The EU Energy System in 2030: Investigating electricity sector challenges

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Abstract

This paper investigates the challenges faced by the European Power system as the EU transitions to a low carbon energy system. It adds value to, and tests the power system results of an energy system model called PRIMES that is used to inform EU energy and climate policy. This paper uses the power system results from a particular scenario (the PRIMES Reference scenario) to develop power plant portfolios for the year 2030 for each Member State and these portfolios are further scrutinized for technical appropriateness through the use of a dedicated power systems model. The power plant portfolios represent electricity system results aligning with a scenario that achieves an overall ambition of a 32% reduction in GHG for the EU as a whole by 2030 relative to 1990 levels. The dedicated power systems model, PLEXOS, is used to construct and model the electricity sector with significantly increased technical and temporal resolution. This enables generation of new results with PLEXOS that add new insights to the results from PRIMES. In particular, it quantifies i) variable renewable electricity curtailment; ii) levels of interconnector congestion and iii) wholesale electricity prices. The value of these additional insights is in the increased understanding of the robustness of a transitional low carbon electricity sector and in identifying challenges and operational concerns which may accompany that transition. The paper concludes that i) Increased variable renewable generation such as offshore wind, onshore wind and solar will lead to levels of curtailment with some Member States experiencing a disproportionate level of curtailment; ii) wholesale electricity prices will increase from current levels but differing installed capacities of renewables and Interconnection capacity levels limit price convergence between Member States; iii) Congestion on interconnection lines limits the efficient movement of electricity particularly in Central and Eastern Europe.

Introduction

The European Council agreed in November 2014 [1] ambitious targets for energy and climate change mitigation for 2030, namely to achieve i) a 40% reduction in greenhouse gas (GHG) relative to 1990 levels, ii) a 27% share of energy use from renewable sources and iii) a 27% improvement in energy efficiency. These targets and the expected high penetration of variable renewable electricity generation pose a number of challenges relating to the adequacy and reliability of the power system and the ability of the power system to absorb variable renewables. The primary software model used to inform EU climate and energy policy is PRIMES, a partial equilibrium model of the European Union energy system developed by the National Technical University in Athens [2][3][4][5] for scenario analysis and policy impact studies. The model was used to assess the impacts of EU GHG mission reduction scenarios for the period to 2030 that in turn informed the European Council's decision [6]. The impact assessment considered different levels of ambition relative to a *Reference* (PRIMES-REF) scenario, i.e. a scenario exploring the consequences of current trends including full implementation of policies adopted by late spring 2012 in the European Union. The impacts of different levels of GHG emissions reduction, renewable energy penetrations and energy efficiency ambitions were assessed relative to PRIMES-REF. PRIME-REF assumes that the EU will meet the target (under Directive 2009/EC/28) for a 20% share of renewable energy penetration by 2020; the target of 20% GHG emissions reduction by 2020 relative to 1990 levels (under Directive 2008/EC/29 for ETS emissions and Decision 406/2009/EC for non-ETS emissions) and that the Energy Efficiency Directive (Directive 2012/EC/27) will be fully implemented. In addition PRIMES-REF includes assumptions that all other policy goals legislated for prior to Spring 2012 (including for example the regulation on car manufacturers regarding light duty vehicles (Regulation 403/2009/EC) will also deliver anticipated targets. The PRIMES-REF scenario extends to the year 2050 and the results indicate that by 2030 the EU can achieve GHG emissions reductions of 32% below 1990 levels; 24% penetration of renewable energy and 21% energy efficiency gains.

This paper considers the results of PRIMES-REF for 2030, and uses them as a starting point for further analysis, with a particular focus on the results for the power system. It uses these results to build and run a unit commitment economic dispatch PLEXOS power systems model (i.e. the PRIMES-REF-2030 EU-28 PLEXOS Model). This enables additional analysis to be carried out using the added value that a power systems model with higher temporal resolution and technical detail can bring, namely to quantify at Member State level levels of curtailment of variable renewable electricity, interconnector congestion and wholesale electricity prices. This multi-model approach of using results from an energy systems model to construct a power systems model builds on previous analyses using the TIMES energy systems modelling tool [7][8] and OSeMOSYS modelling framework [9][10] .

While power system models and energy systems models both model electrical power systems they are fundamentally different modelling tools regarding their practical focus. Dedicated power system models typically focus solely on the electrical power system with significantly higher technical and temporal (up to 5mins) resolution. The primary inputs to the power systems model include electricity load, fuel prices and, power plant and transmission system technical description. Whole energy systems models by contrast, model electrical generation entirely endogenously and are driven by the combined behaviour of end use sectors driven by exogenous energy service demands and by the supply sectors that provide primary fuels. The focus of energy systems models is different to power systems models, providing a technology rich basis for estimating energy dynamics over a medium (15 – 30 years) or long-term (50 – 100 years), multiple period, time horizon. Power systems models tend to have a significantly shorter time horizon (for unit commitment economic dispatch models typically one year). Due to the focus on power systems operation in dedicated power systems models, the problem description can be analysed at a higher resolution compared to full energy systems models which have to handle a much broader range of problems and subsystems. In this way, energy systems models and power systems models are quite distinct from and complementary to each other.

In a power systems model the problem under scrutiny is centred on the determination of the least cost dispatch of generation to meet a given load demand whilst respecting the technical constraints and capabilities of the power system, typically referred to as the Unit Commitment and Economic Dispatch problem. (It is worth noting that power systems models can also focus on shorter term power system dynamics or longer term capacity expansion planning). A number of commercial and non-commercial models are available for power systems analyses, these are well summarized in Foley et al [11]. Unit Commitment refers to the decision as to which Units are to be operational and which aren't for a given period. Economic Dispatch refers to the decision as to what level of power is to be dispatched from the units once operating.

