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Developing a Model of the Irish Energy-System

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Abstract
The transition from a fossil-fuel to a renewable energy system is a modern and complicated challenge for numerous countries. However, as Ireland is an island that is poorly interconnected to other energy systems, this challenge becomes even more complicated. Identifying how to make this transition is a vital step due to the scale of the change required for large-scale renewable penetrations. In this paper, a model of the Irish energy system is created to identify how Ireland can transform from a fossil-fuel to a renewable energy-system. The energy-systems-analysis tool, EnergyPLAN, was chosen to create the model as it accounts for all sectors that need to be considered for integrating large penetrations of renewable energy: the electricity, heat and transport sectors. Before various alternative energy-systems could be investigated for Ireland, a reference model of the existing system needed to be created. This paper focuses on the construction of this reference model, in terms of the data gathered, the assumptions made and the accuracy achieved. In future work, this model will be used to investigate alternative energy-systems for Ireland, with the aim to determine the most effective energy system for integrating significant quantities of renewable energy.

1. Introduction
The Kyoto protocol only allows Ireland[2] to increase its CO_2 emissions by 13% compared to 1990 levels [1] and in 2006, Ireland was 26.7% above the 1990 levels [2]. As a result a major reform of the Irish energy system will be necessary to reduce CO_2 emissions to their required level and below. Considering the task ahead, the aim of this work is to develop a model of the Irish energy-system so that the radical changes necessary and their consequences can be analysed. In this paper a brief description is given about the data used to create the Irish energy-model. Also, the overall accuracy achieved by the model is discussed, concluding that the model will be used in the future to analyse how Ireland can dramatically reduce its CO_2 emissions.

2. Energy Tool
EnergyPLAN is a deterministic input/output tool. General inputs are the demands, renewable energy sources, energy station capacities, costs, and a number of optional regulation strategies. Outputs are energy balances and the resulting annual productions, fuel consumption, import/export of electricity and the total costs including income from the exchange of electricity [3]. The structure of the EnergyPLAN tool is illustrated in Fig. 1.

The main purpose of EnergyPLAN is to assist in the design of national or regional energy-planning strategies on the basis of technical and economic analysis, resulting from the implementation of different energy-systems and investments. A number of key features about the EnergyPLAN model are:

1. It uses an hourly simulation over a period of one year.
2. It uses aggregated data i.e. all power-plants are modelled as a single power-plant, with a combined efficiency.
3. The model uses analytical programming rather than iterations so the calculations are completed in a very short period of time.
4. The tool can identify the optimum technical-operation of the energy system as well as the optimal economic-operation. This is one of the key advantages in EnergyPLAN. A lot of energy models are

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[2] Ireland refers to the Republic of Ireland only throughout this paper unless otherwise specified.

capable of optimising an energy system based on costs. However, EnergyPLAN can optimise the energy system based on the technical operation of its components. This is very useful as it eliminates the constraints imposed by existing financial-infrastructures when analysing future alternatives. Furthermore, the EnergyPLAN model is also able to model the energy system according to the costs if required, so a comparison can be made with and without existing infrastructures.

A more detailed description of the EnergyPLAN model can be found at [4], while a complete review of energy-system-analysis tools for analysing national energy-systems in discussed in [5].

