Modelling Electricity Generation - Comparing Results: From a Power Systems Model and an Energy Systems Model

Alessandro Chiodi[a] , J.Paul Deane[b], Maurizio Gargiulo[c] and Brian P Ó Gallachóir[d]

[a] *Environmental Research Institute*
University College Cork,
Cork, Ireland
E-mail: a.chiodi@umail.ucc.ie

[b] *Environmental Research Institute,*
University College Cork,
Cork, Ireland
E-mail: jp.deane@ucc.ie

[c] *Energy Engineering Economic Environment Systems Modeling and Analysis S.r.l.,*
e4sma S.r.l.
Via Livorno 60,
I-10144 Turin, Italy
E-mail: maurizio.gargiulo@e4sma.com

[d] *Environmental Research Institute,*
University College Cork,
Cork, Ireland
E-mail: b.ogallachoir@ucc,ie

Document type: Full Paper

JEL Classification Code: Q47

Abstract

The focus of this work is to investigate the added value of the inclusion of extra technical detail of the electrical power generation system in an energy system model with high levels of variable renewable generation sources. The high resolution dedicated power systems model, *PLEXOS for Power Systems,* is used to build up and model a detailed portrayal of an electrical power system from the *TIMES* (The Integrated MARKAL-EFOM System) energy systems model. The motivation for the work is to ascertain whether the modelling of the electrical power system within the energy system model is capable of correctly capturing and including the effects of variability, in particular wind power variability, on the power system.

1. Introduction

Power system and energy system models, while both addressing modelling of complex systems, are fundamentally different in their focus and application of use. Power system models focus solely on the electrical power system and the primary inputs are generally exogenous in nature, such as load, fuel prices and power plant technical description. The electrical power system within whole energy system models is by contrast completely endogenous and driven by the combined behaviour of supply sectors that provide primary fuels and end use sectors driven by exogenous energy service demands. The focus is commonly to provide a technology rich basis for estimating energy dynamics over a medium and long-term, multiple period time horizon. Because of the exclusive focus on electricity generation within power systems models, the problem description can be at a higher resolution when compared to full energy systems model, which have to handle a much broader range of problems and sub-systems.

At the most fundamental level, the problem of power system modeling is to determine the least cost dispatch of generating resources to meet a given power demand while respecting the technical characteristics and capabilities of each specific generator. In modeling terms this problem is often referred to the Unit Commitment and Dispatch problem. Unit commitment being the decision of what units to turn on or off and dispatch being the decision of what level to run units at once they are on. A large number of commercial and non-commercial models are available for modeling the power system and power markets and are well summarized in Foley et al. [1]. A modern electricity market acts much like a stock exchange, with generators offering production and loads bidding for supply. Clearing the market can be complicated however because the physical delivery of electricity is subject to the technical and economic constraints on generation. The most important and relevant being minimum stable generation, ramp rate constraints, and minimum up and down times, start costs and fuel costs. Furthermore the market must be cleared and balanced every trading period to ensure supply meet demand.

This paper therefore intends to benchmark the performance of electricity modeling in the Irish power system within TIMES against detailed results of the PLEXOS software by a soft-link between the tools. A test year is taken from TIMES and replicated and modeled in PLEXOS. The outputs from PLEXOS are then feed back into TIMES. The capability of the TIMES model to accurately account for generation adequacy, plant dispatching (with a particular focus on peak hours), renewable generation and wind curtailment is discussed in this paper. Particular attention has been paid in this initial phase of research to the impact of including specific power system characteristics, such as minimum stable levels, start costs, ramp rates and minimum down and up times.

This analysis uses Republic of Ireland (ROI) as case study, but this methodology could be also applied readily to other energy systems. The target year for this exercise is set to 2020, an important year for renewable energy due to the targets set EU Directive 2009/28/EC. Two existing models are used in this paper as starting point: the Irish TIMES model and the PLEXOS_Ireland model.

2. Modelling Tools

PLEXOS for Power Systems:

PLEXOS[1] is a sophisticated power system modeling tool used for electricity market modeling and planning worldwide. PLEXOS is commercial software but is free for non-commercial research to academic institutions. PLEXOS can optimize the power system over a variety of times scales from long-term (1-40 years) to medium-term (1-5 years) to short-term (less than 1 year). Modeling is generally carried out using deterministic linear programming techniques that aim to minimize an objective function subject to the expected cost of electricity dispatch subject to a number of constraints including availability and operational characteristics of generating plants, licensing environmental limits, and fuel costs, operator and transmission constraints. The power of linear programming is its ability to efficiently find the optimal solution to a problem that might have a large number of decision variables. Linear programs are problems that can be expressed in canonical form:

$$\text{maximize } c^T x$$

$$\text{subject to } Ax \leq b$$

where x represents the vector of variables (to be determined), while c and b are vectors of (known) coefficients and A is a (known) matrix of coefficients. The expression to be maximized or minimized is called the objective function $c^T x$ in this case. The equations $Ax \leq b$ are the constraints over which the objective function is to be optimized.

In this analysis we are primarily concerned with short–term modeling. PLEXOS when modeling in short term mode (typically a full year of daily half-hourly optimizations of the power system) models every trading period and maintains chronological consistency across the full optimization horizon. It can model generator start ups and shutdowns and track the status of units across time. Within the modeling unit commitment process on/off

[1] http://www.energyexemplar.com

decisions for each unit must be made. This is necessary to correctly model technical parameters for generators such as minimum stable generation, minimum up and down times. The inclusion of these technical constraints however introduces integer decision variables. The presence of the integer variables means that the problem cannot be solved as a simple linear program. PLEXOS uses mixed integer programming (MIP) to solve these problems. MIP means the software can realistically replicate the actual operation of generator in the physical market as all technical constraints can be modeled and obeyed.

Within the PLEXOS model, wind and other renewables are essentially treated as 'free' generation (i.e. the marginal cost is zero) although this can be changed by the user. This reflects the current market situation in Ireland where wind farm operators typically opt to act as *price takers*, effectively bidding in at zero. These generation sources differ to conventional fossil generation because of their variability and intermittency over longer periods. These resources are generally considered non-dispatchable and pose some challenges for the power system operation and modeling. As more wind and variable generation comes online in future power systems the accurate modeling of these resources becomes important.

