



European
Commission

JRC SCIENCE AND POLICY REPORTS

Addressing flexibility in energy system models

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2015



European Commission
Joint Research Centre
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JRC95354

EUR 27183 EN

ISBN 978-92-79-47235-0 (PDF)
ISBN 978-92-79-47236-7 (print)

ISSN 1831-9424 (online)
ISSN 1018-5593 (print)

doi:10.2790/925

Luxembourg: Publications Office of the European Union, 2015

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Abstract

The present report summarises the discussions and conclusions of the international workshop on "Addressing flexibility in energy system models" held on December 4 and 5 2014 at the premises of the JRC Institute for Energy and Transport in Petten. Around 40 energy modelling experts and researchers from universities, research centres, the power industry, international organisations, and the European Commission (DGs ENER and JRC) met to present and discuss their views on the modelling of flexibility issues, the linkage of energy system models and sector-detailed energy models, the integration of high shares of variable renewable energy sources, and the representation of flexibility needs in power system models. The discussions took into account modelling and data-related methodological aspects, with their limitations and uncertainties, as well as possible alternatives to be implemented within energy system models.

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1 Executive summary

1.1 Background

Most analyses of the future European energy system conclude that in order to achieve energy and climate change policy goals it will be necessary to ramp up the use of renewable energy sources. The stochastic nature of some of those energy sources, together with other sources of short- and long-term uncertainty, have already significant impacts in energy systems operation and planning, and it is expected that future energy systems (and in particular the electricity system) will be forced to become increasingly flexible (that is, able to adapt its operation to both predictable and unpredictable fluctuating conditions, either on the demand or generation side, at different time scales, within economical boundaries [1, 2]) in order to cope with these challenges. Therefore, policy makers need to consider issues such as the effects of intermittent or variable energy sources on the reliability and adequacy of the energy system, the impacts of rules governing the curtailment or storage of energy, or how much backup dispatchable capacity may be required to guarantee that energy demand is safely met. Many of these questions are typically addressed by detailed models of the electric power sector with a high level of technological and temporal resolution, but without considering the rest of the energy system, although these issues affect other energy sectors as well. On the other hand, typical system-wide energy models cannot easily introduce such levels of detail without becoming excessively complex. Therefore, recent research projects have attempted to couple energy system models with more detailed sectoral energy models and other ad-hoc auxiliary tools.

Given the importance of this active field of research for policy-making support, the European Commission's Joint Research Centre – Institute for Energy and Transport has organised an expert workshop on "Addressing flexibility in energy system models". The objective of the workshop was to gather experts from modelling teams currently dealing with these problems from different perspectives, ranging from energy system-wide to detailed sectoral energy models, in order to share and compare modelling approaches and results, identifying gaps and potential solutions.

In the two-day long workshop held on December 4 and 5, 2014, around 40 energy modelling experts and researchers from universities, research centres, industry, international organisations, and the European Commission (JRC and DG ENER) met at the premises of the JRC Institute for Energy and Transport in Petten to present and discuss their views on the modelling of flexibility issues, the linkage of energy system models and sector-detailed energy models, the integration of high shares of variable renewable energy sources, and the representation of flexibility needs in power system models.

The discussions took into account modelling and data-related methodological aspects, with their limitations and uncertainties, as well as possible alternatives to be implemented within energy system models.

The conclusions and recommendations resulting from those discussions, together with the contributions from all the participants in the workshop, are summarised in the present JRC Scientific and Policy Report.

1.2 Summary of the presentations

The two-day workshop was split into four sessions dedicated to:

- Introducing flexibility issues and modelling-related challenges,
- Linking system-wide and sector-specific energy models as the main way of addressing flexibility,
- Modelling the integration of high shares of variable energy sources,
- Modelling flexibility needs in power systems.

All the abstracts and presentations are available through a dedicated link within the SETIS website¹:

The workshop was opened by Mr. S. Peteves, head of the Energy Technology Policy Outlook unit at the JRC's Institute for Energy and Transport. He highlighted the policy relevance of the workshop, in particular as decision and policy makers increasingly need to consider issues such as how intermittent energy sources affect the reliability and adequacy the energy system operations and planning. With the question of how to address properly these issues in energy system models, the workshop began.