The purpose of the paper is to add value to and to check the robustness of the results for electricity generation of the PRIMES-REF scenario for the year 2030. It does this by using the PRIMES-REF results to build a PRIMES-REF-2030 EU-28 PLEXOS model. It then utilises the increased technical and temporal resolution of the dedicated power systems model to scrutinise the PRIMES-REF results for the year 2030. The PRIMES-REF-2030 EU-28 PLEXOS model adds value by generating new results with PLEXOS that add new insights to the results from PRIMES. In particular, the PLEXOS model quantifies i) variable renewable electricity curtailment; ii) levels of interconnector congestion and iii) wholesale electricity prices. The value of these additional insights is in the increased understanding of the robustness of a transitional low carbon electricity sector and in identifying challenges and operational concerns which may accompany that transition. Analysis of the PRIMES results provide a firm test of their robustness and technical appropriateness in relation to the European Power System in the year 2030 as projected by PRIMES. In the PRIMES-REF-2030 EU-28 PLEXOS model, the power system is modelled in detail at Member State level. The model utilises individual hourly electricity generation profiles for solar and wind power for each Member State based on local conditions and capacities for the year 2030, predicted electricity hourly demand profiles for the year 2030 and generation profiles for all other methods of electricity generation outlined in PRIMES (Hydro, Solids Fired, Oil Fired, Gas Fired, Biomass waste etc.) The model also considers the levels of interconnection between Member States and models electricity generation to meet demand based on the merit order.

Modelling Tools

PLEXOS Integrated Energy Model:

PLEXOS is a power systems modelling tool[1] used for electricity market modelling and planning worldwide. The software is a commercial modelling tool but is provided by Energy Exemplar free for non-commercial research to academic institutions. It has the ability to optimise the power system over various time intervals from long-term (1-40 years) to medium-term (1-5 years) to short-term (up to 1 year). In this paper, the focus is on operating PLEXOS in unit commitment and economic dispatch mode, focussing on a single year (2030).

Modelling is generally carried out using deterministic or stochastic programming techniques that focus on the minimization of an objective function or expected value subject to the modelled cost of electricity dispatch and to a number of constraints including availability and operational characteristics of generating plants, licensing environmental limits, and fuel costs, operator and transmission constraints. The model solves using linear or mixed integer linear programming. An important factor to consider as well from a research perspective is that the software is a transparent model, with the mathematical formulations available to the user via diagnostics.

In the power system model solar, wind and other renewables are typically treated as free generation, they are considered to have zero marginal cost, but this can be altered by the user if need be. Zero marginal costs reflects the market situation in a number of Member States where wind farm operators act (in the electricity market) as price takers that effectively bid in at zero. These modes of generation are different to conventional modes of generation because i) they are from variable and intermittent sources and ii) the connection to the power system is generally non-synchronous. They are effectively non dispatchable resources and pose a challenge for the power system to absorb them. Given the large amount of renewable electricity generation expected to come online to meet the ambitious targets in the EU (even in the PRIMES-REF scenario), accurate modelling of these variable renewable resources is very important. Power system issues associated with wind energy's variability are well documented by the IEA [12] [13]. Variability poses a tough challenge for power systems and causes issues surrounding system balancing, unit commitment and economic dispatch. The increasing amount of variable renewables anticipated in the EU-28 in order

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[1] PLEXOS can also model integrated energy systems, combining electricity and gas systems.

to meet ambitious RES targets in the PRIMES 2030 scenario results mean that accurate modelling of this variability is of paramount importance.

The power systems model used in this paper takes account of the variability of renewable electricity generation. It is used to analyse the PRIMES-REF scenario results for the year 2030 and their impact on the power system of individual Member States within the EU-28.

PRIMES Energy System Model

The PRIMES model is a partial equilibrium model for the European Union energy system developed by and maintained at the National Technical University of Athens, E3M-Laboratory led by Prof. Capros. It is the result of collaborative research under a series of projects supported by the Joule programme of the Directorate General for Research of the European Commission. It is a general purpose model conceived for forecasting, scenario construction and policy impact analysis. It covers a medium to long-term horizon. It is modular and allows either for a unified model use or for partial use of modules to support specific energy studies. It is a behavioural model but it also represents in an explicit and detailed way the available energy demand and supply technologies and pollution abatement technologies. [14]

As an energy system model, the calculations in PRIMES reflect a partial equilibrium solution. In other words, energy supply and demand reach an equilibrium in each scenario but the model does not provide feedback to the rest of the economy arising from the alternative energy systems pathways generated in each scenario.

The PRIMES energy system model formulates energy market equilibrium according to the mixed complementary mathematical methodology, this approximately corresponds to the Kuhn-Tucker conditions that are dual to a mathematical programming problem. Therefore, the imposition of a global or sectoral emissions constraint is mathematically strictly equivalent to the inclusion of a shadow variable, a shadow cost, which roughly affects all economic costs, proportionally to their emissions. [15]

Figure 1 illustrates the PRIMES model structure, including the inputs to the model and the different scenarios generated. PRIMES-REF is the EU Reference Scenario, which as mentioned, explores the consequences of current trends including full implementation of policies adopted by late spring 2012. PRIMES-REF provides an indication of expected developments under already agreed policies for the period to 2050. The results assess the impact of current policies and how effective they alone are in achieving long term objectives and serve as a comparison basis for other policy scenarios, in which the ambition for emissions reduction, renewable energy development and energy efficiency are varied.