Variability occurs at various time scales; for example wind can have seasonal variations as well as diurnal and hourly changes. Generally, very short-term fluctuations - in the intra-minute and inter-minute timeframe - are small relative to installed capacity. In this analysis related to power system modeling, it is the hourly and daily variations that are important. Power system issues associated with wind energy's variability are well documented by the IEA [2][3]and have been the focus of many wind integration studies which are summarized in the following [4]. Variability of power sources in a power system can cause issues for system balancing and make the commitment and dispatch of conventional power plant difficult. In general the more variability within a power system the more flexible the power system is required to be. The issue of variability for renewable resource can be mitigated to a certain extend by having the resource spread over a large geographical area and/or by have a diverse portfolio of renewable generation options as each renewable energy technology fluctuates over a different time-scale, important gains from the complementarily of these cycles can be achieved [2]. The benefits of having a geographical spread to a variable resource such as wind are well understood as poorly correlated resources can smoothen out the total net variability (net variability is the demand minus the wind generation) of the aggregated resource.

The challenge when modelling power systems with large amounts of variable generation is to ensure the adequate representation of the variable source, in this case both the wind generation and load. Within the TIMES model, electricity demand is represented as a series of blocks with one block for each of the 12 predefined timeslices. In PLEXOS, demand is represented as a chronological time series at 30 minutes resolution.

TIMES:

TIMES (The Integrated MARKAL-EFOM System) is one of the tools developed and used by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement of the International Energy Agency (IEA). It combines all the advanced features of MARKAL (Market Allocation) models, and to a lesser extent of EFOM (Energy Flow Model Optimization) models. The equations of the initial MARKAL model appear in Fishbone and Abilock [5] and numerous improvements of the model have been developed since then for various applications (Kanudia and Loulou [6]; Kanudia et al. [7]; Labriet et al. [8]). The full technical documentation of the TIMES model is available in Loulou et al. [9].

TIMES is a technical economic model generator for local, national or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon. It is usually applied to the analysis of the entire energy sector, but may also applied to study in detail single sectors (e.g. the electricity sector) [10].

TIMES is a perfect foresight linear programming model generator that computes a dynamic inter-temporal partial equilibrium on integrated energy markets. The objective function to maximize is the total surplus. In the simplest case this is equivalent to minimizing the total discounted energy system cost while respecting environmental and many technical constraints.

The key inputs to TIMES (Loulou et al., 2005) are the demand component (energy service demands), the supply component (resource potential and costs), the policy component (scenarios) and the techno-economic component (technologies and associated costs to choose from). The model is driven by exogenous demand specified by the list of each energy service demanded (disaggregation), actual values in the base year (calibration) and values for all milestone years till 2050 (projection).
Figure 1 shows an overview of a TIMES model. Each economic sector is described by technologies, each of which is characterized by its economic, technological and environmental parameters [11].

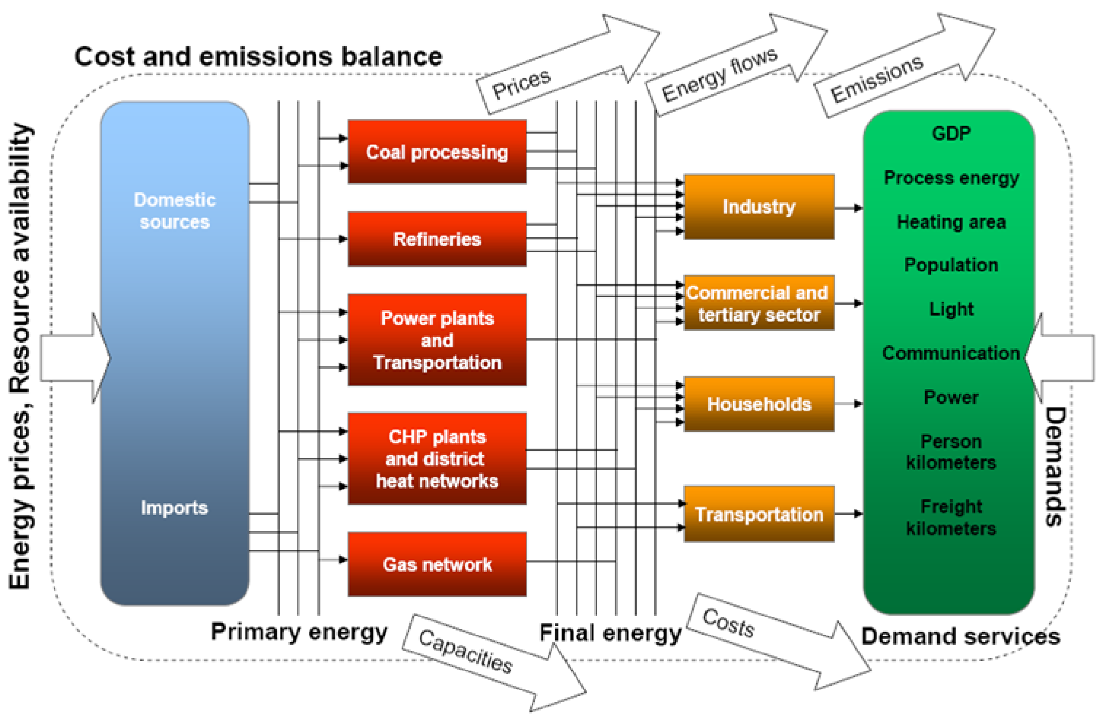

Figure 1 - Overview of TIMES

Source: Remme U., 2007 [11]

TIMES is mainly used for medium and long term optimization, but it is theoretically possible to use this tool also for short term analysis. Each time period is usually divided by sub-period, commonly called timeslice. The timeslice represent the “mesh” of each period and the definition depends strongly to the computing capacity and the time-scale. Long-medium term optimizations (20-50 years of time horizon) rarely use more than 10-15 timeslices. For example the model used in this paper work, the Irish TIMES model, has a 2005-2050 time horizon while each period is sub-divided by 12 time slices, commonly defined by day, night and peak hours for four season.

Electricity generation within TIMES

In TIMES, by contrast with PLEXOS, net electricity demand profiles are not imposed exogenously, but rather are endogenously evaluated to optimally provide the energy service demand for each sector. The electricity generation sector is commonly characterized by various voltage levels transmission (commonly three or four) in which each voltage level of the network is modelled by an equivalent simplified system composed of lines, transformers, infrastructure for electricity transport and distribution.

Power plants are described by processes grouped as base year or post-base year capacities. Each plant is moreover characterized by inputs and outputs commodities that fit into the energy system composing the whole energy chain that starts form the primary energy side to the final energy service demand. To each process of the chain several parameters and constraints can be defined: They can be commonly grouped as technical, economic and environmental parameters (Table 1).

