OESM-IE: Open Energy System Modelling for Ireland

SEAI Research Award: RDD246

Technical Report WP2-D2

Baseline Open Energy System Model for Ireland using PyPSA platform

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WP2 summary

WP No. & Title	WP2: Develop baseline Open Energy System Model for Ireland (OESM-IE)		
Start Month No.	3	**Finish** Month No.	6
WP Lead:	DCU		
WP Contributors	N/A		
Objective(s)	WP2-O1: Implement and calibrate baseline Open Energy System Model for Ireland (OESM-IE)		
Description (max 200 words)	Based on the output of WP1, design and implement baseline model(s) of the Irish Energy System, correctly representing (at least) TPER (with energy carrier breakdown), TFC (with sectoral breakdown), energy carrier stocks (energy storage, including gaseous and liquid fuels), CO_2 emissions, internal energy flows (with balancing to at least 1-hour time resolution in the electricity system, against representative demand time series), external energy flows (import/export), and estimated costs (with appropriate representation of both CAPEX and OPEX). To the extent feasible. include applicable energy use in international aviation and shipping. Calibrate against most recent available reported data (SEAI, EPA).		
Milestones	WP2-M1: Design, and first iteration of full model complete. WP2-M2: Calibration complete.		
Deliverables	WP2-D1: Baseline OESM-IE with full calibration datasets. WP2-D2: Technical report documenting baseline OESM-IE and calibration.		

1 Introduction

The largest contributor of emissions in Ireland is the energy sector (electricity, heating and transport). In 2018 Ireland had 38.6 MtCO_2 of energy related emissions (SEAI 2020). With existing measures in place, emissions from the electricity and heating and transport sectors by 2020 are projected to be 40 Mt CO_2eq, a 3.5% increase compared to 2018 emissions. By 2030, the emissions are projected to increase by 8%, producing 44 Mt CO_2eq (EPA 2019).

The latest EPA projections indicate that Ireland will exceed its carbon budget over the period 2021 to 2030 by 52 to 67 Mt CO_2 equivalent (EPA 2019). With this trend, Ireland is on course to exhaust its cumulative carbon budget of 766 Mt CO_2 (Ó Gallachóir et al. 2020) much earlier than expected, not meeting the Paris temperature goal of 2°C by 2050. Additional urgent measures towards net-zero or net-negative are required to meet the agreed collective goal to align Ireland to the Paris Agreement (DECLG 2014). Ireland has a large resource potential of variable renewable energy (VRE), mainly wind and solar.

The integration of VRE must be thoroughly evaluated to identify the most effective, most technically feasible and cost-effective approach for the necessary deep decarbonisation of the energy system. Deployment of VRE to address the stringent requirements implied by the Paris temperature goals requires models having a temporal resolution for evaluating the techno-economic viability of each VRE technologies (Tarun Sharma et al. 2020).

1.1 Previous work

In previous related research, the EnergyPlan platform had been used to investigate decarbonisation pathways for the Irish energy system with a focus on 100% renewable energy penetration (D.Connolly and H.Lund 2011). Brown and Schlachtberger (2018) demonstrated an open dataset of the transmission system in Germany based on SciGRID. The SciGRID model provides geo-referenced data for substations and medium to high voltage transmission lines. The challenges faced by the European power systems were investigated by (Collins et al. 2017), as the EU transitions towards a low carbon energy system with increased amounts of variable renewable electricity generation using the PRIMES energy systems model. Although the work only investigated EU power systems, this study also recognised, the importance of long term planning for better integration between the electricity sector and various other sectors such as thermal & transport to achieve the significant emissions reductions.

Connolly et al. (2016) presented a conceptual pathway to 100% renewable energy for the EU energy system by the year 2050 using the Smart Energy System concept. The study investigated the transition of the EU energy system from fossil fuels to 100% renewable energy in a series of 9 steps. Although the paper did not address any options to achieve net-negative emission scenarios for the energy and transport sectors to meet their cumulative carbon budget by 2050, this outlined the type of technologies and the scale of the renewable resources required for the carbon reduction of the EU energy system.

Using the Irish TIMES energy system model, Chiodi, et. al (2014) presented results from energy and agriculture system model scenarios to the year 2050, assessing the technical feasibility of the EU commitment of reducing GHG emissions between 80% and 95% relative to 1990 levels.
Gaffney et al (2020) investigated the European electrical power system with negative emission and high renewable energy penetration. Excluding the heating and transport sectors, the work presented three power system scenarios with high temporal resolution to simulate emissions reduction, technical operation and system costs for the year 2050. Yue et al. (2020a) derived marginal abatement cost curves (MACCs) from the Irish TIMES energy systems model by applying increasingly stringent emission constraints. The results show that MACCs are highly dependent on model assumptions and the availabilities of bioenergy and carbon capture and storage (CCS) technologies play critical roles.

In a separate study Yue et al. (2020b), carried out an assessment of 100% renewable energy system in 2050 for Ireland using the Irish TIMES energy system optimization model that studied the technical and economic feasibility towards 100% renewable energy penetration. The research suggested a more ambitious bioenergy supply could be one of the pathways to reach 100% renewables with an additional system cost more than 2% of the GDP when compared to the base case scenario. Although Ireland requires an aggressive carbon mitigation approach to comply with the assigned carbon budget, the study found that focusing on renewable penetration is less cost effective compared to focusing only on carbon mitigation.

From the previous works presented, it is evident that most studies lack providing any insight on the contingency measures in the event of overshooting the cumulative carbon budget for Ireland. In fact, most existing energy system scenarios analysis for Ireland will exhaust Ireland's cumulative carbon budget earlier than 2050 (SEAI 2020). To date there has been no attempt to build a net-negative energy system scenario for Ireland on an open energy system modelling tool that could be utilized in techno-economic analysis in the energy transition pathway to meet the stringent requirement implied by the Paris temperature goals. ….o increase by 8%, producing 42To address this gap, this work aims to develop and evaluate an energy system scenario model that illustrates the possible configurations to meet the assigned carbon budget, after satisfying the total national energy demand.

1.2 Modelling methodology

The energy system model presented in this work is based on an open energy modelling platform as open code and data improve scientific research quality through reproducibility that increases collaboration between different energy policy regime (Robbie Morrison and et al 2017), (Morrison 2018). In a time with a lot of information available, transparent and open modelling approaches can have a strategic advantage for the policymakers to address public concerns towards new technologies, legislation and infrastructure (Francesco Gardumi and Robbie Morrison 2018). Moreover, the open-ness of energy system modelling increases productivity through collaborative efforts to develop large datasets (Stefan Pfenninger et al. 2018).

PyPSA is an open-source modelling tool that enables simulation and optimisation of electrical power systems over different time-series (Hörsch et al. 2018). PyPSA can be used to model electrical power systems comprising conventional power generators, VRE and energy storage, which enables coupling to other energy sectors such as heat and transport. PyPSA models are flexible for scaling an electricity system from small to large networks with different time series (Tom Brown and David Schlachtberger 2018).

This work first presents a base model, from which an existing electricity, heat and transport system can be modelled and simulated. A base electricity model (for the island of Ireland) is built to evaluate different parameters within the system, based on which, a realistic electricity model is developed. The realistic all-island electricity model is then integrated with the heating and transport systems to build a base energy system model for further evaluation and validation with the historical data of 2018. The validated energy system model is then used to extrapolate a model that incorporates generators with carbon capture and storage (CCS) and direct air capture (DAC) that simulates the potential energy demands under three different scenarios in 2030; (i) no carbon control, (ii) carbon neutral, and (iii) net-negative emissions. This is the first attempt to build a net-negative energy system scenario for Ireland on an open energy system modelling tool that could be utilized in techno-economic analysis in energy transition pathway to meet the stringent requirement implied by the Paris temperature goals. This model is limited to a technical analysis that incorporates fixed capacity of total primary energy resources. However, a further model will incorporate capacity expansion with individual component and system costs. Python for Power System Analysis (PyPSA) is used to model the Irish electricity system. A schematic diagram of the different models presented in this work is illustrated in Figure 1.