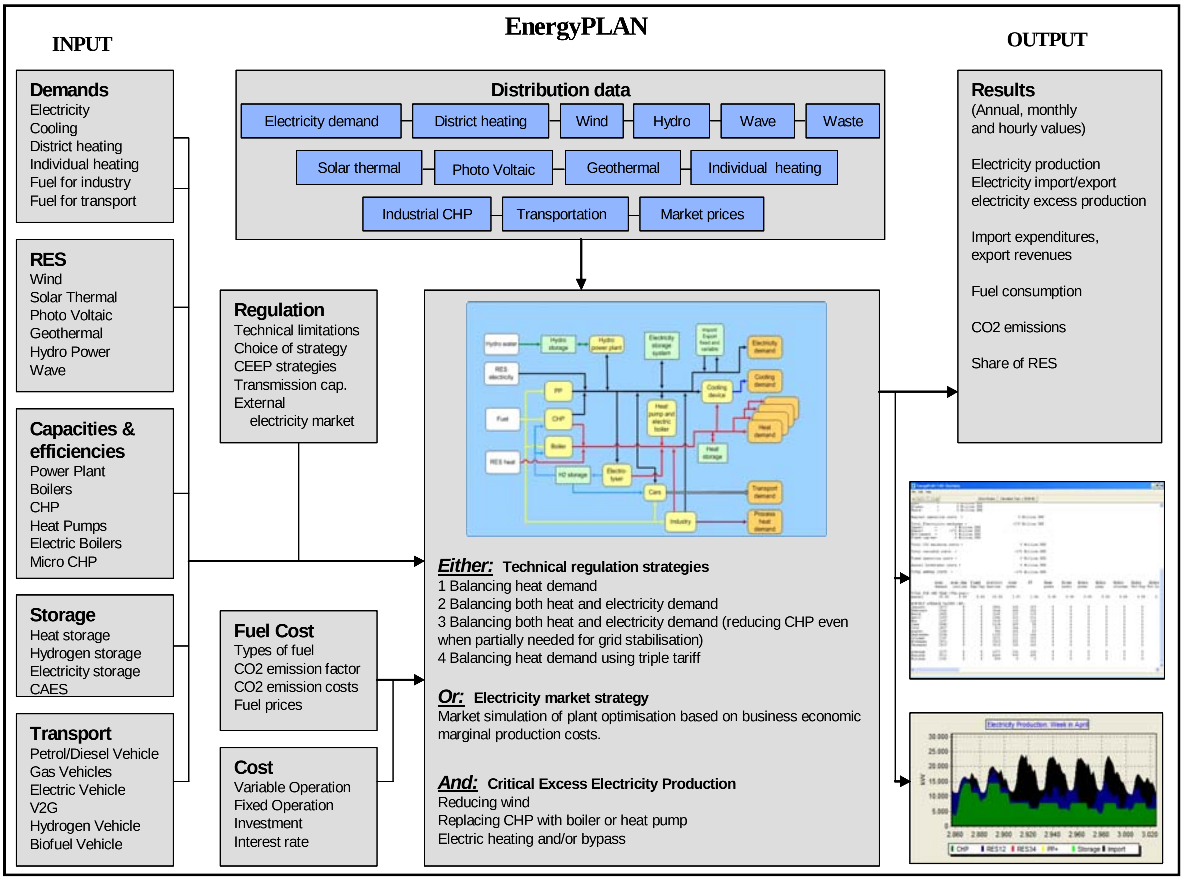

Fig. 1: The structure of the EnergyPLAN model [3]

3. Data Used

In order to create the EnergyPLAN model of Ireland, a number of inputs were necessary including electricity demand, power-plant capacities, renewable-energy production, individual demands, industrial demand, transport demand and more. Below is a brief description about how this data was gathered. The year 2007 was chosen to build a reference model of Ireland as it was the most recent complete year at the time the model was developed. The reference model is then compared to the actual performance of the system in 2007 to ensure the model is accurate.

3.1. Electricity Demand

To simulate the electricity demand, the EnergyPLAN models needs the total annual-electricity-demand and also the hourly distribution for this demand. The hourly electricity-demand for 2007 was obtained from the Irish Transmission System Operator (TSO), EirGrid [6], and subsequently, the total annual-electricity-demand was derived from this data as 28.48 TWh.

3.2. Conventional Power-Plants

Combined heat and power (CHP) and district heating are two key elements within the EnergyPLAN model. However, at present there is no district heating on the Irish energy-system. Therefore, to simulate the power plants in the Irish energy-system, only conventional power-plants needed to be considered. The inputs necessary for the model were:

1. Cumulative power-plant capacity on the Irish electricity network
2. Cumulative power-plant efficiency on the Irish electricity network
3. Cumulative efficiency of the power-plants in each fuel-type
4. Energy generated from power-plants of different fuel-type
5. CO_2 emissions from the power-plants of different fuel-type

The capacity of power-plants was obtained from the Irish TSO, EirGrid [6], as 6,445 MW. The efficiency of the entire power-plant system was identified using the Irish Energy Balance [7].