Within TIMES most of renewable technologies (e.g. wind energy or solar PV) are commonly treated with efficiencies of 100% while the availability of the resource is inserted as capacity or activity constraint. The load fluctuation due to the resource variability (that represent the fuel for the process) is modeled defining by each period a timeslice dependent definition of average availability factors generating different generation profiles.

Table 1 summarizes the main parameters that characterize each TIMES and PLEXOS power plant:

	PLEXOS	TIMES
Technical parameters	Capacities, min. stable generation, max. generation, ramp rates, heat rates[2], min. up and down times, failure rates, maintenance rates and time	Capacities, efficiencies, availability factors, technical life, cap2act[3], starting year
Economical parameters	Individual fuel costs, variable O&M rates, start costs, CO_2 costs and emissions per fuel type	capital costs, O&M costs (fix and variable), discount rates
Environmental parameters	Emissions (CO_2, NO_x, SO_x, …)	Emissions (CO_2, NO_x, SO_x, …)

Table 1: Comparing main PLEXOS and TIMES parameters

[2] Expressed in GJ/MWh
[3] Links the capacity to the activity. For power plants is commonly expressed in PJ/GW

3. Methodology

Modelling approach

To perform this analysis the Irish TIMES model and PLEXOS_Ireland model are used. The Irish TIMES model is the energy system model for Republic of Ireland developed by UCC (University College Cork) Sustainable Energy Research Group in collaboration with the ESRI (Economic and Social Research Institute) [12]. The Irish TIMES model has been developed to develop a range of medium (to 2020) [13] to long term (to 2050) energy and emissions policy scenarios in order to inform policy decisions. Irish TIMES was originally extracted from the PET[36] model (Pan European TIMES Model that includes EU27, Iceland, Norway, Switzerland and Balkans countries) and then updated with local and more detailed data and assumptions [14]. The time horizon used here is the period 2005 – 2020 and the model has a time resolution of four seasons with day-night time (divided into day, night and peak time-slices). [15]

The PLEXOS_Ireland model is the power systems model used to simulate the Irish electricity market. The model, based on primary input information from the Commission for Energy Regulation in Ireland[4] and further developed to the target year 2020 by UCC describes technical and economic characteristic of all thermal power generation plant operating on the island of Ireland. The model also describes renewable generation sources such as wind and hydro. The PLEXOS software which has previously been used to validate and model the Irish Single Electricity Market[5] is the modeling platform used to perform unit commitment and dispatch decisions

There are two phases to the work. In phase one, the alignment phase, the model inputs are modified to align to each other in order to produce consistent outputs. This phase aims mainly to build within PLEXOS a model of one year of the power system (target year) based on main 2020 TIMES outputs, as generation portfolio, plants details, timeslice definition, fuel costs and emission factors. To align the inputs, both models use the same

[4] http://www.cer.ie
[5] http://www.sem-o.com/

demand shape profile (based on pre-recession 2007 profile) and the same wind capacity factors (based on 2008 actual half-hourly CF). At the end of this phase the PLEXOS_Ireland model is able to run at a simplistic level using the same input data of the Irish TIMES model.

The second phase includes sensitivity analysis focused on comparing main models outputs and evaluating the impact of adding single PLEXOS parameters and/or electricity interconnectors. The flowchart of Figure 1 illustrates briefly this workplan.

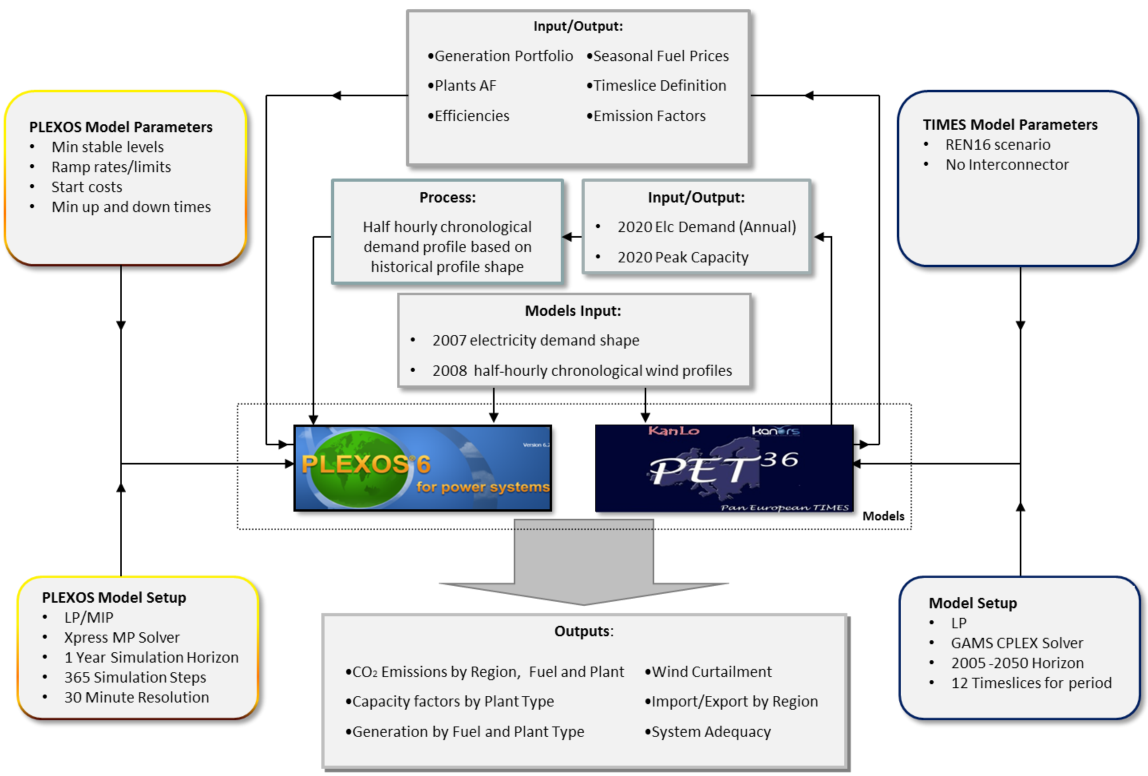

Figure 1: Activity flowchart

Common exogenous inputs are the demand profile shape and wind capacity factors. The demand profile shape is based on ROI 2007 half-hourly electricity demand, while, for wind, ROI 2008 half-hourly capacity factors have been used. Those profiles have been chosen because they represent standard profiles.

