POTEnCIA

A new EU–wide energy sector model

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***Abstract*—This paper lays out the key features of the new modelling tool POTEnCIA (Policy Oriented Tool for Energy and Climate Change Impact Assessment) for the EU energy system. The model follows a hybrid partial equilibrium approach combining behavioural decision with detailed techno-economic data. Special features are introduced in order to appropriately reflect the implications of an uptake of novel energy technologies and of evolving market structures, allowing for the robust assessment of ambitious policy futures for the EU energy system. The model runs in annual time steps with a typical projection timeline to 2050.**

***Index Terms*— energy system modelling, energy policy assessment, energy efficiency, renewable energy, technology dynamics, climate change.**

I. INTRODUCTION

The European energy sector has been experiencing rapid and substantial changes with important consequences over the decades to come. Challenges arise from environmental concerns including increasingly ambitious greenhouse gases emission reductions, the pursuance of policies striving towards improving the energy efficiency in the EU energy system and the substantially increasing role of variable renewable energy sources in satisfying energy needs. Against this canvas of changes, market transformations such as the liberalisation of the European energy supply sectors and the creation of a more integrated, interconnected and competitive market, alongside increasing concerns about the security of supply and affordability, are important boundary conditions with regards to policy making towards implementing the objectives of the EU's Energy Union.

This paper presents the key features of a new modelling tool for the European energy sector named POTEnCIA (Policy-Oriented Tool for Energy and Climate Change Impact Assessment), a mathematical energy sector economic model designed to appropriately address the new major challenges of the energy system [8], [9]. POTEnCIA follows a hybrid partial equilibrium approach combining behavioural decisions with (imperfect) optimisation, using detailed techno-economic data. The model covers each EU Member State separately, while offering, in addition, the option of addressing the EU28 energy system as a whole. It uses annual time-steps, based on historic time series, with projections typically until 2050. [1] The model is designed to assess the impacts of alternative energy and climate policies on the energy sector, under different hypotheses about the framework conditions within the energy markets. In addition, explicit policies can be directly addressed, such as those related to energy taxation, efficiency standards, feed-in tariffs and other type of subsidies, etc. The main use of the tool is to perform comparative analysis of scenarios.

The special mechanisms implemented in the model as to appropriately represent the transformation of today's energy systems and to assess a wide variety of potential energy related policies and measures are presented in the following sections.

II. KEY FEATURES AND CONCEPTS

A. *Demand Side in POTEnCIA*

POTEnCIA introduces a high level of detail for the energy consumed in each demand side sector[2], involving the characterization of energy requirements by sub-sector, process, and end-use, as well as, the associated technological options and energy forms.

The model makes use of the concept of the 'representative economic agent' which summarises the individual choices of the various decision makers within each sector. This yields a

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[1] The *General Algebraic Modeling System* (GAMS) modelling environment is used for POTEnCIA. The computation time with high-end machines reaches up to 3-4 hours when solving for an individual country. Depending on the type of scenario considered, the running time can increase up to two days when solving simultaneously for the all EU Member States.

[2] The model offers a detail representation of the industrial sectors; the identification of different types of building cells characteristics and distinction of building thermal uses to specific electricity uses in the residential and services sectors; a detailed representation of the various transport modes distinguishing between passengers and freight related ones concerning the transport sector etc.

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'representative' consumption profile in the sector in terms of energy related equipment in use, consumer preferences, etc.[3]

The behaviour of the representative agents is captured by causational equations responding to changes in prices, technology characteristics and activity, amongst other key explanatory factors.

Each sector-specific representative economic agent implicitly optimises an objective function (by means of profit/utility maximisation and/or cost minimisation) combining economics and engineering restrictions in a consistent way. The optimisation takes place through adjustments in the level of activity within the sector, the level of use of installed equipment (i.e. involving possible premature replacement and/or under-utilisation), and investment choices under constraints that refer to behavioural preferences, technology availability, degree of comfort sought, equipment installed, resources availability, infrastructure constraints, and environmental considerations. Consequently, although the decision is assumed to be economic, many of the constraints that need to be addressed reflect engineering feasibility.