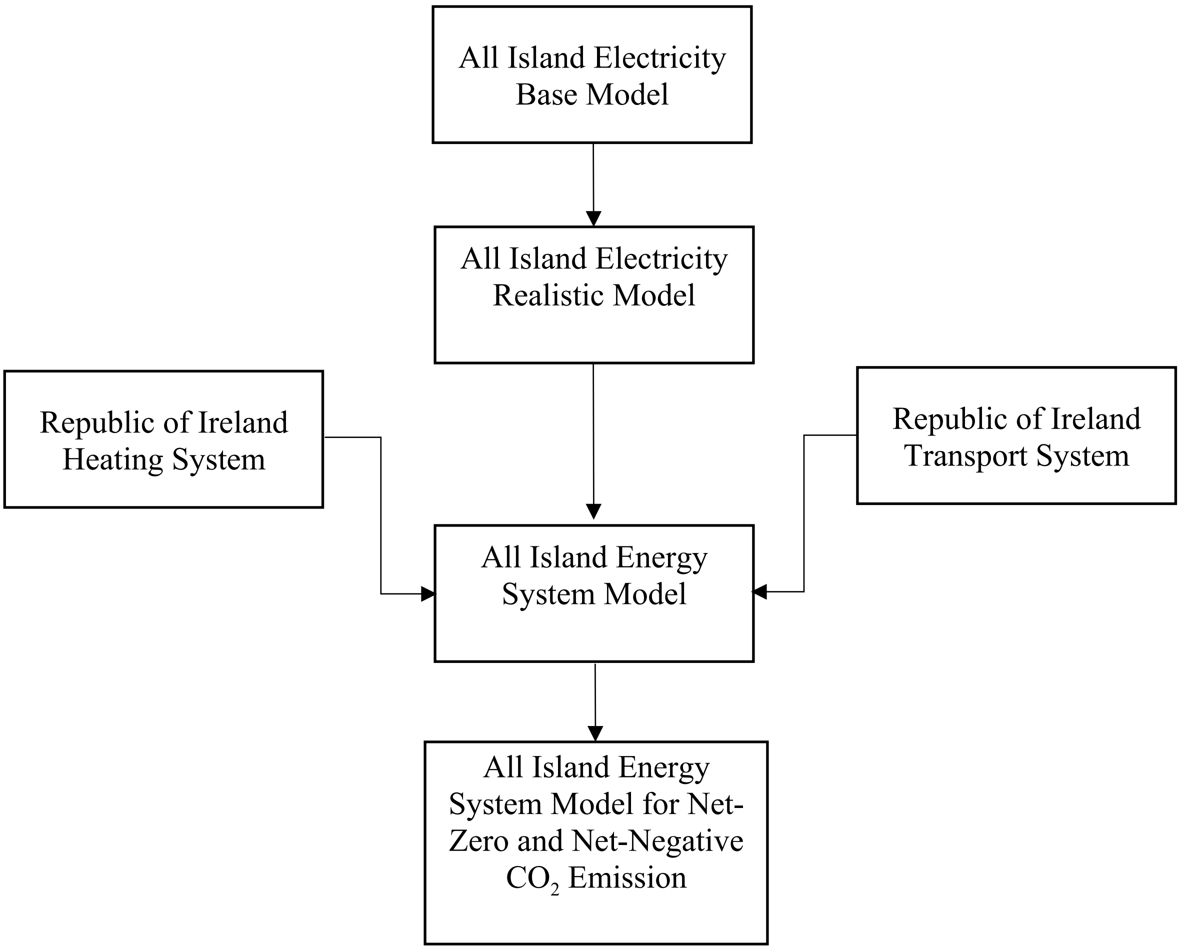

Figure 1: PyPSA model schematic diagram.

This work presents a linear optimal power flow (lopf) analysis for all island energy model. The electricity generation is modelled to include system non-synchronous penetration (SNSP) limit. SNSP is a measure of the non-synchronous generation (i.e. VRE and interconnector import) on the electricity system at a given time. It is the ratio of the real-time cumulative electrical power contribution from non-synchronous generation and net high voltage Direct Current (HVDC) imports over the total number of electrical demand and net HVDC exports (Jon O'Sullivan 2014). The SNSP limit is set to be 65% for 2018 (EirGrid, SONI 2018), therefore a cumulative electricity generation from VRE and electricity import should be no more than 65% of total generation. The model does not estimate either network losses or local network constraint as opposed to system-wide curtailment. The transport system is modelled to include 4% of bio-fuel mix to the conventional fossil fuel. The carrier for heating system includes natural gas, coal and peat, whereas heat-pump is excluded from the base electricity model, but included in the model that accounts additional measures. Input parameters are taken from SEAI (2019), Eirgrid and Central Statistics Office (CSO) for the year 2018 (EirGrid 2018). The PyPSA results of electricity, heating and transport system model are compared with the 2018's statistics of SEAI (2019), Eirgrid and CSO.

2 System Models

In this section four models are described. The first model is implemented to verify the SNSP constraint that requires to be applied in a realistic Irish electricity model. The second mode is the Irish transport system model that incorporates the constraint of bio-fuel mix. The third model is the energy system model incorporating the SNSP and bio-fuel mix constraints. The fourth model is the 2030 electricity and heating model that incorporates various carbon mitigation measures.

2.1 All Island electricity model

This model implements the SNSP constraints to the all-island electricity system. As shown in Figure 2 (A), Republic of Ireland (IE) electricity network is constructed with the main bus (IE Electrical Bus), where one synchronous generator (IE_Sync. Generators) one non-synchronous generator (IE-Non-Sync. Generators) and a load (IE Load) are connected. The IE main bus is also connected to a remote bus (IE Remote Bus) via a link that simulates the bidirectional East-West interconnector. IE remote bus consists of one load that is considered as the interconnection load for Republic of Ireland (IE-IC Load) that is matched to the maximum capacity of the interconnector. The remote generator (IE-IC Generators) services the IE load up to the limit of either maximum capacity of the interconnector or the SNSP. The Northern Ireland (NI) electricity network also has an identical setup (denoted with NI for each component) as shown in Figure 2 (A). Both networks are connected via a North-South interconnector (N-S-Link).

The aim of this model is to implement SNSP constraint to the all Island electricity model. This should allow all non-synchronous generators to generate cumulatively a maximum electrical power imposed by the SNSP limit The non-synchronous should dispatch electricity, which corresponds to SNSP × load. In contrast, the synchronous generators require to dispatch minimum power by calculating the time series of (1-SNSP) × load. Although there is no such component in PyPSA currently available to simulate this type of constraints, the extra-functionality allows writing conditions that can serve this type of specific purpose.

The all-island model in Figure 3 illustrates the elaboration of Republic of Ireland (IE) electrical power system with integration of various conventional and renewable energy carriers. This simulates realistic electricity flow that corresponds to the actual indigenous electricity demand/supply and all-island electricity import/export.

The somewhat more realistic all Island electricity model shown in Figure 2 (B) includes synchronous generators with major contributions such as natural gas, coal, peat, oil, biomass and waste. For the non-synchronous generators, one is being essentially considered as wind and the other is interconnectors. The IE electricity network is connected with the East-West 500 MW HVDC interconnector to the UK, whereas electricity network of Northern Ireland (NI) is connected with Belfast-Moyle 500 MW HVDC interconnector. NI and IE electricity networks are connected with a 300 MW AC interconnector. Since this model is using two types of non-synchronous generators (wind and interconnectors for each jurisdiction), it is complex to realise the SNSP limit, that could enable the synchronous generator to dispatch minimum power by calculating the time series of (1-SNSP) × load. The model presented in Figure 2 (A) can be used to incorporate the extra-functionality to modify a realistic all-island electricity model. This model uses historical inputs data: i) wind availability, ii) wind generation, iii) total demand from EirGrid for IE and NI with 15-minute time series from the year 2018, which are down-sampled to hourly-resolution. This model also used historical data from the Sustainable Energy Authority of Ireland (SEAI) for IE electrical demand. This particular model has not attempted to model network losses or storage (specifically Turlough Hill) so total generation will be equal to total load at all times.