3.3. Renewable Energy

The renewable-energy parameters required for the EnergyPLAN model are:

1. The type of renewable energy in question
2. The installed capacity of the renewable resource
3. The distribution profile (hourly for one year)

The various forms of renewable energy that need to be considered for the Irish reference model are wind, hydro power and solar thermal. Solar thermal will be discussed later as it is part of the individual's energy requirements, and does not contribute to a common grid like wind and hydro.

For wind energy, the installed wind-capacity and the hourly wind-output for 2007 were obtained from EirGrid [6]. This was also used to evaluate the total wind-energy produced in 2007 which was 1.93 TWh. The data required to create the hydro simulation was:

1. The hydro-power capacities which are displayed in Table 1, were obtained from the EirGrid [6].
2. The total annual-electricity generated from Irish hydro-power in 2007, which was obtained from the Irish energy-balance as 0.66 TWh [7].
3. The hourly distribution of the hydro power generated in 2007, which was created using the hourly output from the hydro stations for 2007 (obtained from two Irish TSO's[3] [6, 8]).

Table 1
Power Capacity of hydro stations in the Republic of Ireland

Hydro Facility	Power Capacity (MW)
Ardnacrusha	86
Erne	65
Lee	27
Liffey	38
Total	216

3.4. Storage

Pumped-Hydroelectric Energy Storage (PHES) is the only large-scale energy storage in use in Ireland. Only one facility exists which is called Turlough Hill and located in Co. Wicklow [9]. To model PHES in the EnergyPLAN model, the following parameters are necessary:

1. Pump Efficiency
2. Turbine Efficiency
3. Pump Capacity
4. Turbine Capacity
5. Storage Capacity

From the 2007 Irish Energy Balance [7], the round-trip efficiency of Turlough Hill, η_{TH}, was calculated using,

$$\eta_{TH} = \frac{E_{OUT}}{E_{IN}} \tag{2}$$

[3] EirGrid [6] provided the data for January to October of 2007, and SEMO [8] provided the data for November and December of 2007

where E_{OUT} was the total electricity produced from Turlough Hill in 2007 and E_{IN} is the total electricity consumed by Turlough Hill in 2007. The resulting round-trip-efficiency was 63.9%. However, no details could be obtained for the pump and turbine individually. Therefore, the pump efficiency was inputted as 75% and the turbine efficiency as 85.2%, resulting in a round-trip-efficiency of 63.9% (0.75*0.852) which was the value calculated using Equation 2.

The Turlough Hill storage facility was contacted directly to obtain the pump/turbine power capacities as well as the storage capacity of the facility. The pump capacity is 272.8 MW, the turbine capacity is 292 MW, the head was 285.75 m and the volume of water that can be stored in the upper reservoir is 2.3 million m^3. Using these details the storage capacity was calculated using

$$S = \frac{\rho g H V \eta}{3600} \quad (3)$$

where ρ is the density of water, 1000 kg/m^3, g is acceleration due to gravity, 9.81 m/s^2, H is the head, V is the volume of water and η is the efficiency of the turbine (which is 85.2%). The resulting storage capacity was calculated at 1.525 GWh.

3.5. Individual

Below is a description of the energy consumption defined for the residential and commercial sectors within Ireland. Only heat consumed by individuals needs to be accounted for here as the electricity and transport requirements are specified elsewhere. Therefore, the three inputs needed in the EnergyPLAN model are:

1. The total annual consumption of each fuel by individuals (fuels are oil, natural gas, peat/coal and electricity)
2. The boiler efficiencies for each fuel
3. An hourly heat-distribution for the year 2007

The fuel consumed by the residential and commercial sectors for heating was obtained in the Irish energy-balance [7] and are outlined in Table 2. For the boiler efficiencies, the Building Energy Rating (BER) documentation [10] provided by the Irish energy agency, Sustainable Energy Ireland (SEI), was consulted. This documentation is used by assessors to complete energy ratings for homes in Ireland. Therefore, it provided the typical type and efficiency of different domestic boilers used in Ireland which is also displayed in Table 2.