PLEXOS_Ireland's exogenous inputs, such as electricity demand, fuel prices, generation portfolio, generators main details and other model details are provided by the Irish TIMES model. The 2020 electricity demand from Irish TIMES have been used in PLEXOS_Ireland, setting the same annual electricity demand and peak demand (winter peak). Using PLEXOS_Ireland utilities, the demand profiles have been quadratically extrapolated to chronological half-hourly profile according to 2007 shape.

To generate outputs Irish TIMES have been set to meet by 2020 Directive 2009/28/EC target that for Ireland is set to achieve at least 16% of gross final consumption from renewable sources [14]. Two main energy system configurations are discussed:

1. **REN16 scenario:** Least cost optimal pathway delivers the energy system demands meeting Directive 2009/28/EC target in the absence of specific minimum shares of renewables share in the power system.
2. **RES40 scenario:** This scenario energy system is required to meet the future energy service demands meeting Directive 2009/28/EC target by 2020 subject to at least 40% of renewable electricity production (RES-E).

Portfolio

The main assumptions regarding PLEXOS_Ireland and Irish TIMES portfolio assumptions are summarized in Table 1. The assumptions regarding future plant capacities are drawn from reports from Ireland transmission system operator, Eirgrid [16] and have been subdivided into generation units, while other exogenous parameters such as thermal efficiencies (inputted in PLEXOS as heat rate curves), capacity factors, prices and emissions are drawn from Irish TIMES. The same principal technical and economical parameters, such as maximum capacity factors, efficiencies, emission factors and variable operational and maintenance (O&M) costs are used mutually within the two models. It's worth nothing that fixed O&M costs, even included within PLEXOS, are ignored in dispatch problems.

Code	Description	REN16 (GW)	RES40 (GW)	PLEXOS Number of Plant	TIMES Efficiency (%)	PLEXOS Efficiency (GJ/MWh)	Maximum Capacity Factor (%)	Variable O&M (€/MWh)	$C0_2$ Emissions (kg/GJ)
EUICBGS00	Internal Combustion biogas plant	0.022	0.022	1	33.5	10.75	57	0.04	56.1
PUSPMUN101	CHP: Steam Turb condensing - Municipal waste	0.021	0.079	1	25	14.40	60	2.56	85.9
EUSTCOH00	Steam Turbine - Hard Coal	0.840	0.840	3	39.5	9.11	86.8	0.04	95
EUSTCOL00	Steam Turbine – Lignite	0.347	0.347	3	41.5	8.67	81.6	0.04	110.6
EUCCGAS00	Combine Cycle – Gas	1.422	1.422	4	47.5	7.58	57	0.04	56.1
EUCCGAS201	Combine Cycle – Gas	1.664	1.664	4	55.1	6.53	85	1.53	56.1
EUGTGAS01	Gas Turbine – Gas	0.200	0.200	1	40	9.00	55	2.05	56.1
EUHYDDAM00	Hydro Dam Plant	0.215	0.215	15	100	3.60	25.5	0	0
EUHYDRUN00	Run of River Plant	0.019	0.019		100	3.60	25.5	0	0
EUHYDRUNM101	Run of River Plant	0.000	0.000		100	3.60	68	0	0
EUGTOIL01	Gas Turbine - Distillate Oil	0.496	0.496	8	38	9.47	55	2.05	77.4
EUHYDPSOUT	Storage Hydro Plant	0.292	0.292	4	70	5.14	13.8	0	
EUWIN00	Wind (from base year)	0.455	0.455		100	3.60	31.9*	0	0
EUWINON201	On-Shore wind	2.066	3.607		100	3.60	30.2*	0	0
Total		8.060	9.658						

*Average annual value

Table 1: TIMES and PLEXOS portfolio assumptions

Fuel costs

Fuel costs for power generation are endogenous in integrated energy system models as TIMES, while for single energy sector models as PLEXOS this definition is exogenous. Table 2 shows for each scenario the main assumptions regarding fuel cost assumptions by 2020 as extracted from Irish TIMES and uploaded within PLEXOS_Ireland. It's worth nothing that Irish TIMES primary energy prices are based on IEA World Energy outlook 2008.

Commodity	REN16	RES40	Unit
Biogas	4.19	4.06	(€/GJ)
Hard Coal	2.87	2.77	(€/GJ)
Peat	1.14	1.14	(€/GJ)
Distillate Oil	4.03	4.21	(€/GJ)
Natural Gas	4.50	4.44	(€/GJ)

Municipal Waste	0.34	0.34	(€/GJ)

Table 2: Power generation fuel costs

Electricity demand

In 2020 EirGrid & SONI [15] forecast that the total electricity requirement (TER) for ROI will be 30.7 TWh/year, with a peak demand of about 5.2 GW. Irish TIMES endogenously provides for both scenario the TER of 29.6 TWh/year and peak demand of 4.7 GW. Figure 2 shows TIMES TER and average power demand for REF scenario between model timeslices, while Figure 3 shows 2020 chronological demand profile with 30 minutes resolution as built in PLEXOS.