Session 1: introducing flexibility issues and modelling-related challenges

Mr. J. Dillon (University College Dublin) in his presentation on "**Addressing flexibility in energy system models**" (section 3.1.1), introduced flexibility issues in energy modelling. Flexibility needs in energy systems are driven by the increasing penetration of renewable energy sources. Flexibility requirements are forcing a convergence of planning and operations decision-making in energy systems. Properly capturing flexibility in energy system models requires increasing levels of details which, given the limitation in modelling techniques and computing power, implies finding the proper balance between details and scope. Two main options are possible to cope with this problem: i) use conventional modelling paradigms and carry out ex-post flexibility assessments, or ii) revise the modelling paradigm, develop and use new modelling tools, trade detail for scope, and increase computing power. The second option seems to be most appropriate according to the latest studies available, but this approach raises some key research questions:

- What are the key details missing in current models?
- What are the relative impacts of increasing detail levels? This is model-specific, and results cannot be easily transferred across models.
- What can be done to ensure that models are fit for purpose?
- How much detail can be left out while still meeting the desired scope of the model?

The presentation on "**Model coupling across scales**" (section 3.1.2), by Ms. H. Heinrichs (Forschungszentrum Jülich), introduced the methodological aspects related to model coupling. Her first consideration concerned the definition of flexibility, since there are several interpretations available and it is important for the analysis to establish clearly the type of flexibility that is addressed. Once defined, flexibility needs can be approached by means of basic heuristics (such as ad-hoc formulae to determine reserve requirements), model coupling (energy system models coupled with unit commitment models and macroeconomic models), or using specific indicators (derived from specific metrics such as loss of load probability, loss of load expectation, etc.). With respect to model coupling,

¹ <http://setis.ec.europa.eu/setis-deliverables/setis-workshops-hearings/international-workshop-addressing-flexibility-energy>

given the features of energy system models (namely: it is not possible to take into account short-term uncertainty, they represent full energy systems, are technology rich, and consider mid and long-term impacts) it is necessary to carry out temporal (limiting the time slices) and spatial aggregations (limiting the number of regions considered). Models can be coupled in different ways: i) unidirectional (the output of one model is the input of another), ii) iterative (the models are combined in a loop), or iii) heuristically. Coupling can also happen along one or more dimensions (e.g. time resolution, geographical scale, or sectoral specification). The features of the available models and the specific research questions addressed determine the possibilities for coupling. Model coupling requires computational resources, high model expertise, and data, while it is limited by convergence issues or the existence of optima. Other challenges of model coupling are temporal (e.g. behavioural vs. structural challenges), spatial (e.g. renewable potentials or demands depend on geographical aspects), system boundary (how to adapt policy measures to different sectoral detail levels?), or methodological (e.g. cost minimisation vs. profit maximisation, different discount rates for different sectors and actors, basic assumptions and approaches). As a conclusion, model coupling seems to be the outstanding approach to address flexibility issues, but it raises capacity challenges and may lead to correlations between different uncertainties.

In her presentation "**Challenges of representing electricity system flexibility in energy system models**" (section 3.1.3), Ms. V. Silva (Electricité de France R&D) discussed the suite of coupled models used by EDF to analyse flexibility adequacy problems in the power sector. The goal of these tools is to model long-term system expansion considering energy system-wide long-term uncertainties and short-term operational constraints. The models coupled by EDF are: i) MADONE: a deterministic TIMES model of 29 interconnected European countries, used to run multiple scenarios that determine long-term base load needs and the merit order of the capacity generation mix, ii) CONTINENTAL: a power system model with investment loop, water management, and stochastic hydro-thermal generation scheduling based on chronological data with hourly (or lower) resolution, used for complementing and improving the outputs of MADONE in terms of system reliability and feasibility; and iii) FLEX ASSESSMENT/OPIUM: a probabilistic tool used to estimate flexibility adequacy considering the operation margin requirements to handle short term load-generation balancing uncertainty. FLEX ASSESSMENT is used to further improve the results of CONTINENTAL by assessing the flexibility adequacy of the generation mix. Besides those models, EDF uses time series with 31 years of meteorological data to study weather-related uncertainty. They conclude that the high penetration of renewable energy sources leads to investment in peaking units in order to meet the needs for backup capacity that needs to be built to handle periods with low wind and PV generation. Since this backup capacity will be used for limited number of hours per year that best candidate solutions are flexible plant such as OCGT. These plants will provide the flexibility required to handle near term uncertainty. This means that the solutions from CONTINENTAL provide sufficient flexibility without the need to perform stochastic optimisation. Model coupling seems to be the state-of-the-art technique for analysing energy systems with realistic size and a highly-detailed representation of the power sector.