Table 2
Energy consumed by individuals and boiler efficiencies [7, 10]

Fuel	Residential Consumption (TWh)	Commercial Consumption (TWh)	Total Individual Consumption (TWh)	Boiler Efficiency (%)
Biomass	0.26	0.09	0.35	65
Coal / Peat	5.6	0.3	5.9	60
Natural Gas	6.9	3.9	10.8	84
Oil	13.1	6.4	19.5	75

Electricity used for heating was not available from the Irish energy-balance. However, within a report completed by SEI, it was found that 14% of all domestic electricity is used for space heating and 23% of domestic electricity is used for hot water [11]. In a separate report by SEI, it was found that 12% of commercial electricity was used for heating [12]. From the 2007 Irish energy-balance, the electricity consumed in the residential and commercial sectors were identified as 8.064 TWh and 8.711 TWh respectively. Therefore, using these figures it was concluded that 4.029 TWh (0.37*8.064 + 0.12*8.711) of electricity was used for individual heating in Ireland.

3.6. Solar Thermal

There are two types of solar thermal in the EnergyPLAN model: Solar thermal that contributes to district heating and solar thermal for individual households. At present, only individual solar-thermal energy is used in Ireland and hence it is discussed in this section under the individual's heating-demands. The inputs required for the EnergyPLAN model are the:

1. The total solar-thermal-production for 2007

2. Hourly distribution of the solar-thermal production in 2007
3. Solar-thermal share

The total solar-production in Ireland for 2007 was got from the 2007 Irish energy-balance [7] as 0.015 TWh. For the distribution, an attempt was made to obtain the hourly power-output from a solar panel for an existing installation[4] in Ireland, but this could not be obtained. As a result, a solar-thermal output distribution that was constructed for Denmark was used [13], as the solar radiation in Denmark is very similar to the solar radiation in Ireland [14]. This solar-thermal distribution was created by a Danish energy consultancy, PlanEnergi [15] for the 2030 Danish Energy-Plan [16, 17]. The distribution represents the production from an individual-solar-thermal installation of 4.4 m^2 during a typical Danish year. The production is calculated on the basis of a consumption of 150 litres per day, heated from 10°C to 55°C in combination with a 200 litre storage tank. The 4.4 m^2 represents a solar-thermal installation designed for hot water and some contribution to space heating.

The final input required for the EnergyPLAN model was the solar share. This is the percentage of homes in Ireland that have a solar-thermal system installed. To estimate this in Ireland, data was obtained from SEI [18]: SEI stated that there was 33,600 m^2 of domestic-solar-thermal panels installed in Ireland by the end of 2007. SEI also stated that a typical solar-thermal installation for individuals in Ireland uses 5 m^2 of solar-thermal panels. Therefore it was calculated that there are approximately 6,720 homes in Ireland with a solar installation. From the 2006 census in Ireland, it was stated that there are 1,469,521 homes in Ireland [19]. Consequently, it was concluded that there is a solar-thermal system in 0.45% of Irish homes.

3.7. Industry

Industrial energy requirements are also considered separately in the EnergyPLAN model. The inputs required for this area are:

1. Consumption of each fuel: coal/peat, oil, natural gas and biomass
2. Electricity produced from industrial CHP
3. Heat produced from industrial CHP
4. Distribution of electricity/heat from industrial CHP

The quantity of each fuel consumed within industry was found in the 2007 Irish energy-balance [7] and is displayed in Table 3. For electricity production from industrial CHP, the statistics department within SEI provided a breakdown of existing CHP plants as well as the energy they produced. A total of 0.93 TWh was exported from CHP installations to the grid in Ireland in 2007. There is currently no heat provided by industrial CHP to a district-heating network so no data was gathered for this area.

Since the industrial CHP in Ireland was not controlled by the TSO, the distribution used for Industrial CHP was inputted as a constant. This means that the output from Industrial CHP was simply constant during the entire simulation. This is a proxy for modelling a production that cannot be controlled.

Table 3
Fuel consumed within the industrial sector in Ireland for 2007 [7]

Fuel	Industrial Consumption (TWh)
Biomass	1.95
Coal / Peat	1.72
Natural Gas	10.4
Oil	14.8

3.8. Transport

To model the Irish transport-sector in EnergyPLAN, the only input required was the consumption of the various fuels in this sector: they are jet fuel, diesel, petrol and biomass. This data was also available from the 2007 Irish energy-balance [7].