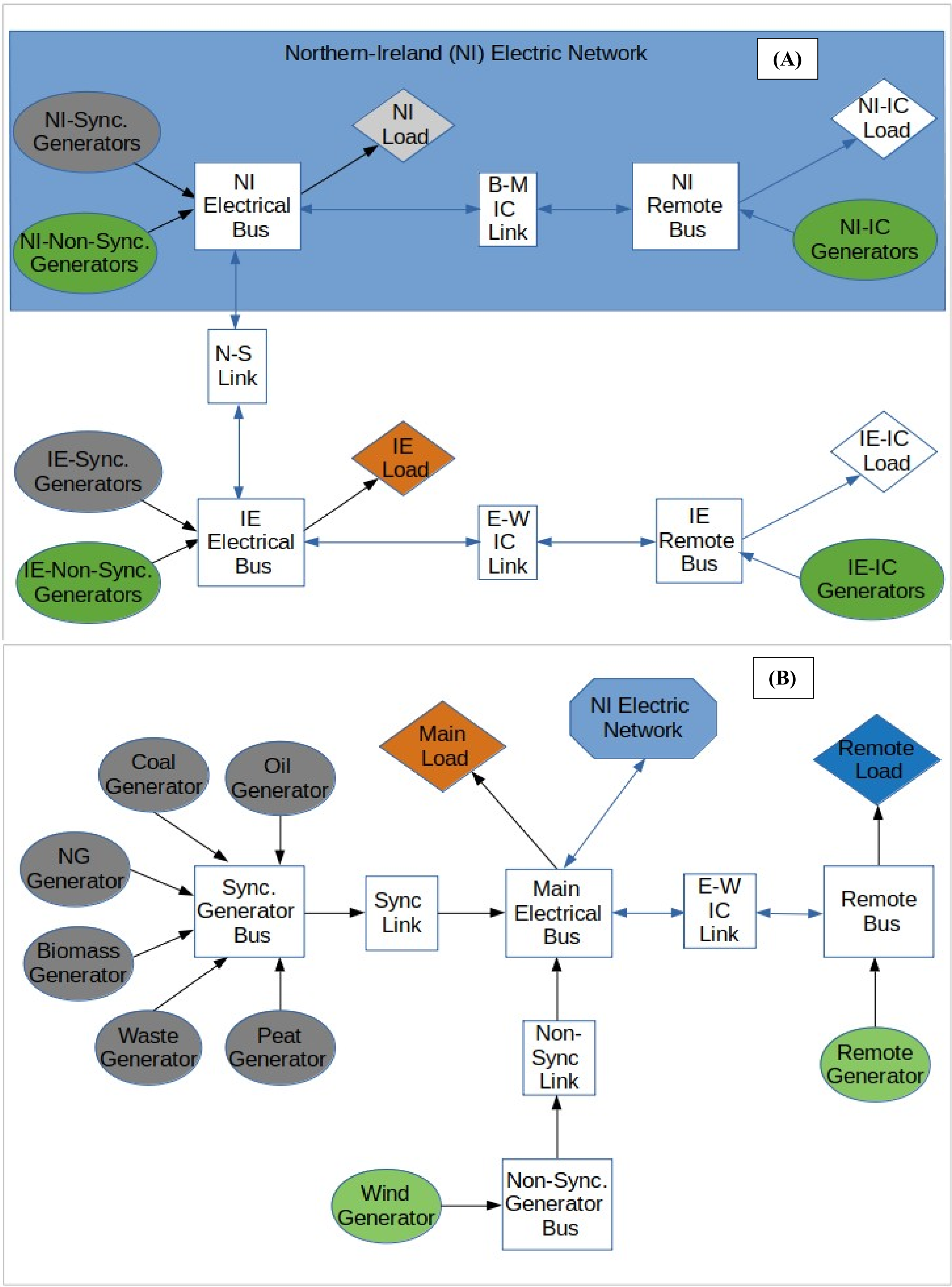

Figure 2: (A) All-Island of Ireland electricity base model, (B) All-Island of Ireland electricity mode with various fuel mix.

2.2 Transport model

A significant amount of oil is consumed in various modes of transportation mainly in the form of diesel and petrol. These fuel types are also required to be mixed with a certain percentage of bio-fuel. This model aims to simulate the scenario to incorporate bio-fuel automatically into diesel and petrol with an appropriate ratio. The data from the central statistics office (CSO) as shown in Table 1 is used in this model (CSO 2019).

Table 1: Fuel Consumption (MW) by Transport Sector-2018 (CSO 2019).

Transport Sectors	Petrol	Jet kerosene	LPG	Diesel	Liquid Biofuel
Road freight	0	0	0	925	40
Road private car	883	0	3	1742	104
Road public passenger services	9	0	0	169	8
Road light goods vehicle	0	0	0	422	19
Rail	0	0	0	50	0
Sum of all aviation transport	1	1463	0	0	0
Fuel tourism	0	0	0	235	11
Navigation	0	0	0	112	0
Unspecified	198	0	0	453	27

The fuel consumption is given in ktoe which has been converted to MW for the use of PyPSA simulation. The model considers 4% of bio-fuel to be mixed with both types of fuels (SEAI 2019). As shown in Figure 3, diesel and petrol intermediate connectors (pypsa jargon: buses) are connected to their corresponding generators and a set of loads. The diesel load consists of private cars, public transport, rail, heavy and light goods vehicles, navigation, fuel tourism and unspecified load, whereas the petrol load consists of private cars, public transport and unspecified load. Aviation is connected as a separate load that consumes jet-fuel. Bio-fuel intermediate connectors (bus) has its dedicated generator and also connected with a set of diesel and petrol loads via two controllable links (Bio-D for diesel load and Bio-P for petrol loads). These links operate under the constraint that specifies the percentage of bio-fuel mix into diesel and petrol. For simplicity of the model, the minor energy use in electric vehicles in 2018 is not considered.

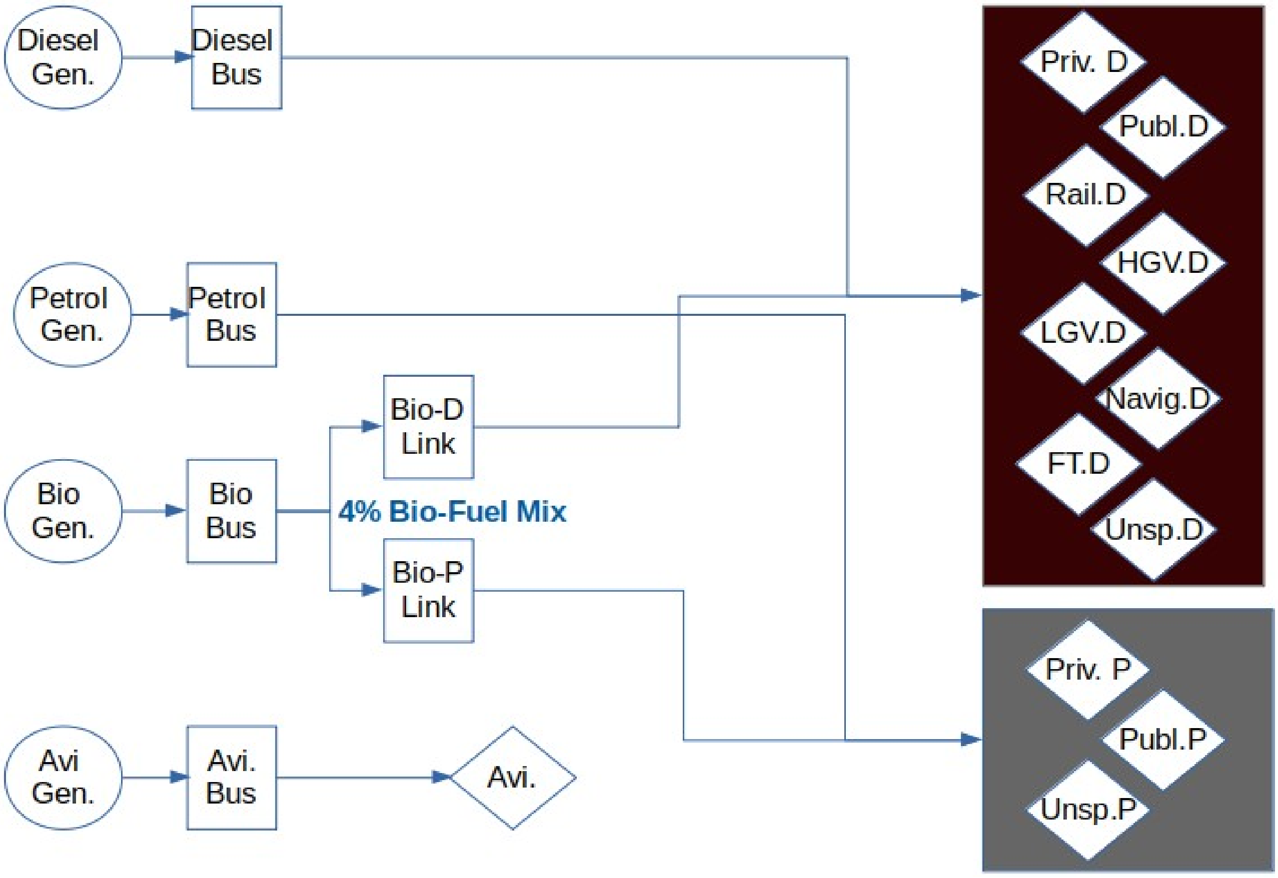

Figure 3: IE transport system model.