In the fourth presentation, "**Modelling urban energy systems: a tentative approach**" (section 3.1.4), Mr. F. Martinsson (Swedish Environmental Research Institute) focused on the most relevant factors to analyse uncertainty in the building sector. The main challenges in this case are locational aspects (e.g. variability and availability of energy

supply sources, demand patterns), and the links between energy efficiency trends and supply options. Three main research questions are considered:

- Can a decentralised urban energy system enhance overall energy system efficiency?
- What is the most cost-effective strategy for improving energy efficiency in buildings?
- What are the impacts of this strategy on total system emissions and costs?

The key to answer these questions is to integrate models, namely the TIMES model for Sweden with the IVL/ITU buildings model. The buildings model is based on archetypes that capture characteristics of building types, technology options, and efficiency measures with finer resolution. Key issues that need to be integrated in the building models and the linked tools were highlighted, including: storage, demand side measures in the building sector, and allocation of grid cost and grid uses among consumers.

Session 2: linking system-wide and sector-specific energy models as the main way of addressing flexibility

The presentation on "**Holistic approaches in addressing flexibility in energy system models**" (section 3.2.1) by Ms. T. Koljonen, Technical Research Centre of Finland (VTT), stressed the importance of flexibility in order to integrate renewable energy sources cost-effectively. Such integration is possible only if i) large areas may be balanced, and ii) balancing can be done a few hours ahead. There are several sources of flexibility (such as transmission, hydropower, thermal plants, or district heating) but current models are not able of representing them accurately without becoming extremely complex, and therefore new holistic approaches relying on suites of tools are needed. These new approaches must improve the representation of the decision making processes, consumer behaviour, and the new business models that are appearing, without neglecting market aspects, but these elements lead to even more complex models. The value of current and future flexibility needs to be estimated as a function of the value of flexible generation, flexible demand, and flexible storage, in order to assess the different options to integrate variable generation across different time scales and regions. At VTT this analysis is carried out with a toolbox of models comprising:

- Fully integrated models:
 - Balmorel: generation planning
 - WILMAR: unit commitment and economic dispatch
 - PSS/E: power system simulation
- Soft-linked models:
 - VTT EMM: electricity market model for the Nordic market area
 - TIAM/TIMES: integrated energy system model

Currently, a new modelling and analysis framework to analyse up to 100% renewable energy systems is being developed and tested, including the above toolbox and other models for dynamic process simulation of regions/districts, for robust decision making, and for business analysis of new flexible energy systems. From the experiences at VTT, soft-linkage of several models is the preferred option to address flexibility, given the effort required by other approaches. Besides that, they have found that flexibility is not the only constraint to the integration of renewable energy sources in energy systems: another important limiting factors are the consideration of constraints on the availability of resources (for instance, lack of critical materials may significantly constraint installed

capacity derived from TIMES-based projections by 2050), and the availability and ability to handle data for the models.

Mr. T. Kober (Energy Research Centre), focused on the **"Experiences of modelling intermittent renewable energy"** (section 3.2.2) using the models TIMES PanEU, COMPETES, and E2M2s. COMPETES is an electricity market model with a comprehensive database behind (capacity factors from the SODA and TradeWind databases, part load efficiencies from TSOs, etc.), while E2M2s is a stochastic power generation model. One way of addressing flexibility is by coupling the energy system model TIMES PanEU with E2MS by transferring electricity system parameters (e.g. wind capacity credit). Flexibility may also be tackled directly in TIMES by introducing a high number of time slices which even could contain time slices representing 'extreme' system operation conditions. The drawbacks of this approach are that the running time increases with the number of time slices, and that more data need to be identified for each new time slice. The conclusions of this presentation are that i) coupling is valid, indeed crucial, for improving analyses, but soft-linking is preferred to model integration, given the features and complexity of the models to couple, ii) TIMES offers a right framework to address flexibility, iii) there is a trade-off between infrastructure investments and system flexibility that must be incorporated in the models.

The presentation on **"Increasing the level of operational detail in long-term energy system models"** (section 3.2.3) by Mr. K. Poncelet, University of Leuven, began from the fact that the importance of the level of temporal and technical detail used in long-term energy-system planning models increases with the share of intermittent renewable energy generation. This level of modelling detail impacts the main results obtained by this group of models, such as projections for primary fuel consumption, greenhouse gas emissions and costs. To deduce qualitative policy advice, there is a need for a higher level of detail in the energy-system planning models at hand. However, a drastic increase of the level of detail cannot be realized due to computational restrictions. Thus, the key is to determine the required level of detail.