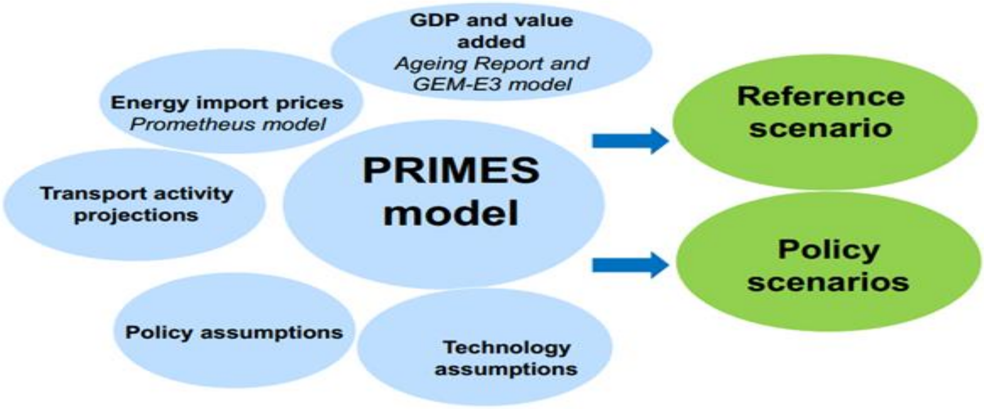

Figure 1 - Diagram of PRIMES Model Structure [16]

The various technology parameters used in PRIMES are exogenous, demand side and supply side technologies are considered, technology parameters are based on existing databases, studies and expert judgement. Technology parameters are also regularly compared to other sources. [16]

Technology learning assumptions are made regarding the predicted future development of technology over the running period of the model. In the model eco design regulations drive a reduction in cost of energy efficient equipment and devices. CO_2 car standards facilitate the uptake of more efficient ICE vehicles and reasonable emergence of electric cars. PV costs are assumed to continue to decrease into the future. The cost of offshore wind generation is assumed to reduce over the long term. New generation biomass supply technology is anticipated to emerge gradually after 2020. Following the nuclear disaster at Fukushima, nuclear power generation is expected in the model to become more expensive. Carbon capture and storage technology is anticipated in PRIMES to reach maturity after 2030 provided it is possible for it to be commercially deployed which depends also on ETS price. These assumptions are included in the model so as to improve modelling accuracy over the model run. [14][15]

As mentioned previously it is the power sector results from the PRIMES-2030 Reference Scenario that are under scrutiny for this study. The assumptions made are to provide a reference case to which other scenarios can then be compared in analysis of various policies. This study will test the robustness and technical appropriateness of these results for the power sector in 2030.

Below is a graphic illustrating the generation mix by Member State as in the Reference Scenario Results for 2030:

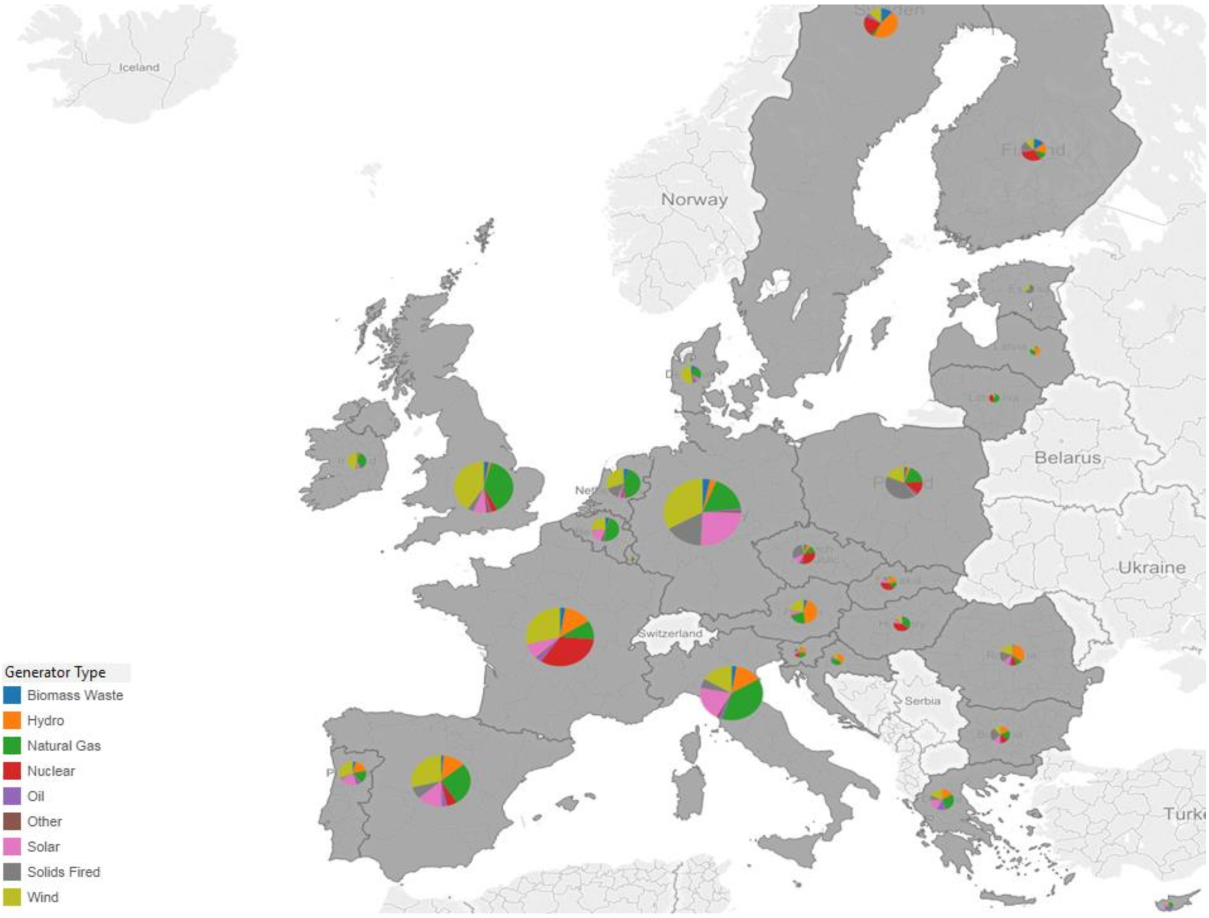

Figure 2 - The generation mix by Member State in the 2030 Reference Scenario Results