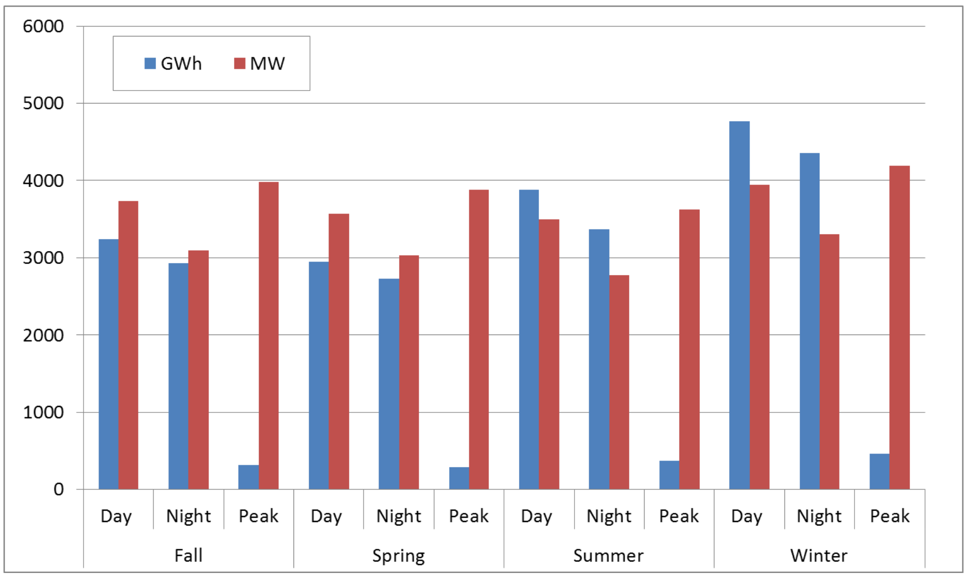

Figure 2: TIMES TER and power requirement for REF scenario

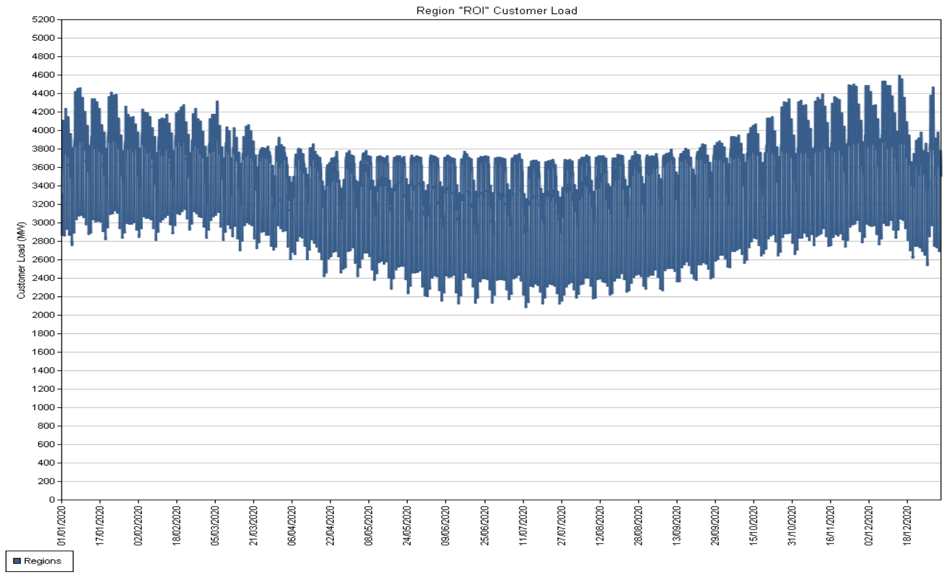

Figure 3: PLEXOS chronological electricity demand for REN16 scenario

4. Results

The paper presents and discusses a selection of results into two main sections, where firstly the impact on generation adequacy and unit commitments of high resolution electricity demand is discussed. Secondly the impact on unit commitment of improving power system description within PLEXOS is presented. Some of the main outputs are singularly extracted and analyzed focusing mainly on differences and similarities due to different nature of the models. Finally the benefit of high resolution portrayals soft-linked with long term energy system optimizations is discussed in terms of possible single model reinforcement and for future possible research activities.

Phase 1: Alignment and system adequacy

Generation adequacy is assessed by determining the likelihood of there being sufficient generation to meet customer demand. It does not take into account any limitations imposed by the transmission system, reserve requirements or the energy markets. PLEXOS is able to assess generation adequacy of any modeled power system by the evaluation of PASA (Projected Assessment of System Adequacy) reliability indices.

Firstly generation system adequacy is determined as Loss Of Load Expectation (LOLE) and is expressed as days per year. This is a measure of how long, on average, the available capacity is likely to fall short of the demand. LOLE is a statistical measure of the likelihood of failure and does not quantify the extent to which supply fails to meet demand. LOLE can be used to set a security standard. Ireland has an agreed standard of 8 hours LOLE per annum (0.33 day per annum) [16]. If this is exceeded it indicates the system has a higher than acceptable level of risk. Alternatively system adequacy could be expressed as LOLP (Loss of Load Probability), which indicates the probability is a measure of the probability that demand will exceed the capacity of the system in a given period. Secondly the EDNS and the EENS indexes indicate the expected demand not served. EDNS is determined, by taking the total area where the demand is greater than the installed capacity, while EENS is simply the total amount of time multiplied by the expected demand not served.

To evaluate the adequacy of the power system provided by Irish TIMES, Table 3 illustrates some of the main reliability indices assessed by PLEXOS. EirGrid & SONI [16] forecast that in the base case scenario the thermal capacity reserve will be 637 MW by 2020[6]. Soft linked PLEXOS/TIMES model accounts very similar values for REN16 and RES40 scenarios. However these results are relatively conservative as they assume that wind cannot provide any firm capacity. In reality, wind has the ability to contribute to system adequacy and generally the capacity credit of wind is used to take this into account. This will be included in further work.

	REN16	RES40	unit
Capacity Reserves	614.3	614.3	MW
Capacity Reserve Margin	13.21	10.13	%
EENS	253.3	1382.9	MWh
EDNS	0.03	0.16	MW
LOLE	0.07	0.35	days
LOLP	0.02	0.10	%

Figure 4: PLEXOS reliability parameters

Moving to simulation results, Figure 5 compares optimal annual production yields on REN16 scenario for each power plant according to soft-linked PLEXOS_Ireland and Irish TIMES models, while Figure 6 shows plant capacity factors (CF). Gray bar of Figure 6 shows the theoretical maximum capacity factor for each plant according to the input technical characteristics.

Looking firstly at the REN16 scenario with relatively modest levels of renewable generation in the electrical power system (approximately 25%) the two models show in this phase very similar results. Because for both the lower short run marginal costs (SRMC) are accounted for municipal waste CHP plant (7.5 €/MWh), peat and coal steam turbines (respectively 9.43 and 25.17 €/MW) those plants work at its full capacity for the whole time horizon. Also renewable capacities (hydro and wind) produce at full load. Differently to the TIMES model that almost saturates also production from Gas CC-01 (EUCCGAS201), the forth plant in SRMC merit order, PLEXOS allocated to this plant a

[6] Low growth demand scenario

CF of 66%. In PLEXOS, additional gas powered generation is accounted for Gas CC-00 (EUCCGAS00) with a CF of 13%. This difference is related to the fact that PLEXOS uses high resolution chronological detail instead of 12 average timeslices. The PLEXOS model with its chronological representation of the system, uses older CCGT plant (EUCCGAS00) more often than TIMES. These units generally come online if all of the newer and cheaper CCGT units (EUCCGAS201) are online and more capacity is needed. They also come online if any of the EUCCGAS201 units are out for maintenance. The PLEXOS software represents generation categories as a discrete number of units, this has the advantage of providing a more realistic representation of unit outages and maintenance schedules. During peak times a very limited use of pumped hydro storage is also observed within PLEXOS, while no production from "peaker" and storage plants is observed in TIMES.