1) Capturing the real domain for policy implementation

A realistic domain for policy implementation is explicitly quantified by distinguishing between the number of representative agents with installed energy consuming equipment (a detailed capital stock ageing approach is adopted with vintage-specific techno-economic characteristics for a given sector at each point in time, including the size of the equipment – e.g. kW of an installed boiler) and that of new agents who need to invest in new equipment as to satisfy their service needs.

The approach retained allows making a clear distinction between the energy related equipment that needs to be installed when making an investment decision and the rate of use of the installed equipment. For this purpose the concepts of 'desired' and 'realised' energy service requirements at the level of the representative agent are introduced.

The purchasing of the equipment is decided based on how the representative agent would ideally like to operate it and not on how this equipment will actually be used. The desired energy-related service requirements represent a notion of 'welfare target' of the representative agent at each moment in time. They depend on the economic/demographic assumptions and on the evolution of technical and comfort standards, while accounting for the penetration rate of the equipment and saturation effects.

On the other hand, the realised energy related service requirements adjust the desired levels of use of the equipment by also considering changes in the incurred costs of operation (for example fuel prices, effects of policies in place etc.) in conjunction with the vintage specific technical characteristics of the existing stock. In other words, the representative agents that fall into different vintages differentiate the rate of use of their installed equipment at the level of end-uses. At the same time, by explicitly considering the representative agents' flexibility to adapt to the prevailing policy assumptions, their willingness to revise comfort standards is captured.[4]

Through this approach, energy consumption and installed capacities of the energy related equipment are calculated independently the one from the other; they are matched through endogenously calculated utilisation rates.

2) Endogenous technology dynamics

The new modelling instrument implements a high level of technological disaggregation. For each technology option defined in POTEnCIA consumers may choose to invest in an 'almost ordinary', 'advanced' or 'state of the art' technology, the characteristics of which are endogenously calculated for each projection year.

The efficiencies of the alternative technologies dynamically evolve over time towards a 'backstop' technology (a technical optimum reflecting the limit of potential efficiency improvements) depending on prevailing scenario assumptions, e.g. strength of emission reduction policies, energy efficiency support policies etc.

The related capital, fixed O&M and variable O&M cost of the competing technologies are endogenised as a non-linear function of their distance in terms of efficiency to the backstop and the pace of the efficiency improvement. The formulation applied in the model allows distinguishing between radical and more progressive technology changes and their impact on equipment costs. It captures the deployment and learning effects (learning by adopting, learning by doing) that partially or fully offset over time the additional costs[5] incurred by technology progress.

Furthermore, the approach retained allows differentiating the technology dynamics across the different countries as they depend on the gap described above. Such a differentiation allows for a faster deployment of efficiency improvements in inefficient energy systems compared to efficient ones; in other words, a gradual convergence of available technologies across countries takes place. Similarly the costs of the installed equipment vary across countries, better reflecting the fact that countries with less efficient equipment face lower equipment costs.

3) Response mechanisms

Acknowledging that the challenges faced by the European energy system cannot be tackled by solely performing actions regarding the energy equipment (see for example [2]), a variety of response mechanisms are applied in the demand side.

The first one concerns the possibility of adopting non-energy equipment related measures that lead to a reduction of energy requirements, expressed in the model through an *infrastructure efficiency factor*. Measures of technical nature

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[3] The notion of the representative economic agent has a different physical meaning in each sector. In the residential sector it represents a household or an appliance whereas in the transport sector it represents a mean of transport and in industry the production volume.

[4] The flexibility for changes in the realized level of use is largely sector and end-use dependent

[5] See [5], [6], [9].

such as thermal insulation in buildings, heat recovery in industry, etc. are captured in this way, providing a notion of the potential and costs for optimising the entire process at an aggregate level. In the presence of the appropriate policy incentives, non-energy equipment related investments towards energy savings may take place for both new installations and existing vintages.