2.3 All Ireland energy system model

The all-island energy system model incorporates electricity, heating and transport sectors. The aim is to simulate the energy flow for each sector that corresponds to the actual indigenous energy demand/supply and all-island electricity import/export. Figure 4 shows the schematic of the all-island energy system model. The IE energy system is further detailed from the model illustrated in Figure 2 (B), where IE network incorporates the heating and transportation sectors. However, in NI jurisdiction, no heating and transportation are modelled. NI electrical network is only considered as it is associated with all Island SNSP constraint. The transport sector model shown in Figure 3 is combined in the energy system model by collapsing it into the three components (i.e Oil-T Link, Trans. Bus and Trns. Load). Oil transport link (Oil-T Link) acts as an oil generator, while transport bus (Trans. Bus) connects the oil generator and transport load as illustrated in Figure 4. This model uses synchronous generators with major contributions such as natural gas, coal, peat and oil. For simplicity of the model, the minor synchronous energy input from biomass and non-synchronous from solar energy are not considered.

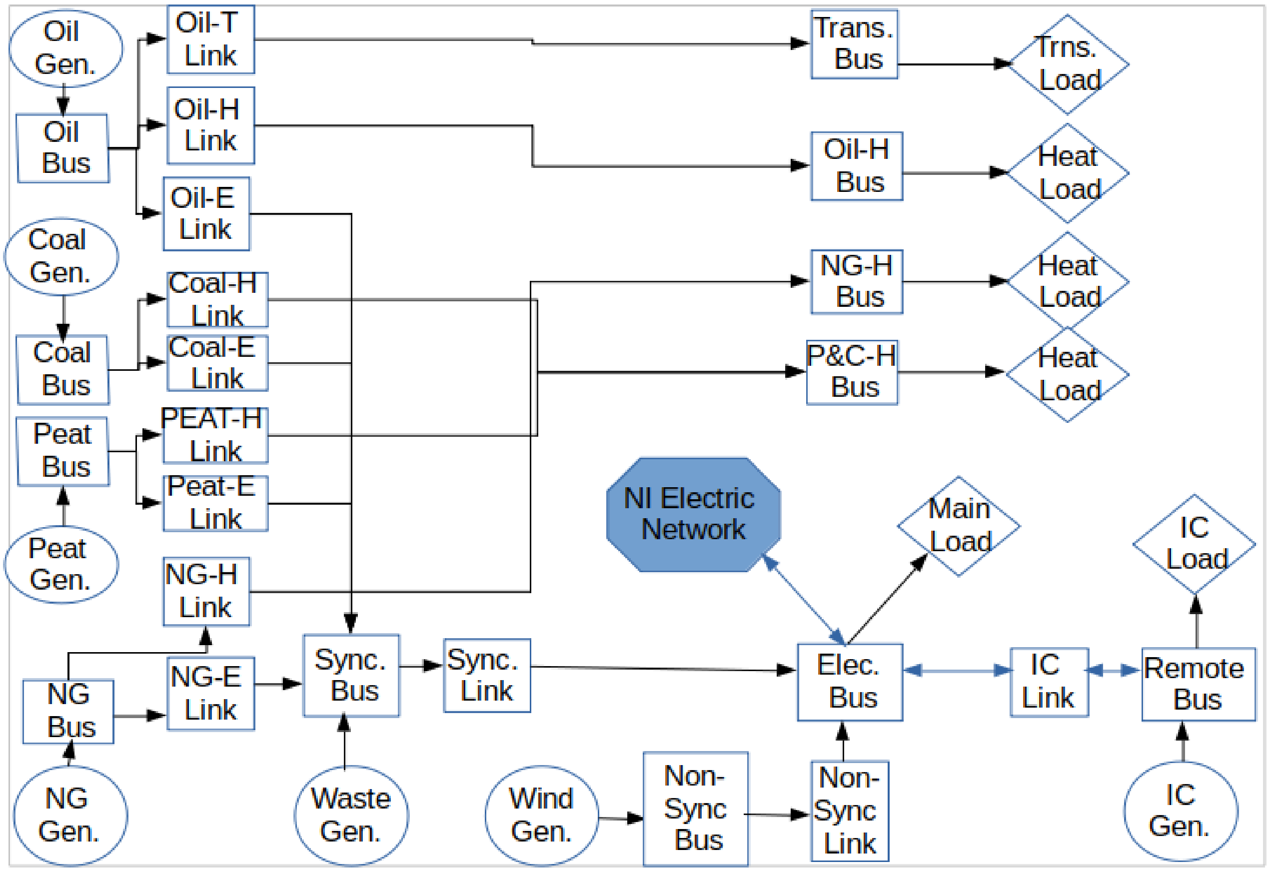

Figure 4: All Island Energy system model

2.4 A net-zero, net-negative energy system model

The energy systems model illustrated in Figure 5 includes carbon capture and storage (CCS) and direct air capture (DAC). This is to evaluate the required annual capacity of different energy carriers to achieve a net-negative energy system. In this model only electricity and heating systems are illustrated with three scenarios in 2030 considered; (i) no-CO_2-control, (ii) carbon-neutral, and (iii) net-negative. The model considers a post-2025 scenario, when all peat and coal power plant generates are planned to phase-out. It is assumed in this model that both natural gas (NG) and biomass power plants are deployed with both CCS and non-CCS. The model estimates different energy carrier's capacity while transforming from no-CO_2-control to a net-negative scenario. The solar energy potential is estimated to be 1.5 GW (DCCAE 2019), while onshore and offshore wind potentials are 7.5 GW and 3.5 GW respectively by 2030 (DCCAE 2020). This model first estimates the total capacity required for NG+CCS and biomass+CCS power plants to achieve a carbon-neutral then net-negative electricity and heating systems.

The coal and peat power plants are replaced by biomass, biomass+CCS, and NG+CCS power plants. A DAC is connected to the main 'Electric Bus' as a load that is designed to draw CO_2 from the atmosphere to store it into a CO_2 storage unit (Figure 5). The biomass, NG, oil and waste (other renewables) power plants are connected to the synchronous bus to be considered as the despicable generation, while solar and wind generators are connected to the non- synchronous bus. Heat-pump is connected via a link connected between the main 'Electric Bus' and heat-pump bus (HP Bus) with a 0.3 coefficient of performance. Heat loads are also supplied by coal and oil.