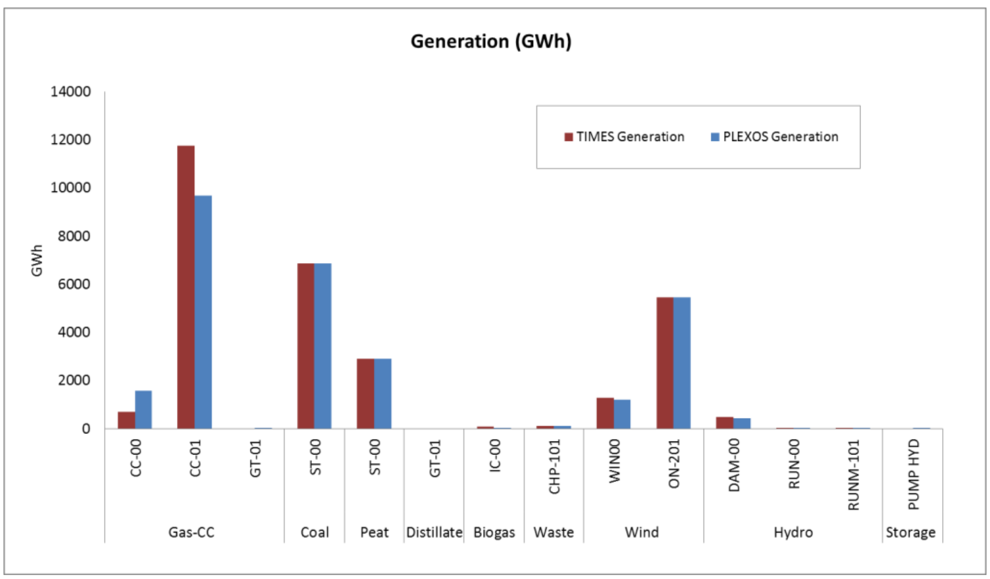

Figure 5: Comparing Phase 1 generation in REN16 scenario

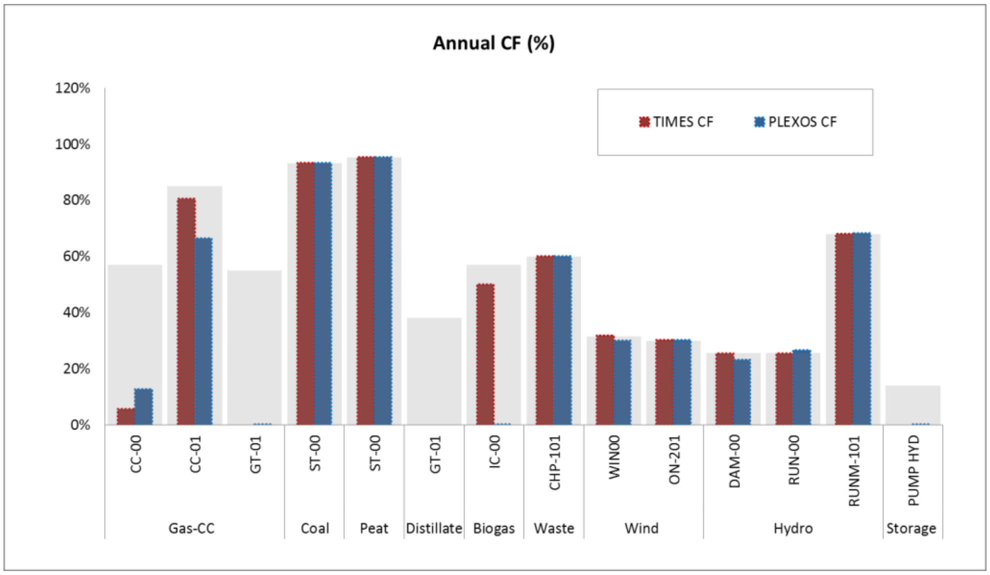

Figure 6: Comparing Phase 1 generation portfolio CF in REN16 scenario

Moving to the energy system delivering the 40% of renewable electricity generation (RES40 scenario). Comparing the reference model runs in PLEXOS and TIMES some fundamental differences can been seen. PLEXOS runs the baseload coal and peat plants to their maximum availability throughout the year. EUICBGS00 and EUGTOIL01 remains outside the merit order due to its higher short run marginal cost and does not come online at all in the PLEXOS simulations. EUGTGAS01 is bought online on brief occasions when wind speeds are very low or it there are large plant out for maintenance. Levels of wind production are lower in the PLEXOS simulations as the model enforces a 70% maximum penetration level on wind and thus more wind is curtailed. The TIMES model with it limited timeslice definition is unable to capture this. Figure 7 shows that in PLEXOS the impact of higher shares of variable load generation as wind energy implies about 0.65% of lower electricity production from wind than in TIMES due to curtailment. Most of curtailments during winter and autumn night time, when high wind productions face low electricity demands. This scenario shows that the optimal share of renewable production is 35.1%.

Pumped storage does not appear to be used in TIMES whereas it comes online very briefly in the PLEXOS simulations. Pumped storage can provide flexibility to the power system, however in the reference modelling case in the absence of technical limitations on other plant such as minimum stable generation and ramp rates, it is not used.

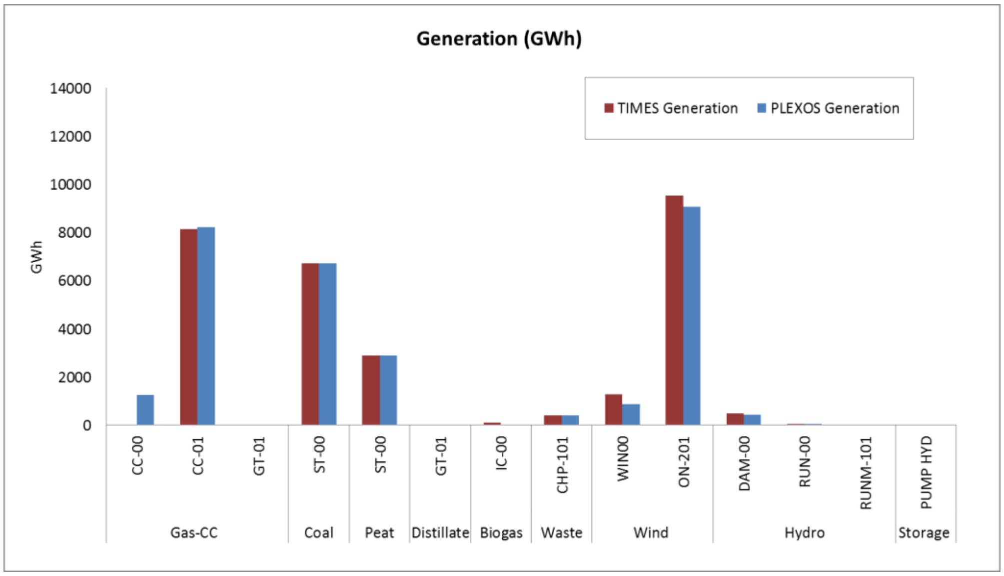

Figure 7: Comparing Phase 1 generation in RES40 scenario

Phase 2: Improving characterization of power system:

Table 3 summarizes the main parameters that have been used to improve the power system portfolio within PLEXOS. Additional parameters are subdivided in three main groups: start cost, minimum stable level (MSL) and ramp rates.