Methodology

Modelling Approach

To perform this analysis of the PRIMES Reference Scenario 2030 results, PLEXOS was used to construct a detailed power system model of the EU28. A soft-linking methodology was employed to develop the power system model and scrutinize specific results from the electricity sector for the target year. [7]

Model Structure

Generation Portfolio

Given the enormity of the model, the way in which it structured is critical to ensuring an accurate representation of the European power system. In PRIMES the installed power generation capacities for each Member State are detailed and broken down into various modes of generation such as Hydro, Solids Fired, Oil Fired, Gas Fired, Biomass waste etc. The results issued from PRIMES are aggregate figures, therefore a challenge to the model's construction surrounded the disaggregation of this generation. Disaggregation was carried out through a standardisation of generators across the EU28 for each mode of generation that is to say that for each aggregate generation capacity was to be made up by numerous identical generators summing to the total capacity in the reference scenario results. Aside from capacity each plant has identical characteristics such as minimum stable factor, ramp rates, maintenance rates, forced outage rate, start cost etc. Heat rates for the various types of power plant are calculated on a Member State by Member State basis, using the PRIMES results.

Interconnection

Net transfer capacities are limited here to Interconnection between MS, i.e. no interregional transmission is considered. The electricity network expansion is aligned with the latest 10 Year Development Plan from ENTSO-E, without making any judgement on the likelihood of certain projects materialising. [17] Fuel prices are also consistent across scenarios for each year and are shown in the Table 1.

Table 1: Fuel prices used in study

Fuel prices	2030
Oil (in €2010 per boe)	93
Gas (in €2010 per boe)	65
Coal (in €2010 per boe)	24

Figure 3 - Interconnection as modelled with the EU-28 Power Sysyem Model

Demand

The Reference scenario results detail overall annual electrical demand (Gross and Net). The power system model constructed is at an hourly resolution, thus requires an hourly electrical demand profile. To achieve this hourly electrical generation data was obtained from ENTSOE for each individual Member State of the EU28 and scaled to 2030 overall demand detailed in the PRIMES results.

Variable Renewable Generation modelling

The amount of variable renewables for 2030 in the Reference scenario are considerable and form a key part of the analysis of this paper. The ability of the grid in 2030 to absorb these renewables is a crucial part of the analysis. Therefore the modelling process must capture the variable and intermittent nature of these modes of generation at an hourly resolution to accurately capture their effects with localised profiles for each EU28 Member State in the PLEXOS model.

Wind Generation

Localised hourly wind profiles for each Member State of the EU28 were used within the model. Physical wind speeds at an 80m hub height we gathered for multiple locations in each of the 28 Member States through use of MERRA Data which is freely available from NASA, made easily accessible by EWC Weather Consult GmbH. The multi turbine approach developed by Per Nørdgaard et al was used to account for the multi turbine and geographic spread nature of wind generation. [18] A moving average was applied to every wind speed profile to smoothen the profile and account for reduced variability due to the aggregate nature of wind generation. Each wind profile produced for each individual Member State was applied to a standard power generation curve. To ensure capacity factors were in line with those outlined in PRIMES an iterative process had to be carried out to bring wind generation profiles in line with PRIMES. All wind profiles gathered for each Member State were summed and in each case a single profile was iteratively shifted until the overall capacity factor of the sum was in line with the PRIMES capacity factor. This iterative process was carried out through use of a script written in Python which manipulated the data bringing it in line with the desired capacity factors and outputting all wind profiles for all 28 Member States normalised with generation capacity.

Solar Generation

Localised hourly solar profiles for each Member State of the EU28 were created and used within the model. This was done through use of NREL’s PVWatts® Calculator web application. NREL's PVWatts® Calculator is a web application developed by the National Renewable Energy Laboratory (NREL) it estimates the electricity production of a grid-connected roof- or ground-mounted photovoltaic system based on a number of inputs. [19] In order to use the calculator it must be provided with information about the system's location and basic design parameters including system size, module type, array tilt angle and array azimuth angle. For the imputed parameters PVWatts® calculates estimated values for the system's annual and monthly electricity production. The profiles created were then normalised with the generation capacity for each Member State as per the Reference scenario 2030 results.

Hydro Generation

Hydro generation is modelled at a monthly resolution in the model via generation profiles provided by ENTSOE for each individual Member State of the EU28 and Norway. These generation profiles were then normalised with generation capacities as per the 2030 Reference scenario results. It was also imperative that generation capacity factors were brought into line with those in the PRIMES results. In a similar fashion to wind generation, the annual hydro profiles were iteratively shifted through use of a script written in Python to manipulate the data.

Upon completion the PRIMES 2030 EU 28 Model consisted of over 3,000 generators, 22 Pumped Hydro Electrical Storage Units and 53 Interconnector Lines running at hourly resolution for the year 2030.

Results

This paper presents and discusses a selection of results under a series of headings outlining the primary insights gained from this analysis. The main outputs are extracted and analysed with a particular focus on the impact of variable renewables on the operation of the European power system. This presentation of results illustrates the additional insights that can be gained through use of this methodology in the analysis of energy system model results for the power sector.