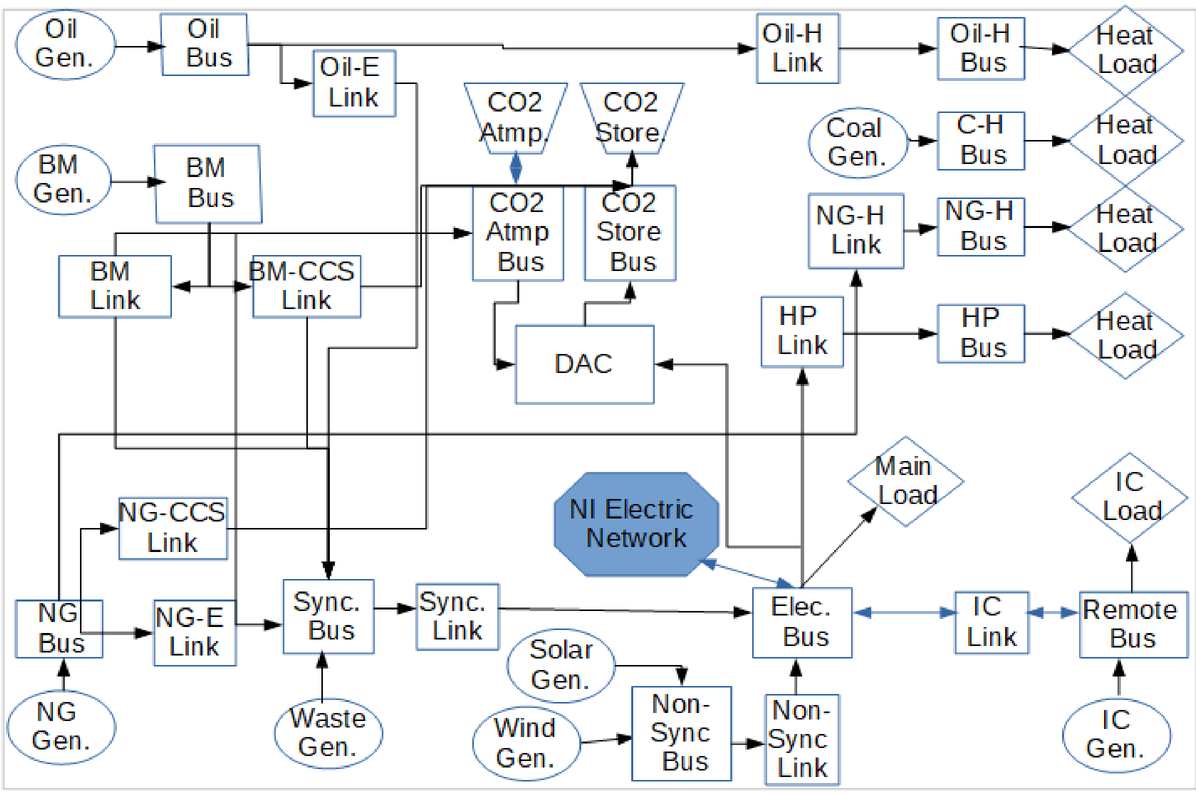

Figure 5: Electricity and Heating with CCS and DAC.

3 Simulation Results

This section presents the PyPSA simulation results of the models presented in section 2.

3.1 All-Island electricity model

In a base electricity model shown in Figure 2(A), the total load of Republic Ireland and Northern Ireland is set to 150MW for a single snapshot. Wind generators from both jurisdictions have a priority to dispatch as its marginal cost (MC) is set to zero. The MC for remote generator is set to non-zero, but lower than the MC of IE+NI Sync generators, thus it has the 2nd priority) to dispatch. System Non-Synchronous Penetration (SNSP) limit is set to 70% in the model presented in Figure 2(A), thus, a minimum of 45 MW should come from IE+NI Sync. generators in any circumstance. The remaining 105 MW should be supplied by the Non-Synchronous generation (Wind +Remote generator)

When export, the IE+NI wind generators should be accompanied by the IE+NI Sync. generators with the same ratio of SNSP limit. After servicing local load, the mix of the wind generators and Sync-generator are expected to export electrical power (up to its full interconnection capacity) to the remote load as the marginal cost of synchronous. and wind generators mix is lower than the remote generator. When it reaches the maximum interconnection capacity, the wind is expected to be curtailed if there is an excess of wind. Import is expected to take place when there is not enough wind available. As the MC of remote generator is less than Sync. generators, it imports up to the maximum interconnection capacity.

The model presented in Figure 1 has been simulated with fifty scenarios (snapshots) having random electricity demands for both IE and NI jurisdiction, of which one snapshot result is presented in Figure A in the appendix. As illustrated in Figure A (i), the IE+NI sync. generators produce 45 MW cumulatively whereas 105 MW comes from all IE+NI Non-Sync. generators (wind + remote generators) to satisfy 70% SNSP limit. Even when sufficient wind is available, due to 70% SNSP constraints, wind does not exceed 105 MW to service total load. In case of indigenous fuel mix with higher MC, the tendency is to import from remote generators (up to the SNSP limit and interconnection capacity). The SNSP constraints are found to be satisfied in all snapshots for all-Island case (appendix Figure A (ii)).

The SNSP constraint then is applied to the realistic electricity model of all-Island of Ireland (see Figure 2 (B)). The SNSP limit in the year 2018 was considered as 65% of the cumulative load of the Republic of Ireland and Northern Ireland. Therefore, the wind penetration and interconnection import to the all Island electricity system cannot exceed 65% of the load at any snapshot. The rest of 35% of demand has to be met from the synchronous generators (i.e. natural gas, coal, peat, oil, waste and hydro). The curtailment of 3% from the Republic of Ireland and 4% from Northern Ireland is also accounted for network constraint. As can be seen in Figure B in the appendix, the PyPSA simulated actual wind generation does not exceed the 65% SNSP limit of the network at any snapshot, thus satisfying the constraint applied to the model.

3.2 IE transport system model

The annual fuel consumptions in transport section are given in ktoe, which is converted into MWh, which is then sampled in hourly resolution to use as a PyPSA model load for each snapshot. Due to the nature of this model for transportation, PyPSA requires to calculate the biofuel mix automatically. According to the CSO data, 4% biofuel was mixed to diesel and petrol before it's delivered to the loads. Therefore, the biofuel generator has to generate at least 4% of the total transport load. The constraints are applied separately for diesel and petrol via links (see Figure 3) that is connected from bio-fuel generator to the diesel and petrol load. With 4% biofuel constraints the PyPSA simulation results deviated from total fuel consumption provided by SEAI and CSO by 0.07% for diesel, 0.1% for petrol and 1.2% for biofuel. When data of bio-fuel mix from CSO.ie were examined, it was found that the average bio-fuel ratio to diesel and petrol were approximately 3.95%. When this ratio was applied the results were found to be more accurate, which deviated by 0.06% for diesel, 0.09% for petrol and 0.11% for bio-fuel as shown in Table 2.

Table 2: Transport fuel consumption comparisons.

Transport Fuel Type	CSO (GWh)	PyPSA (GWh)	Difference (%)
Diesel	35983	36005	0.06
Petrol	9548	9540	0.09
Bio-Fuel	1814	1812	0.11

3.3 All Island energy system model

In the all-Island energy system model, the total primary energy consumptions (including electricity for all Ireland, heat and transport for the Republic of Ireland) are set up as the energy demand. These data were obtained from SEAI, EirGrid and CSO energy database. Using the primary energy consumptions, the PyPSA model simulates the total final consumption (TFC) of energy for each energy carriers. The TFC for each carrier is compared with the reference database. As shown in Table 3 the simulated results deviated by 0.39% (coal), 1.44% (peat), 2% (oil), 0.06% (natural gas) and 2.42% (wind) from the reference data.

Table 3: Total final energy consumption 2018 data to model comparison.

Energy Carriers	SEAI (GWh)	PyPSA (GWh)	Difference (%)
Coal	3,035	3,047	0.39
Peat	2,291	2,325	1.44
Oil	82,166	80,568	1.98
Gas	22,655	22,642	0.06
Wind	11,068	11,342	2.42

Using the energy conversion efficiency of each energy carriers, total primary energy requirements (TPER) is calculated. These are then multiplied by CO_2 intensities to estimate CO_2 emission from individual energy carriers used. The conversion efficiency and the CO_2 intensity used to estimate emissions are presented in Table 4. The comparison between PyPSA simulation results and reference data for CO_2 emission is illustrated in Table 5. While coal, peat and natural gas are mostly utilized in the electricity and heating sectors where the energy is converted into a useable form having a certain conversion rate of each energy carrier, oil is mostly used in transport where TPER is considered to be equal to TFC. Thus the conversion rate of oil is higher.

Table: 4: Conversion parameters (SEAI 2020)

Energy Carriers	Conversion Efficiency (%)	CO_2 intensity (thermal)
Coal	36	0.34
Peat	29	0.41
Oil	93	0.26
Natural Gas	42	0.2

Table 5: CO_2 emissions.