The level of exploitation of the saving potential through the *infrastructure efficiency factor* is determined within each sector by comparing the corresponding costs with the costs savings occurring from the lower capacity needs and lower energy consumption. Hence it is driven by economic and policy assumptions while being also vintage specific. In the case of existing installations the stranded costs arising from the induced underutilisation of installed equipment are also considered.

Premature replacement of equipment may also take place across all vintages and in all sectors in response to the prevailing policy assumptions, the decision being based on the comparison of corresponding costs by means of net present values of the new installation plus the induced stranded cost of the equipment that will be prematurely replaced on one side, and operating costs of existing vintages for the remaining lifetime plus a fraction of the net present value of the new installation, reflecting the period following the normal replacement of the installed equipment, on the other side. On top of its use in the costs comparison, the remaining lifetime of the equipment also affects the consumer's willingness to perform premature replacement.

Specific policy initiatives may also be explicitly introduced (e.g. subsidising the replacement of inefficient equipment) as to accelerate the rate of premature replacement. In all cases stranded and, where applicable, policy support costs arising from premature replacement of equipment are explicitly considered and quantified.

Finally, the possibility of modulating the level of activity in the different sectors (initially driven by macroeconomic and demographic assumptions) to the scenario specific assumptions is offered in POTEnCIA through the introduction of the *structural response parameter*. Such adjustments can be interpreted as a response of the representative agents by means of altering the mix and quality of their service (and/or, depending on the sector, its productivity).

B. Power Generation in POTEnCIA

For the power generation sector POTEnCIA follows a non-linear, priced-lagged optimisation approach, simultaneously addressing capacity planning and power plants dispatching under constraints related to demand for electricity and distributed steam and heat, power plants operation, fuel supply, system stability and reserve margin, grid and policy constraints.

1) Unit commitment

Rather than following an approach that considers the total installed capacity of a given power plant type, POTEnCIA considers both in the simulation of the investment decision and of the dispatching the discrete character of the explicit typical plant sizes, mimicking a mixed integer programming approach. To this end it accounts for the number of (representative) units available, their corresponding (unit-specific) size and operating constraints, including additional costs and efficiency losses that may occur when the unit is operated in part load or with frequent ramp-ups and -downs.

This results in a more realistic representation of the power plants' annual dispatching, imitating a unit commitment approach. In doing so the model

- explicitly considers the hours of availability of each resource;
- respects the units' size and their operating conditions (minimum stable load etc.); and
- identifies the efficiency of the power plant in operating mode, taking into account the real hours of operation, as well as the cycling effects.

This approach makes it possible to distinguish, within a given load, between a unit’s contribution to satisfy the electricity demand in terms of kWh and its contribution to meet the load in terms of power (kW). Whereas a thermal unit’s contribution to electricity generation also implies a corresponding contribution to the load it is allocated to, this may not be the case throughout all loads for intermittent renewable energies due to constraints arising from their naturally limited hours of availability. For example, even though PV units can satisfy part of the electricity generation within the base load, they cannot contribute in satisfying power needs due to the fact that they can generate electricity only during daylight hours.

The distinction between a unit’s contribution in terms of electricity and in terms of power within a certain load makes it possible to derive: *i)* the exact number of units in operation and the un-used ones (reserve); *ii)* the actual rate of use of the units in operation, taking into account also their operation in part load conditions; *iii)* the costs, the additional fuel consumption and related CO_2 emissions caused by operating units in cycling mode.

In this same context, variable renewable energies are considered within the dispatching problem as a whole, i.e. alongside other power generators, and their contribution to different loads is based on economic criteria while respecting the resources availability constraints and taking into account the types of power plants they replace. A flexible allocation of intermittent renewable energies takes place while accounting for the opportunity costs induced in the competing traditional technologies. The approach retained allows identifying possible curtailment of intermittent renewable energy units and, at the same time, quantifying the impact of their operation on traditional technologies.