Wholesale Energy Prices

The high penetration of variable renewable generation sources contributes to containing and even lowering the wholesale prices of electricity by causing a shift in the merit order curve and substituting part of the generation of conventional thermal plants, which have higher marginal production costs. This merit order effect in combination with priority grid access can affect revenues of conventional power plants in particular in Member States experiencing the rapid deployment of renewables. In some Member States this raises the question of how to ensure adequate investment signals and generation adequacy. [20]

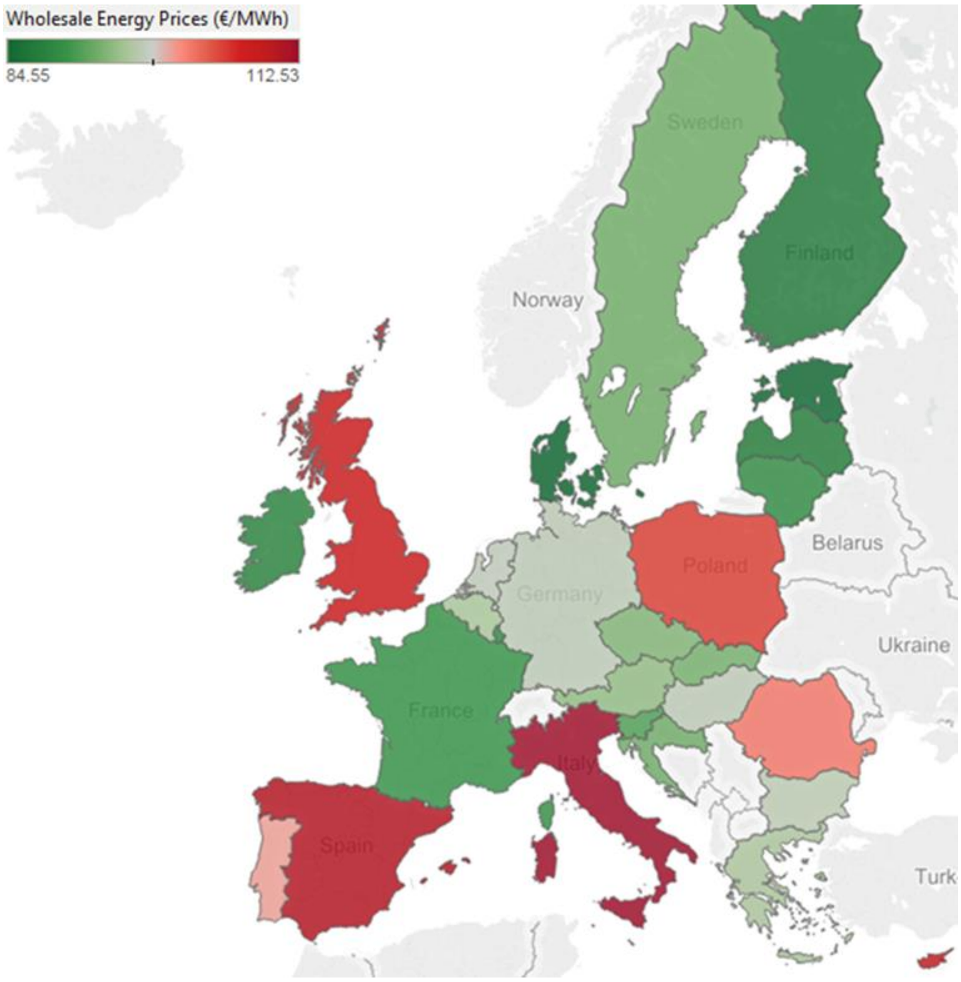

Figure 4 - 2030 Wholesale Energy Prices by Member State

The wholesale energy price by Member State can be seen in figure 4. This figure was generated for the year 2030 power system under the reference scenario results as simulated in the model constructed. These prices provide an insight into the effect of achieving RES targets through use of a high proportion of variable renewable generation. A number of Member States can be seen to have the low wholesale energy prices, especially Ireland with a price of 88 €/MWh. In Ireland's case, this is directly attributable the high proportion of variable generation which is planned to be installed and presents concerns. This has a strong seasonal impact and tends to reduce prices in the winter months when wind speeds are high and demand is also highest. This reduces the need for higher marginal cost generators to meet peak demand and long term affects the revenue base of conventional thermal power generation.

Within the power sector in Europe today, current market prices are not sufficient to cover the fixed costs of all plants operating on the system, a situation that is expected to become more critical in particular due to the current overcapacity induced by the economic slowdown in recent years and the penetration of renewables, which predominantly have fixed costs. The low capacity factors for natural gas fired plant, particularly in 2030 as can be seen in figure 5, suggest that natural gas fired plant may still struggle to achieve sufficient financial remuneration in an energy only market in some Member States.