Energy Carriers	SEAI (tCO_2)	PyPSA (tCO_2)	Difference (%)
Coal	2,877,000	2,878,018	0.04
Peat	3,271,054	3,318,917	1.44
Oil	21,614,122	21,193,694	1.98
Gas	10,466,000	10,414,569	0.49

3.4 A 2030 net-zero/net-negative emissions energy system model

The model presented in Figure 5 is simulated. An estimated energy demand (electricity, heat and transport) for the 2030 scenario is considered for this simulation. The estimated energy demand for 2030 is compared with historical SEAI data for 2018 that shows a distinctive demand shift by energy carrier (shown in Figure 6).

Oil and coal are mostly consumed for heating in Ireland, thus variations in annual generation capacity are not noticeable in Figure 6. The VRE and other renewables do not vary significantly, as being power plants with the zero CO_2 emission and lowest marginal cost, they are utilized to its max capacity, although a 2.3% decline in VRE is noticed in the net-negative scenario. An obvious increment is observed for natural gas (NG) and biomass annual generation capacity in a transition pathway from no-CO_2-control to a net-negative scenario. These changes in VRE, NG, and biomass consumption are due to a heavy deployment of NG+CCS and biomass+CCS and DAC. An additional 37% NG and 63% biomass systems are required to realize a carbon neutral (net-zero) energy system, while a further 19% NG and 44% biomass are required to achieve a net-negative scenario when it compared to the energy system scenario with no carbon control as shown in Figure 6. It can be seen that the major shift occurred in oil as by 2030 most of the oil powered utility scale electricity generators and heating systems will be phased out and more than 36% of entire car fleet is estimated to be powered by electricity. Therefore, the energy demand from oil is expected to drop by approximately 80% by 2030.

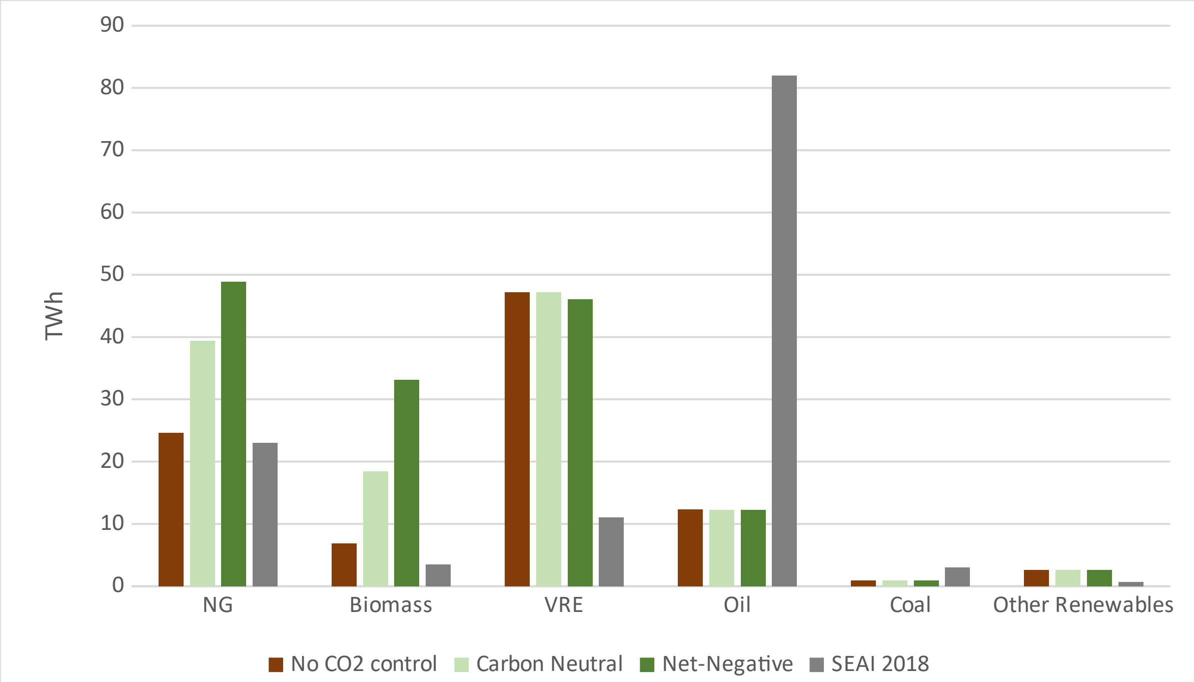

Figure 6: Annual generation capacities of different energy carriers.

A clear breakdown of the NG and biomass from Figure 6 is presented in Figure 7 (A). With the lower marginal cost among all non-VRE power plants, the NG and biomass without CCS are mostly utilized in a no-CO_2-control scenario. In a carbon-neutral and net-negative scenario, NG is also used to service heating loads. A similar effect is observed in biomass without CCS. In the carbon neutral and net-negative scenarios, NG+CCS and biomass+CCS are mostly used to service DAC. Significant energy is required to operate DAC, estimated 2.4 MWh of energy is required to remove 1 ton of CO_2 (Wilcox et al. 2017). As most of the VRE and other renewables are utilized to its maximum capacity, NG and biomass are required to be extended to operate DAC (Figure 7 (B), (C)). Due to the high operating cost, DAC is chosen to operate only when it is necessary to meet the environmental constraints to limit the amount of CO_2 in the atmosphere. It can be seen in Figure 7 (B), where the average electricity consumption of DAC is 2500MW most of the year, however, to keep the CO_2 limit zero the electricity consumption increases to an average 3800 MW. In all cases the energy supply from both fossil and VRE sources is set to be sufficient to service the loads. With this approach PyPSA optimize the cost of the system while meeting all given constraints. Although the marginal cost of the power plants with CCS are higher than the conventional power plants, the CCS configurations (NG+CCS and biomass+CCS) are chosen to operate in the simulation due to the low CO_2 emission. In both cases, NG and biomass without CCS were not operated.