2) Standard discrete choice portfolio management

POTEnCIA moves away from the linear optimization and instead of seeking the least cost solution for electricity generation [3], [4] it follows a standard discrete choice portfolio management approach. The adoption of such a methodology allows capturing effectively the fragmentation observed in real life dispatching and planning conditions.[6]

The economic decision making both in the capacity planning and in the power plants' operation is obtained through applying a multinomial logit formulation. The operating costs in combination with the producers' preferences and the hours of operation of the power plant types are used in order to identify an indicator of the "attractiveness" of a certain power generation technology option compared to all other competing options.

The real operating cost of each power plant type in the different load regimes is calculated based on the techno-economic characteristics of each unit, the fuel costs, other costs elements influenced by policies in place (e.g. ETS prices, energy efficiency premiums, renewables support, etc.) and the impact of cycling operation[7] [7].

The producers' preferences reflect non-economic, exogenously defined and specific to the power plant types, drivers that influence producers’ decision. Moreover, possible changes in producers’ behaviour as a response to scenario-specific assumptions are taken into account.

The attractiveness indicator can directly act as a driver in the ordering and allocation of different power plant types within a given load. However, in order to enable the comparison of this attractiveness across the different loads, a normalisation by load is required.[8]

According to discrete choice theory [10], the output of this normalization could be seen as the probability of choosing a certain power generation option compared to the available alternatives following the principles of the multinomial logit formulation for market shares calculation. In deterministic terms it equals to the 'desired' contribution of a certain option by means of energy generation and can therefore be interpreted as the *desired market share* of that option within each load.

On the basis of these desired market shares the 'potential' generation (i.e. unconstrained by means of capacity, rate of use, fuel availability etc.) by power plant type and load is calculated. This potential generation in combination with the specificities of the above described unit commitment approach is then used as to allocate the power plant units across all loads. Thus, the discrete character of the representative power plants units is respected.

As regards the capacity planning, it is important to highlight that an explicit unit size representation for power plants is considered, meaning that investment in new capacities takes place in quanta that are multiples of the technology specific, minimum plant unit sizes.

3) Dynamic recursive foresight with imperfect information

Capacity planning in power generation follows a dynamic recursive foresight with imperfect information, rather than the (usual) perfect foresight framework. POTEnCIA tries to mimic real world decision making by not considering with certainty fixed, predetermined values for the future key policy and economic parameters.

To this end, uncertainties concerning the evolution of such parameters are introduced by default in the investment decision making, reflecting different expectations with regards to the likelihood and/or the stringency of implementation of future policies such as (for instance) the ETS, renewable support schemes, efficiency policies, or any possible combination of these. At the same time, these expectations take into account the reality of the prevailing policy.

4) System stability

POTEnCIA introduces a number of novel concepts going beyond the notion of the 'reserve margin' in order to carefully address the power system stability. To this end, endogenously derived signals are sent from the dispatching of the power plants to the capacity planning, affecting both the level of investment needs and the attractiveness of competing investment options.

- Boundary conditions for the capacity in use versus the total capacity installed are introduced, which ensure that sufficient capacity is available to meet the load in all circumstances, and which in consequence have an impact on the level of investment.
- A system stability indicator is computed at the same time, as the ratio between the capacity in operation and the peak load. Through this the bundling of power plant units and the exploitation of capacities that contribute mainly in satisfying the energy but do contribute to the load only to a very limited extent due to e.g. constraints in the availability of their primary resource (wind, PV), are reflected. When this indicator reaches high levels the investment options that contribute to the reliable available capacity become more attractive compared to options that further contribute to the satisfaction of energy and not load.

The methodology implemented allows for a better representation of the already observed and evolving power systems transition and the arising challenges.

