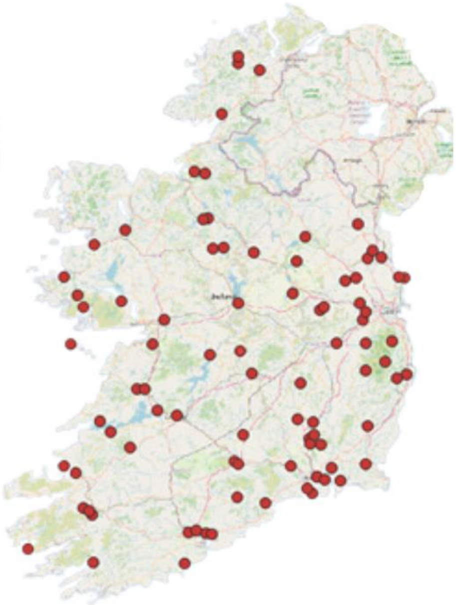
Settlements



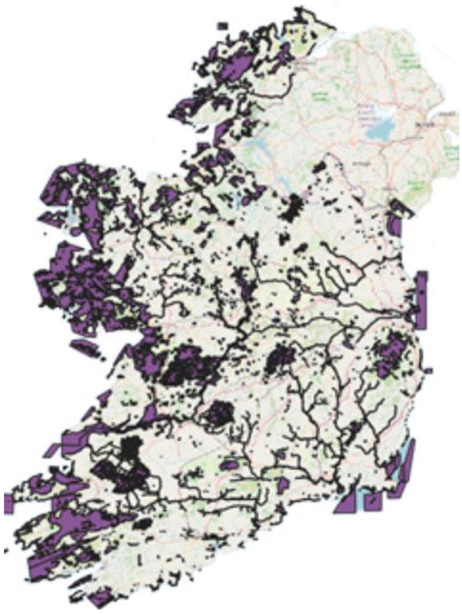
Landcover



Roadways



Railways **Heritage Sites**



Conservation Areas