Code	**Description**	**Start Costs**		**MSL**	**Ramp Rate**	
			Offtake at start		*Up*	*Down*
		(€)	(GJ)	(MW)	(MW/min)	(MW/min)
EUCCGAS00	Combine Cycle – Gas (base year)	60000	400	150	12	12
EUCCGAS201	Combine Cycle – Gas	60000	300	220	30	30
EUGTGAS01	Gas Turbine – Gas	60000		110	15	15
EUSTCOH00	Steam Turbine - Hard Coal	50000	6920	180	4	4
EUSTCOL00	Steam Turbine – Lignite	50000	500	80	2	2
EUGTOIL01	Gas Turbine - Distillate Oil	5000		10	10	10
EUICBGS00	Internal Combustion biogas plant	1000				
PUSPMUN101	CHP - Municipal waste					
EUWIN00	Wind (from base year)					
EUWINON201	On-Shore wind					

EUHYDDAM00	Hydro Dam Plant	500		0.03 ÷ 10	2 ÷ 22.5
EUHYDRUN00	Run of River Plant				
EUHYDRUNM101	Run of River Plant				
EUHYDPSOUT	Storage Hydro Plant				

Table 3: PLEXOS_Ireland model parameters

Figure 8 shows the effect on generation assessment of additional plant parameters comparing plant capacity factors under the RES40 scenario. The graph compares Irish TIMES outputs with two alternative models setup. The first one the PLEXOS model is set in "phase 1" configuration, while the second one is set with Table 3 model additional parameters (PL-Phase 2). The main effect of improved definition of generation portfolio is related to the activity relation between "baseload" plants and "peaker" plants

The enforcement of starts costs on the simulations has a relatively small effect on overall simulation results as it produces little change to the merit order of plant. The objective function of the PLEXOS software is to minimize total systems costs (production, start-up costs and no load costs) over the course of each day. It does however stop the model from bringing on and off baseload plant for short periods of time. In place mid merit gas plant are used more often and hence an increase in generation from these plants is seen relative to the reference case. Pumped storage starts to come online more often as it is used to provide cycling that in the reference cases were provided by baseload plant.

The enforcement of MSL has a more important effect by reducing the generation from baseload plant further. In general baseload plant come on and off at the same time during all simulations however with the introduction of MSL baseload run at slightly lower capacity factors. This is because baseload plant generation is sometimes 'pulled back' to allow mid merit plants come online at generation above their MSL. Mid merit generation from CCGT's is also increased as the model can no longer call upon cheaper baseload plant to come on and off quickly for sets of load less than its MSL. This has a beneficial effect on CO_2 emissions (Figure 9), as emissions are reduced due to the higher generation now from more efficient mid merit plant (note though the total system generation cost goes up). Generation again from Pumped hydro energy storage goes up (almost three-fold) as it is called upon more often to provide peaking capacity and also store excess generation from baseload plant and allow them to stay online longer.

The Introduction of ramp rates has a relatively minor effect on overall results. Ramp rate restriction primarily effect mid-merit plant by reducing their flexibility o generate during strong wind ramp events. A reduction in generation is seen from these plants with pumped hydro energy storage stepping in to fill the gap.