[4] Solar-thermal output can be found by measuring the inlet and outlet temperatures of the collector, and also the flow rate.

Table 4
Fuel consumed within the transport sector in Ireland for 2007 [7]

Fuel	Industrial Consumption (TWh)
Biomass	0.25
Diesel	31.3
Jet Fuel	12.1
Petrol	22.3

3.9. Import/Export of Electricity

The model can simulate the import and export of electricity based on the optimal technical performance of the energy system. However, for the reference system, a forced import/export has to be included to represent the actual performance of the energy system in the reference year, in this case 2007. To do this, the following inputs are required:

1. The net transfer of electricity in/out of the energy system (exports are positive and imports are negative)
2. The hourly distribution of the imported/exported electricity

The Republic of Ireland is only interconnected to Northern Ireland. Therefore, to simulate the imported/exported electricity in 2007, the hourly distribution of imported/exported electricity from/to Northern Ireland was obtained from EirGrid [6] and SEMO [8]. This data showed that 1.31 TWh more electricity was imported than exported in 2007, with a total of 1.39 TWh imported and 0.08 TWh exported. These values were added to the EnergyPLAN model.

3.10. CO_2 Emission Factors

In the EnergyPLAN model, three CO_2 emission factors are required: one for coal, oil and natural gas. However, in this study coal and oil do not just account for a single fuel but instead, they account for a group of fuels. The coal category represents peat and coal as were modelled as a single fuel: this is a method which has been carried out in previous models of the Irish energy-system [20] due to the similar power-plant efficiencies and CO_2 emissions of the two fuels. The oil category represents a number of different types of oil including kerosene, diesel, coke etc. Therefore, the CO_2 emission factors for coal and oil were calculated based on fuel consumptions from the Irish energy-balance [7], and CO_2 emission factors recommended by SEI [21] for the various fuel they represent. In conclusion, the CO_2 emission factor used for coal/peat was 100.63 kg/GJ (see Table 5), for oil was 73.19 kg/GJ (see Table 6) and for natural gas was 57.1 kg/GJ [21].

Table 5
CO_2 emission factor for coal/peat

Fuel	Consumption (TWh) [7]	Consumption (% of Total)	CO_2 Emission Factor (kg/GJ) [21]
Coal	17.425	65.09	94.6
Milled Peat	6.186	23.11	116.7
Sod Peat	2.167	8.09	104
Briquetted Peat	0.992	3.71	98.9
Total	26.77	100.00	100.63

Table 6
CO_2 emission factor for oil

Fuel	Consumption (TWh) [7]	Consumption (% of Total)	CO_2 Emission Factor (kg/GJ) [21]
Gasoline	17.425	21.40	70
Kerosene	10.620	10.18	71.4
Jet Kerosene	12.134	11.63	71.4
Fuel Oil (Residual Oil)	8.528	8.17	76
LPG	1.856	1.78	63.7
Gasoil	45.230	43.35	73.3
Coke	3.637	3.49	100.8
Naphtha	0.012	0.01	73.3
Total	104.342	100.00	73.19

3.11. Summary

In summary, once the data gathered above was inserted into the EnergyPLAN model, it represented the electricity, heat and transport sectors of the Irish energy system for the year 2007. Once the simulation was run, the results were compared to actual values in the year 2007.

4. Results

Once the inputs were completed the EnergyPLAN model was run using a Technical Optimisation[5]. Subsequently, a comparison was made between the actual figures obtained from 2007 and results created by the EnergyPLAN model. The first parameter that was compared was the distribution of the electricity demand which can be seen in Table 7. It is evident that the results from EnergyPLAN provide a very accurate representation of the electricity demand in Ireland for 2007.