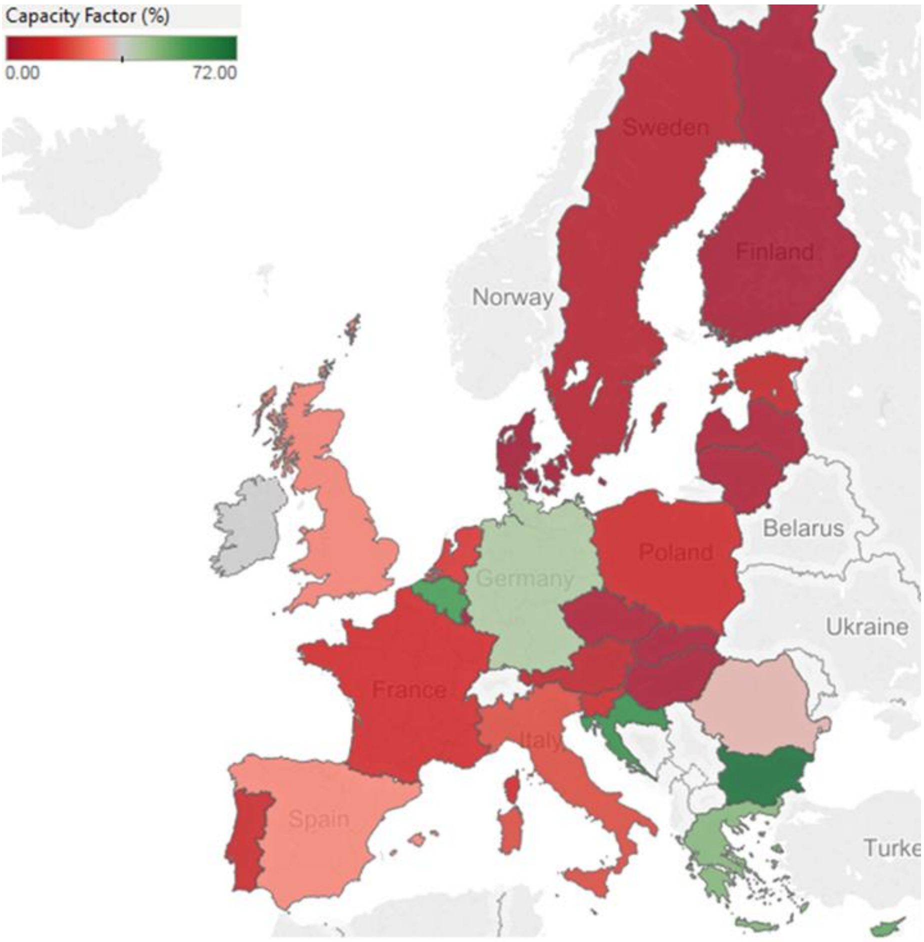

Figure 5 - 2030 Natural Gas Fired Plant Capacity Factors by Member State

Figure 6 identifies the differences in capacity factors for Natural Gas generation between the 2030 PRIMES Reference scenario results and the results of the PRIMES-REF-2030 EU-28 PLEXOS

Model. This is a direct insight into the effect of greater resolution modelling on results. It is clear that the capacity factors differ substantially across the EU-28 between both models, at an average absolute difference of 15%, with the PRIMES model having a tendency for overestimation in this case.

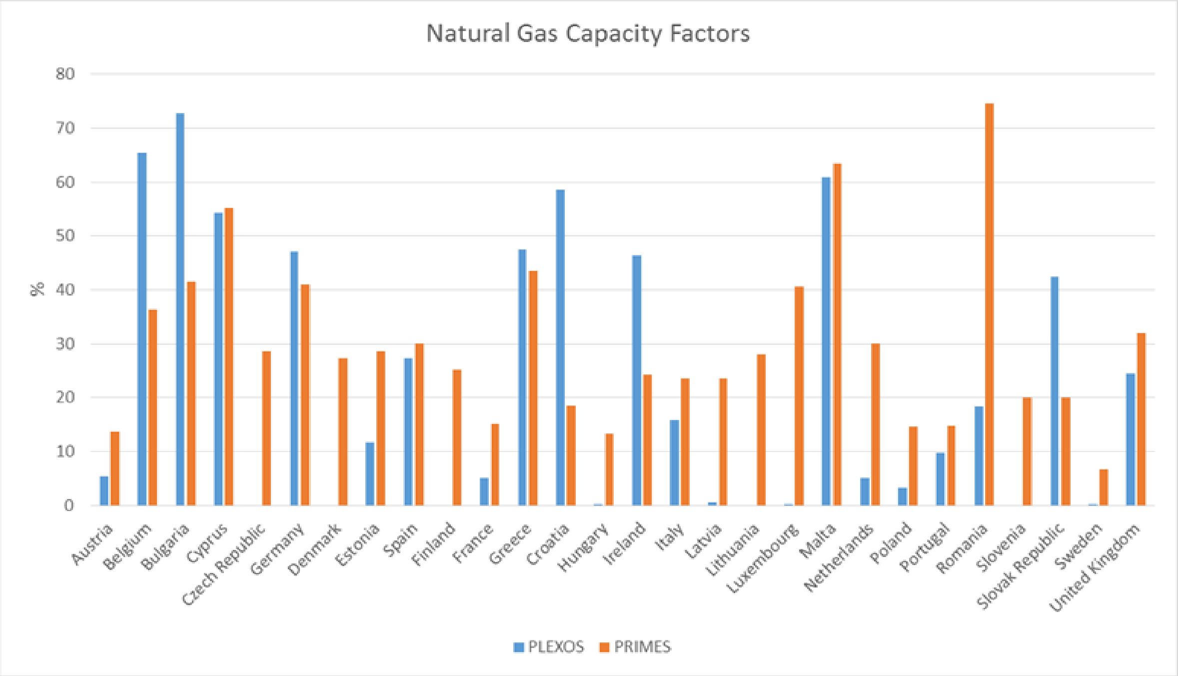

Figure 6 – 2030 PLEXOS and PRIMES Natural Gas Fired Plant Capacity Factors by Member State