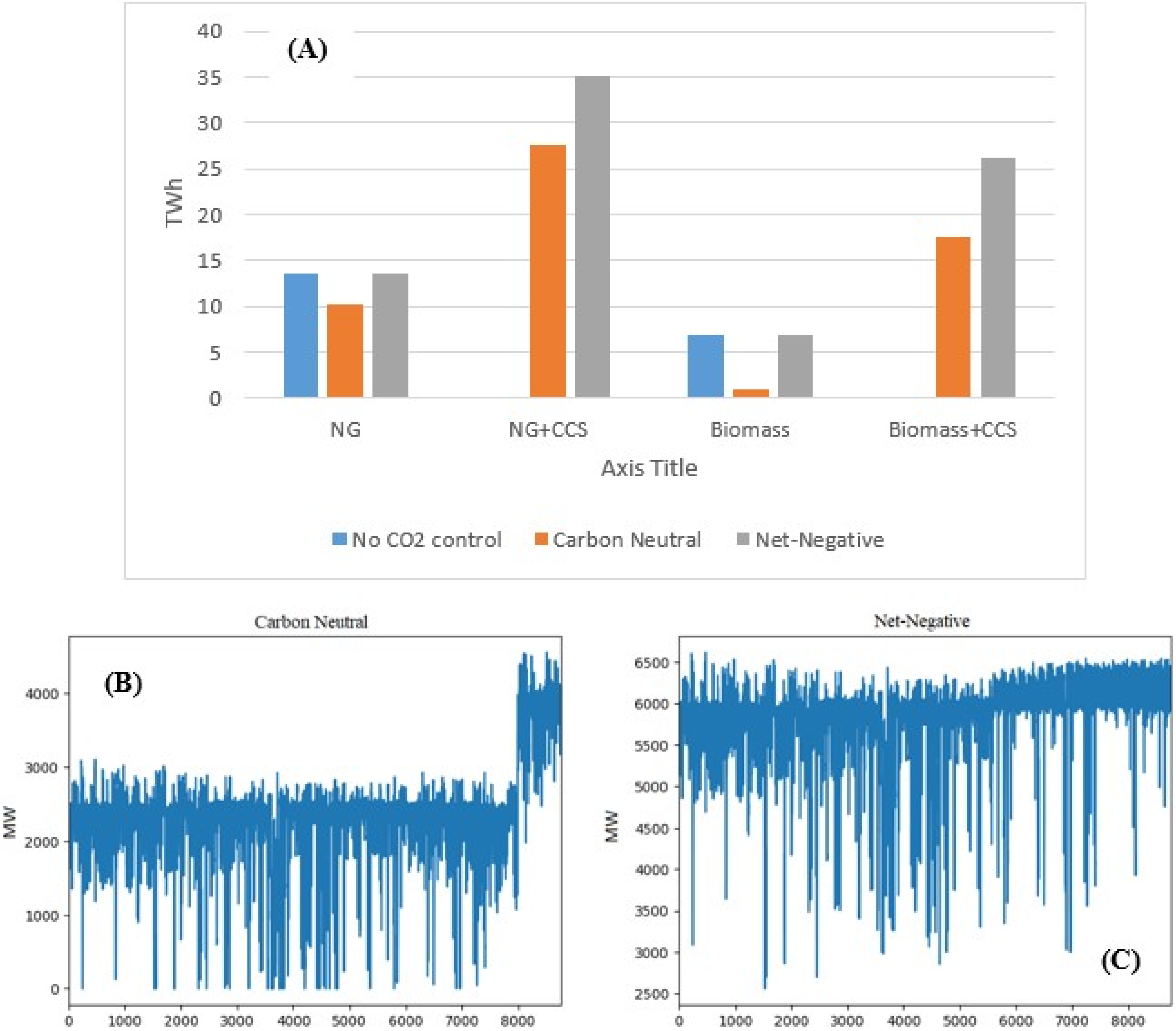

Figure 7: (A) NG and biomass generation breakdown;
(B) and (C) Annual energy consumption by DAC.

4 Discussion

This work modelled the Irish energy system for 2030. A base energy system model was first simulated and validated with the historical data for 2018 from various sources (i.e. SEAI, CSO, and EirGrid). Using the 2018 load profile, the base model was then extrapolated to include potential environmental contents to satisfy the Paris Agreement temperature goal of well below 2°C. In the 2030 model, the electricity and heat system was primarily simulated to estimate annual energy consumption in three different scenarios. The transportation system was not included in this model for the complexity due to the uncertainties of transportation fleet configurations and the lack of resources to meet the net-negative energy scenario. However, a partial attempt was made to simulate a net-zero model configuration that includes electricity, heat, and transport. In this case, the model presented in Figure 3 is integrated with the transport system that assumes a tentative fleet configuration for 2030.

It is difficult to estimate the potential configuration of the transport fleet, due to various key drivers such as technological changes/improvement, technology readiness, government policy, and most importantly economic factors. There have been many publications (DCCAE 2020), (Mulholland et al. 2020), (Dey et al. 2017) assessing the preferred transport fleet by 2030, which has also been argued in many cases by experts. This work attempts to estimate the fleet configurations by recent literature. The NECP 2020 report (DCCAE 2020) indicates that there will be 13.4% of renewable energy share (RES) in the transport sector if an additional measure is taken, otherwise, the RES will be approximately 7.2%. Decarbonizing the transport system will be essentially driven by including electric vehicles (EV). In a different report (Dey et al. 2017) it has been found that the passenger cars will be increased by 28.7% compared to the 2015 fleet. The primary energy consumption in 2018 for transport was found to be 47.3 TWh equivalent of fossil fuels (diesel, petrol, and biofuel) as illustrated in Table 2. This number is kept unchanged; although there is an expected increase of total vehicle numbers in 2030, the efficiency of the fleet may improve with an increased portion of hybrid vehicles, (which are not considered as a full EV). It is projected that a total of 2.6 M vehicles will be on the roads of Ireland by 2030, business as usual, of which 936,000 will be EVs. As the passenger cars are the most dominant candidate in transport sector for electrification, this requires approximately 17.3 TWh of electricity if 36.6% shift is made from fossil fuel to electric vehicles. The rest 30 TWh equivalent of energy will be supplied by fossil fuels. This energy supplied by fossil fuel will release the CO_2 directly to the atmosphere which is difficult to capture due to various techno-economic and policy barriers. However, the same parameters used in the model illustrated in Figure 6 can achieve a net-zero configuration as shown in Figure 8 (A). It has been projected that between 10,000 to 30,000 hydrogen vehicls will on the road by 2030 which will be a maximum of 1% of the entire transport fleet (Hydrogen Mobility Ireland 2019). Due to the negligible transportation share, hydrogen vehicles are not included in 2030 model. However, this segment is expected to be a key driving factor in the energy system beyond 2030 scenarios.

Total required installed capacity for natural gas and biomass are 45 TWh and 33 TWh respectively. The installed capacity for the rest of the energy carriers remains unchanged when compared to the previous model. The increase of natural gas and biomass in the form of primary energy resources refers to the fact that the VRE has been maxed out to its estimated 2030 capacity, yet the system requires energy with minimum CO_2 emissions. This can be provided by the power plants with CCS, the natural gas and biomass with CCS power plants produce 35 TWh and 31 TWh of electricity respectively as illustrated in Figure 8 (B).

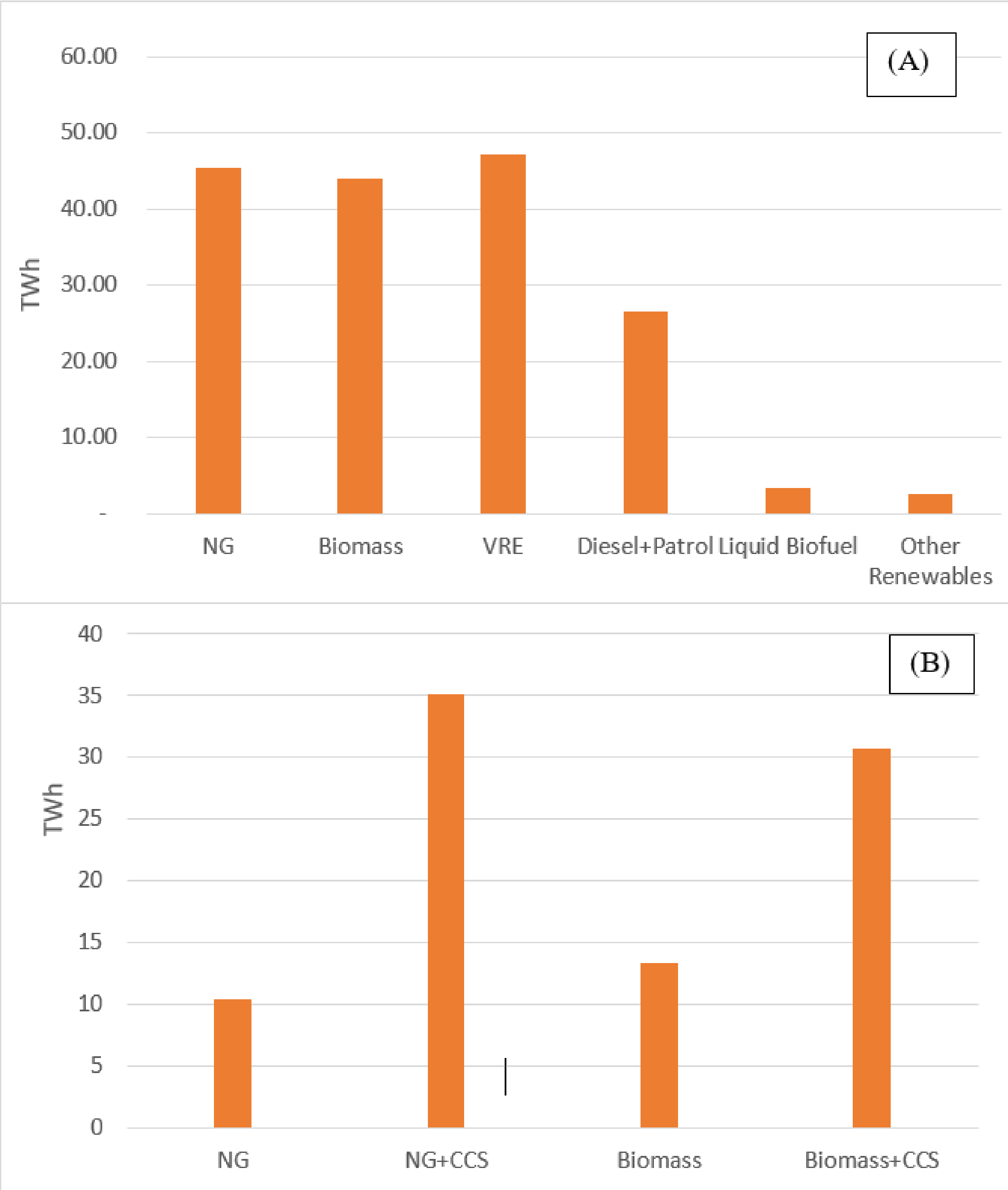

Figure 8: (A) Required annual generation capacity to service the transport sector for the net-zero scenario; (B) NG and biomass generation breakdown to service transport sector for the net-zero scenario.