C. Behavioural aspects in POTEnCIA

The introduction of policies generates a response in the decision-making of the representative agent as regards the investment in new equipment and/or the use of the installed equipment. This response is multifaceted and includes, beyond pure price-driven changes, reactions in the agent’s behaviour.

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[6] Assuming, for example, a simplified case in which two different power plants type *A* and *B*, each having *n* units equal in size and where the aggregate power plant *A* is marginally cheaper than *B*, must satisfy a load equivalent to *n* units. In a least cost solution approach, all units of power plant *A* will be dispatched and none of the *B*. However, in real life conditions, in which the explicit characteristics of each unit available are known, a fragmentation of units dispatching would occur, as most likely some units of power plant *B* would be more cost effective than some others of *A*.

[7] In most of the energy models, power generation is modelled implicitly assuming a steady-state operation of the plants at their nominal or rated power output. However, the rising share of generation from intermittent renewable energies increasingly leads to operating modes implying partial loads (ramping and cycling).

[8] This is not the same as normalising over all loads, which will result in a loss of load specific information.

To this end, in POTEnCIA a number of features are introduced that endogenously capture policy-induced changes in the behaviour of energy consumers and suppliers. These mechanisms limit the need for exogenous interventions when addressing specific policies scenarios.

1) *Subjective financing capability*

For the investment decisions a subjective financing capability rate is used. Assuming unlimited access to financing capital and no risk aversion, the discount rate applied in the investment decision for an agent, reasoning on pure economic grounds, should be equal to the interest rate the agent has to pay for a credit (cost of capital financing). However, in the presence of budgetary constraints, risk factors and/or asymmetric information the perceived cost of capital for the energy consumer may be higher than the nominal capital costs annuities. In order to capture these deviations from optimality, POTEnCIA assumes the existence of a subjective financing capability that reflects a 'perceived' risk premium for the investor.

The inclusion of budgetary constraints in the subjective financing capability rate allows for a differentiation of the investment related discount rates not only across sectors, but also across Member States. Whereas budgetary constraints have a limited impact on the investment decision for large industrial investors and power generators, they affect individual choices of private consumers to a much larger extent. Hence, the subjective financing capability rates applied in investment decision making for households or private transport can differ largely across Member States, linked to their level of income. However, under the typical assumption of an economic convergence in the EU these differences would dynamically decrease in the long run [1].

2) *Market acceptance / maturity indicator*

The market acceptance factor reflects the investor's preferences that result in investment choices which deviate from economic optimality as defined if only engineering costs were taken into account. Such preferences, however, may change as a function of the prevailing policy conditions. For example, within a policy framework that strongly supports a certain technology type the representative agent may perceive signals of a collective 'societal' appreciation of such technology, thereby favouring it beyond pure economic criteria. This is captured through a policy-dependent element of the market acceptance factor in POTEnCIA. In addition a learning-by-adopting effect from the representative agent's point of view is also taken into account as a function of the penetration level of the option considered.

3) *Moving towards rationality*

The introduction of a strict policy framework may also result in a better understanding of the costs of competing options when performing an investment-decision. As a result, the choice made by the representative agent would become more rationality driven, more economically optimal rather than being influenced by non-economic considerations. To this end, POTEnCIA introduces the possibility of a policy driven (endogenously derived) change in the elasticity of substitution of the market sharing function.

III. CONCLUDING REMARKS

This paper has introduced the special features of the new energy sector economic model POTEnCIA, implemented as to appropriately represent the complex and challenging dynamics of the EU energy system. Through these mechanisms the model conceived is able to appropriately address the key policy challenges faced by the energy sector and carry out policy assessment analysis. In doing so the real domain for energy policies implementation is correctly identified, the transition to a new energy system and ambitious long term policy targets are handled, technology dynamics and multi-faceted responses of energy users to policy regimes are captured, while accounting for behavioural changes and going beyond perfect foresight.

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