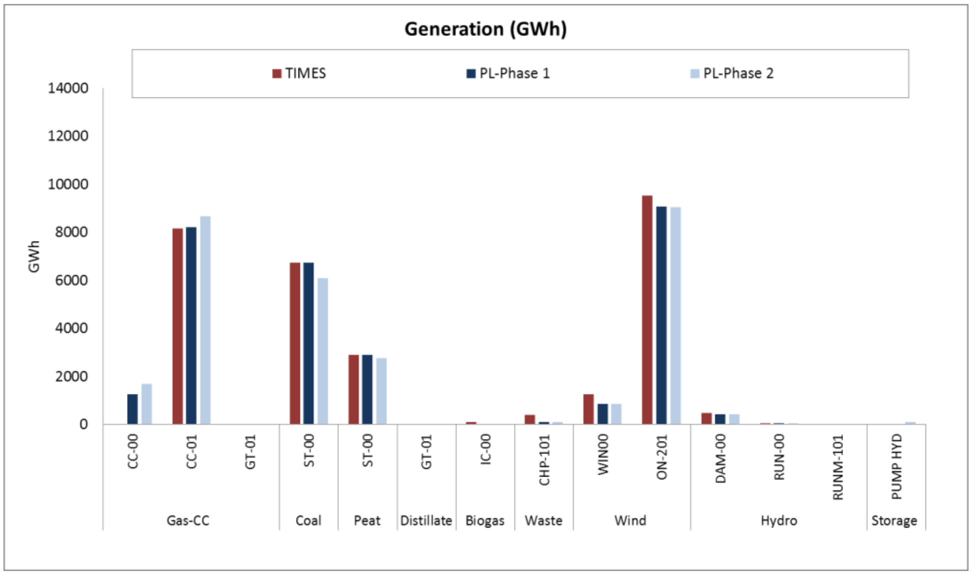

Figure 8: Comparing phase 1 and phase 2 CF in RES40 scenario

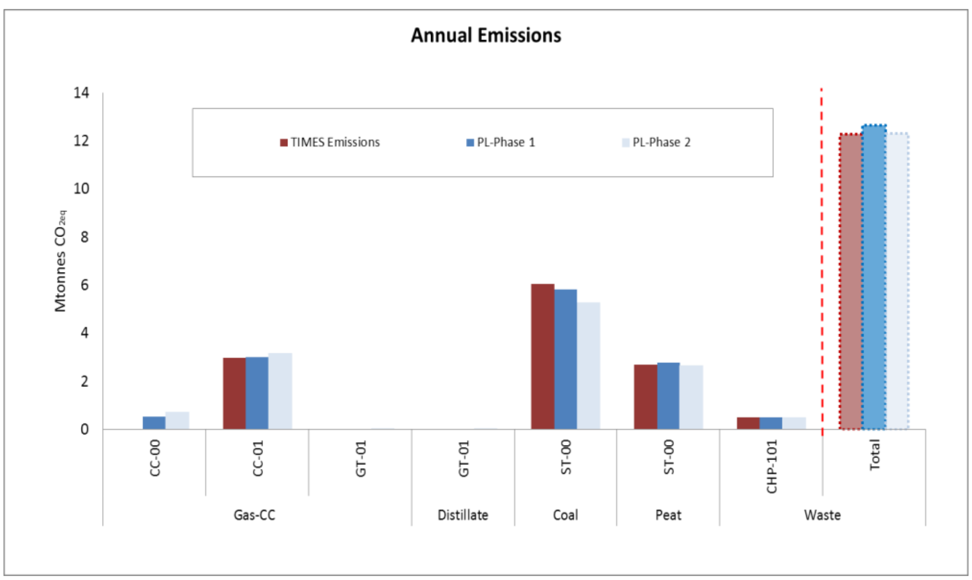

Figure 9: Comparing phase 1 and phase 2 emissions in RES40 scenario

5. Conclusion and Discussion

The initial results from this paper suggest that the development of a soft linking between energy system models and power system models could represent an important added value in terms of improving electricity generation modeling. There are clearly a number of important caveats relating to this model but the results will contribute to validate some of the most challenging pathways in terms of energy policy and greenhouse gas emissions reduction. Most of energy modeling activities indicates, for the next years, increasing levels of high variability power generation, due to high shares of wind energy or hydro power; and electrification within transport and residential sectors. The development of methodologies to validate those future energy scenarios will be of primary importance to inform future power generation assessments and energy policies. While this paper focuses on Ireland because of challenging policy targets that will face in the future years, the huge development of wind energy and the absence of nuclear, this could be applied to similar cases also elsewhere inside and outside EU.

The next steps in this work are to apply this methodology to different Irish TIMES scenarios focusing on the impact of increased heating electrification in residential due to the achievement of 2020 EU directives (Decision 2009/406/EC) [13] and the generation adequacy of the development “0 carbon” generation portfolios by 2050 to drive the 80% CO_2 emissions reduction target [17].

References

[1] Foley, A., Ó Gallachóir, B.P., Hur, J., Baldick, R. and McKeogh, E.J, 2010. A Strategic Assessment of Electricity Systems Models. **Energy** Volume 35 Issue 12 Pages 4522 - 4530.

[2] Variability of Wind Power and other renewables-management options and strategies, 2008 International Energy Agency

[3] IEA. 2011 *Harnessing variable renewables-A guide to the balancing challenge*. Published by IEA

[4] H. Holttinen, P. Meibom, A. Orths, F. Van Hulle, C. Ensslin, L. Hofmann, J. McCann, J. Pierik, J. Tande, and A. Estanqueiro, "Design and Operation of Power Systems with Large Amounts of Wind Power, results of IEA collaboration," in *8th International Workshop on LargeScale Integration of Wind Power into Power Systems as well as on Transmission Networks of Offshore Wind Farms*, 2009

[5] Fishbone L.G. and H. Abilock, MARKAL, a linear-programming model for energy systems analysis: technical description of the BNL version, Energy Research **5** (1981), pp. 353–375.

[6] Kanudia A. and R. Loulou, Advanced bottom-up modelling for national and regional energy planning in response to climate change, International Journal of Environment and Pollution **12** (1999), pp. 191–216.

[7] Kanudia, A, M. Labriet, R. Loulou, K. Vaillancourt and J.-P. Waaub, The World-MARKAL model and its application to cost-effectiveness, permit sharing, and cost-benefit analyses. In: R. Loulou, J.-P. Waaub and G. Zaccour, Editors, Energy and Environment, Springer, USA (2005), pp. 111–148.

[8] Labriet, M., R. Loulou, A. Kanudia, (2005), "Global energy and CO_2 emission scenarios: analysis with a 15-region world MARKAL model", in *The Coupling of Climate and Economic Dynamics, essays in integrated assessment*, A. Haurie and L. Viguier (Guest Editors), Advances to Global Change Research, Vol. 22, Kluwer Academic Publishers, Dordrecht (Netherlands), pp. 205-235.

[9] Loulou, R., Remme, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. Documentation for the TIMES model, Energy Technology Systems Analysis Programme (ETSAP). Available from: http://www.etsap.org/documentation.asp

[10] Loulou R., Remne U., Kanudia A., Lehtila A., Goldstein G. Documentation for the TIMES model. ETSAP, April 2005. http://www.etsap.org/tools.htm

[11] Remme U. 2007 *Overview of TIMES: Parameters, Primal Variables & Equations.* Proc. ETSAP Workshop November 2007 Brazil.

[12] UCC (University College Cork); Sustainable Energy Research Group; www.ucc.ie/en/serg/energypolicy/projects/irishtimes/

[13] Ó Gallachóir B. P., Lavigne D., Rout U. K., Chiodi A., Gargiulo M. Modelling ambitious CO2 reduction targets for Non-ETS sectors. 2010 International Energy Workshop. Stockholm, Sweden, June 21-23 2010

[14] Ó Gallachóir B. P., Lavigne D., Rout U. K., Gargiulo M. and Kanudia A. 2010 *Building Irish TIMES from PET Ireland.* Proceedings of the Joint TERI ETSAP Workshop on Energy Modelling Tools & Techniques to Address Sustainable Development & Climate Change. New Delhi, India Jan 20 – 22 2010.

[15] Rout U. K., Lavigne D., Chiodi A. Gargiulo M. and Ó Gallachóir B. P., 2010 *Determining least cost sectoral renewable energy targets using TIMES* Renewable Energy (In Review).

[16] EirGrid & SONI. 2010 *All-Island Generation Capacity Statement 2011-2020*. Report published by EirGrid and SONI

[17] Ó Gallachóir B. P., Lavigne D., Rout U. K., Chiodi A. and Gargiulo M. A. *Meeting Ireland's Ambitious GHG 2050 Emissions Target*. *Proc* UCC IEA-ETSAP Energy Modelling Conference. Cork, Ireland, Nov. 15 2010.