Table 7
Comparison of Average-Monthly Electricity-Demands obtained from the EnergyPLAN model and actual values for 2007

Month	Average-Monthly Electricity-Demand (MW)		Difference (MW)	Difference (%)
	Actual 2007	EnergyPLAN 2007		
January	3564	3559	-5	-0.14
February	3576	3573	-3	-0.09
March	3414	3386	-28	-0.82
April	3079	3084	5	0.18
May	3029	3025	-4	-0.14
June	2991	2970	-21	-0.71
July	2937	2947	10	0.34
August	2964	2960	-4	-0.15
September	3094	3105	11	0.36
October	3279	3281	2	0.07
November	3515	3508	-7	-0.2
December	3531	3519	-12	-0.35

Once it was verified that the electricity demand was being simulated correctly, the electricity production was compared. As seen in Table 8, the total-electricity generated from the various production units is very similar in both the actual 2007 figures and the results from the EnergyPLAN model. The only significant difference occurred for wind power production, which is most likely attributed to the variation in installed capacity at the beginning and end of 2007[6].

[5] A technical optimisation in the EnergyPLAN model simulates the energy system so that the minimum fossil-fuel is consumed.
[6] There was an 8.5% increase in wind capacity in Ireland in 2007 from 723.8 MW to 785.2 MW

Table 8
Comparison of electricity produced for Ireland in 2007 and the EnergyPLAN simulation

Production Unit	2007 Production (TWh) [7]	EnergyPLAN Production 2007 (TWh)	Difference	
			TWh	%
Power Plants	23.56	23.54	0.02	0.08
Wind Power	1.96	2.04	0.08	4.08
Hydro Power	0.66	0.66	0	0
Industrial CHP	0.93	0.93	0	0

Subsequently, the total fuel-consumption within the Irish energy-system was compared with those calculated in the EnergyPLAN model. As seen in Table 9, the actual 2007 total fuel-consumption and the predicted total fuel-consumption for 2007 by the EnergyPLAN model are very similar for all fuels. The largest relative-difference occurred for biomass at 2.17%.

Table 9
Comparison of total fuel consumed in Ireland in 2007 and the EnergyPLAN simulation

Fuel	2007 Fuel Consumption (TWh)	EnergyPLAN Fuel Consumption	Difference	
			TWh	%
Biomass	2.77	2.83	0.06	2.17
Coal/Peat	25.70	25.69	0.01	0.04
Natural Gas	49.92	50.29	0.37	0.74
Oil	105.22	104.42	0.80	0.76
Renewables	2.65	2.69	0.04	1.51

Finally, the CO_2 emissions for Ireland in 2007 and the CO_2 emissions from the EnergyPLAN simulation were compared with one another. The total energy-related CO_2 emission for Ireland in 2007 were calculated using fuel consumptions from the Irish energy-balance [7] and emission factors from SEI [21], as seen in Table 10. The results in Table 10 indicate that 46.8 Mt of CO_2 was emitted in Ireland in 2007 due to energy-related activities. In comparison, the EnergyPLAN model calculated the CO_2 emissions for Ireland in 2007 as 47.16 Mt. This is only 0.77% (0.36 Mt) higher than those calculated from the statistics, and thus indicates that EnergyPLAN is providing an accurate representation of the Irish energy system.

Table 10
CO_2 emissions for Ireland in 2007 and CO_2 emissions from the EnergyPLAN simulation

Fuel	Consumption (TWh) [7]	CO_2 Emission Factor (kg/GJ) [21]	CO_2 Emitted (Mt)
Electricity	25.867	150.83	14.05
Coal	4.354*	94.6	1.48
Sod Peat	2.167	104	0.81
Peat Briquettes	0.992	98.9	0.35
Gasoline	22.325	70	5.63
Kerosene	10.62	71.4	2.73
Jet Kerosene	12.134	71.4	3.12
Fuel Oil (Residual Oil)	4.295*	76	1.18
LPG	1.853*	63.7	0.42
Gasoil	45.188*	73.3	11.92
Coke	3.637	100.8	1.32
Naphtha	0.012	73.3	0.003
Natural Gas	18.424*	57.1	3.79
Total			46.80

*Excludes fuel required for electricity generation

5. Conclusions

The development of an energy-model of the Irish energy-system has been discussed in this study. The accuracy of the model has been verified by comparing the results of the model with actual statistics from the year 2007. The model is sufficiently accurate for use in future studies, that will focus on the integration of renewable energy into the Irish energy-system. Future studies include analysing the feasibility of CHP, electric vehicles, energy storage, increased interconnection, introduction of demand side management, as well as identifying the optimal mix of wind, wave, tidal and solar energy for Ireland.

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