Variable Renewable Curtailment

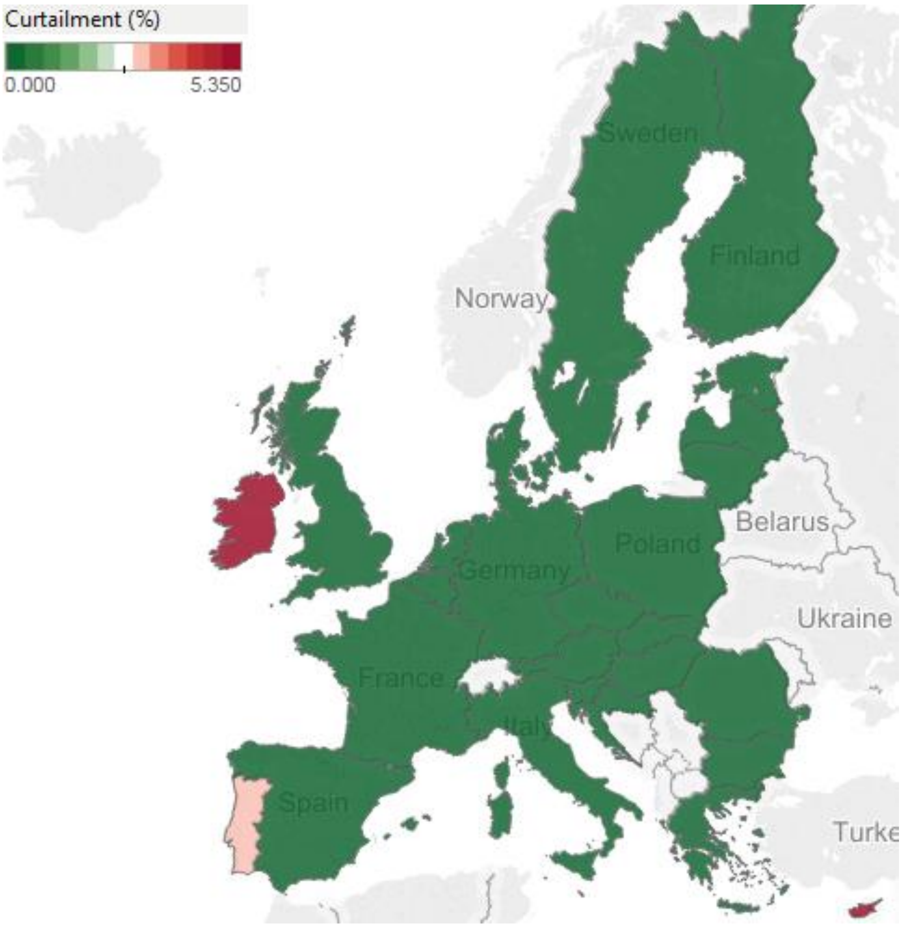

Figure 7 - Variable Renewable Curtailment by Member State

The insights gained into curtailment of variable renewable generation enabled by this analysis are another added value of applying this methodology. Figure 7 is a graphic displaying the variable renewable generation for Member States in the model that experience the highest amounts of curtailment. In the above figure curtailment is defined as undispatched solar photovoltaic and wind energy generation divided by total dispatchable, energy expressed as a percentage. Isolated power systems such as those of Malta and Cyprus have high amounts of curtailment, over 35%, by virtue of their isolation. Other Member States however that encounter curtailment are Ireland and Portugal, who are significantly better interconnected, thus raising concerns. Although the levels of curtailment in Portugal are relatively low, at just below 1%, the levels experienced by Ireland are considerable, in excess of 5%. It is also worth noting that these results are for an unconstrained system in which the penetration of renewables is theoretically unlimited within Member States. Should the system be constrained, accounting for important power system operational requirements such as minimum system inertia levels to mitigate rate of change of frequency limits (to which variable renewable solar and wind generation do not currently meaningfully contribute), curtailment levels across each of the 28 Member States within the model would increase. In addition to this, the scenario being analysed here is the reference scenario which is similar to a business as usual scenario, any further measures to increase the penetration of variable renewables in policy scenarios will also increase curtailment of variable renewable generation across the EU.