5 Conclusion

The recent Irish energy system model for 2018 developed by the open modelling tool PyPSA is presented in this work. A constraint was developed to simulate the System Non-Synchronous Penetration for electricity model. The results for the electricity model were verified then applied to a realistic all Island electricity model. The simulation results were compared against the reference data obtained from SEAI, EirGrid, and CSO. The transport system was first modelled separately and the simulation results were compared with the historical datasets from CSO. This model along with the electricity model and the heating system were combined to develop an Irish energy system model. When compared with the reference datasets, the PyPSA simulation results for total final energy consumptions deviated from 0.06% to 2.49%, whereas the CO_2 emission was found to be within the range of 0.04% - 2%. This validated model was used to simulate an energy system model to reflect a 2030 scenario.

It was found that, despite of the coal and peat generators being phased out by 2030, the natural gas generators kept maintaining the similar power generation capacity as seen in 2018 scenario due to the additional deployment of the VRE. The energy generation from fossil fuel reduced significantly in ‘no carbon scenario’ in 2030. However, the use of fossil fuel will increase if the additional measures are to be taken to remove carbon from the atmosphere with the planed VRE deployment in Irish energy system by 2030. To address this crisis, Ireland needs to deploy more VRE and energy storage systems that requires a rigorous techno-economic analysis, which is the future scope of this work.

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Appendix

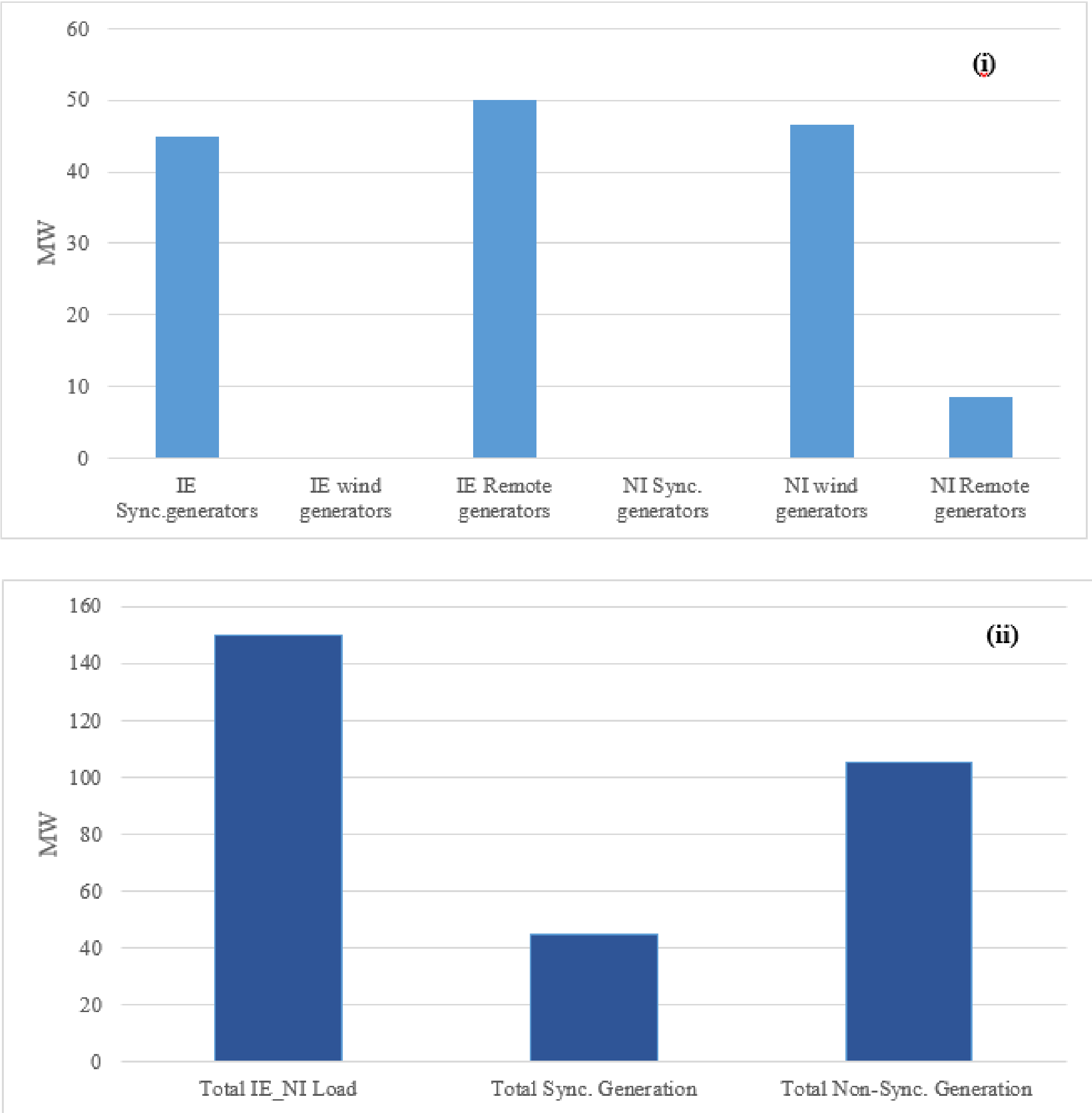

Figure A (i): All Island Energy system model.

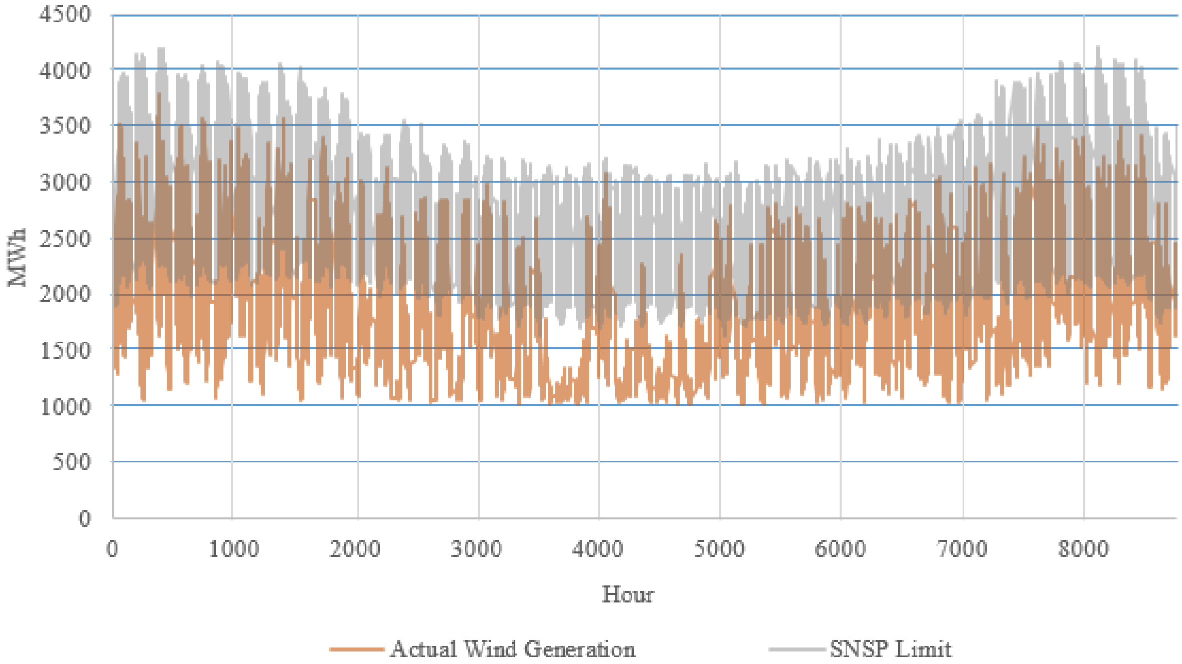

Figure A (ii): Comparison of total final energy consumption