Interconnector Congestion

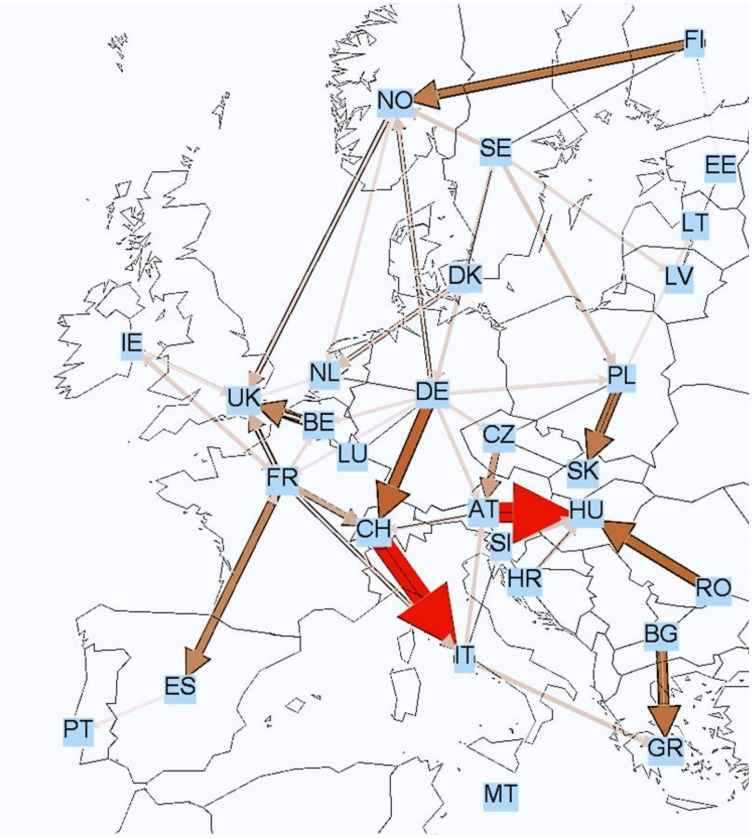

Figure 7 - 2030 Interconnector Congestion by Member State

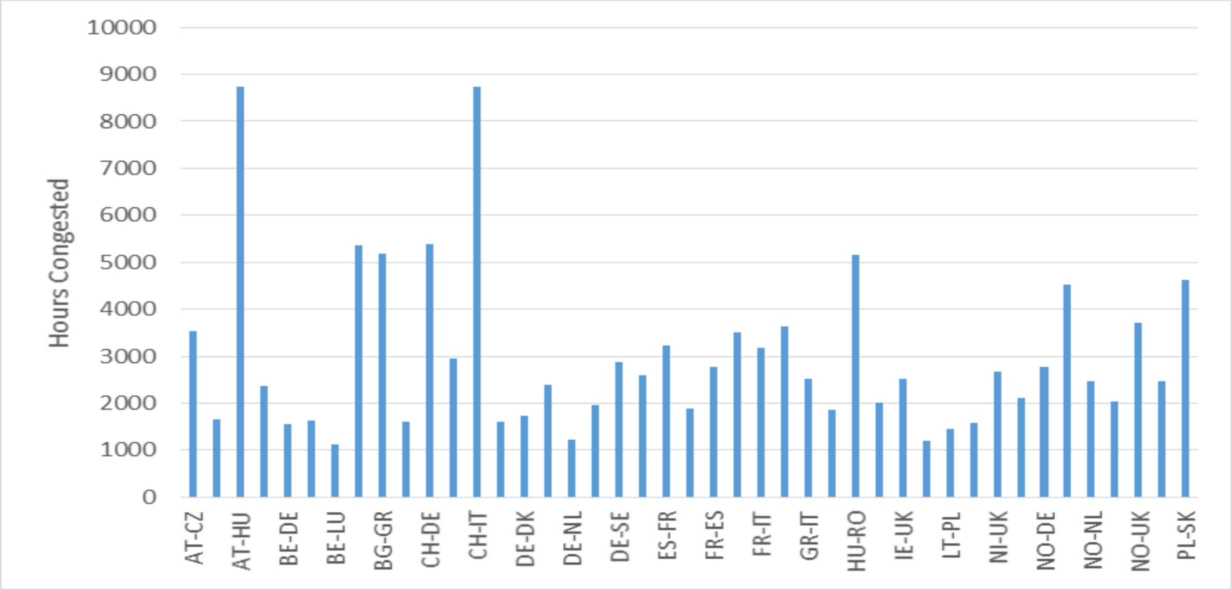

Figure 8 - 2030 Interconnector Congestion by Member State

In figures 8 and 9 the number of hours congested can be seen for the interconnection lines in the model simulation of 2030 which experienced high amounts of congestion (in excess of 1000 hours). Congestion on interconnection lines limits the efficient movement of electricity particularly in Central and Eastern Europe lines which raises concerns over the flexibility of the power systems within these Member States. Increased amounts of variable renewables coming online up to 2030 will put pressure on interconnection levels so that supply may meet demand to avoid curtailment. The heavy congestion, as presented in figures 8 and 9, raises concerns given the increasingly variable nature of power generation within the EU and highlights the need for increased interconnection especially in eastern and central European Member States under the reference scenario. Policy scenarios with greater amounts of variable renewables would encounter even more congestion. The congestion identified on interconnectors cannot all be appropriated to the increased penetration of renewables; it may also indicate pre-existing infrastructural inadequacy within the system.

Conclusions

This paper adds value to, and tests the power system results of the energy system model used to inform EU energy and climate policy called PRIMES. The power system model developed has enabled the analysis of the power sector results from PRIMES for the 2030 reference scenario under great technical and temporal resolution. From the results a number of insights are gained regarding the challenges faced by the European Power system as the EU transitions to a low carbon energy system particularly concerning wholesale energy prices, variable renewable curtailment and interconnection congestion.

The high penetration of variable renewable generation sources contributes to containing and even lowering the wholesale prices of electricity by causing a shift in the merit order curve and substituting part of the generation of conventional thermal plants, which have higher marginal production costs. In some Member States this raises the question of how to ensure adequate investment signals and generation adequacy. Wholesale energy prices are not sufficient to cover the fixed costs of all plants operating on the system, low capacity factors for natural gas fired plant suggest that natural gas fired plant may still struggle to achieve sufficient financial remuneration in an energy only market in some Member States.

A number of Member States are concerning regarding variable renewable curtailment and the ability of their power systems to absorb the variable renewables. A concerning factor in this is that a number of the Member States experiencing curtailment are relatively well interconnected. It poses questions of the practicality of large renewable electricity targets being achieved by means of variable generation in certain Member States. The imposition of constraints that impede instantaneous penetration of variable renewables to regulate system inertia would further increase levels of curtailment across the 28 Member States. Policy scenarios which impose greater amounts of variable renewable generation would also encounter greater levels of curtailment.

Congestion on interconnection lines raises concerns over the flexibility of the power systems within certain Member States. This work highlighted congestion in lines limiting the efficient movement of electricity particularly in Central and Eastern Europe lines. The heavy congestion, given the increasingly variable nature of power generation within the EU, highlights the need for increased interconnection especially in eastern and central European Member States under the reference scenario conditions.

The PRIMES-REF-2030 EU-28 PLEXOS model utilises the increased technical and temporal resolution of the dedicated power systems model to scrutinise the PRIMES-REF results for the year 2030. The PRIMES-REF-2030 EU-28 PLEXOS model adds value by generating new results with PLEXOS that add new insights to the results from PRIMES regarding i) variable renewable electricity curtailment; ii) levels of interconnector congestion and iii) wholesale electricity prices. The value of these additional insights is in the increased understanding of the robustness of a transitional low carbon electricity sector and in identifying challenges and operational concerns which may accompany that transition.

Future Work

To develop this model further and gain a deeper insight into the PRIMES power sector results, the next step is to incorporate system constraints into the model to better reflect the limitations of the power system. In particular the inertia of the power system, which is essential to maintain frequency and avoid related outages. The next development of this work will see inertia constraints established within the model, identify the analytical added value of its inclusion and highlight potential issues regarding system security & generation adequacy.

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