Although the importance of the temporal resolution is stressed, the focus in this presentation lies on the techno-economic operational detail, both on plant level (e.g., ramping rate restrictions, minimum up and down times) and system level (e.g., operating reserve requirements, minimum synchronous capacity).. It is clear that TIMES alone, when it is used without special attention for operational constraints, is not able to provide accurate results. Therefore, different approaches to increase the operational detail are currently being explored. Here, we can distinguish between directly integrating additional detail into the planning model ("direct integration"), and soft-linking the planning model to operational models. Soft-linking of two models may decrease computational costs, but implies handling a planning and an operational model. Furthermore, the question of which information and how this information is fed back from the operational model to the planning model needs to be addressed. Finally, this iterative approach has the drawback that convergence might not be reached, and optimality cannot be guaranteed. On the other hand, direct integration of operational aspects into an energy-system planning model has the advantage of having to develop and maintain a single model. However, this will come at the expense of increasing computational needs.. To limit the computational cost, this level of techno-economic detail is often integrated in a highly stylized manner. These highly stylized constraints are often not validated, or only based on historical data. As a result, this approach cannot simply be extrapolated to systems with a very high share of

VRE. To obtain a generally applicable set of operational constraints, it is essential to identify which constraints (e.g. ramping rate restrictions, minimum stable generation level, start-up related costs) strongly influence results (and must be incorporated into the model) and which constraints can be omitted. In a second step, the impact of reformulating (e.g., relaxing integer variables) the most critical constraints with the goal to reduce the computational cost must be analysed. Preliminary results indicate the importance of operating reserve requirements and maintenance scheduling. Furthermore, the impact of dynamic constraints (ramping restrictions, minimum up and down times) seems to be limited. Finally, relaxing integer variables seems to have little effect on results, while simultaneously strongly reducing the computational cost. However, it is very difficult to generalise these results, which hold for a specific single-country model, and are strongly dependent on the assumptions made about the technological parameters and the lay-out of the generation system.

Mr. W Nijs and A. Zucker (JRC-IET) concluded this session with a presentation on **"Flexibility in JRC-EU-TIMES and Dispa-SET"** (section 3.2.4). They showed the latest developments at the IET in order to improve the JRC-EU-TIMES and Dispa-SET models, a European-wide unit commitment and dispatch model designed to analyse flexibility and storage-related issues. The presentation included some illustrative results from JRC-EU-TIMES and explained the current coverage of flexibility needs in this model. As regards Dispa-SET, the presentation highlighted its recent improvements and the different options considered (coupling or further development of JRC-EU-TIMES), the current status of the model, and the planned extensions to be carried out during 2015.

Session 3: modelling the integration of high shares of variable energy sources

Ms. A. Miketa (International Renewable Energy Agency) opened this session focusing her intervention on **"Renewable energy options and strategies in energy plans"** (section 3.3.1). One of the main items in IRENA's work programme focuses on energy transition planning, in which renewable energy sources are becoming more and more relevant. IRENA consolidated methodologies supporting energy planning span different time and spatial scales, including grid stability studies with a shorter-time horizon and capacity expansion planning with a longer-time horizon in the context of developing countries. IRENA developed its own tools for African member states supporting the development of energy master plans. As regards flexibility, the AVRIL project (Addressing Variable Renewables in Long-term energy planning) looks into concerns on power system reliability linked with long-term goals of a high share of renewable energy. Such concern may not be justified and may be strongly linked with knowledge gaps and communication problems. In order to bridge the gaps between policy makers, TSOs, and modellers, the AVRIL project aims at assessing the short-term issues related to variable energy sources that are relevant for long-term policy making, and also at transferring existing experience and knowledge to developing countries and contexts. The presentation also included an introduction to several of the tools and resources available from IRENA, such as the renewable cost database or the global atlas for renewable energy.

In his presentation, **"Economic aspects of renewable energy sources"** (section 3.3.2), Mr. L Hirth (Postdam Institute for Climate Research) explained the economic implications derived from the intermittent nature of the main renewable energy sources. Although typically there is a single price for electricity in each country (although that is not the case in some countries, e.g. Sweden) , electricity generation varies across time, lead-time, and regions, which implies that the market value and the costs of electricity differ as well

across those scales. Using concepts such as levelised cost of electricity (LCOE) or grid parity ignoring the heterogeneity of electricity in energy models can lead to wrong conclusions since the optimal solutions derived from models rely on the correct estimation of the equilibrium between costs and values. Using better metrics such as "system LCOE" would provide better insights. From the analyses carried out by PIK, the results obtained from a model differ significantly depending on how the costs are calculated (assuming full or partial load). These studies conclude that balancing costs are not significant in comparison with profile costs. Costs are not due mostly to ramping or cycling; therefore those constraints could be simplified in models. At high penetration levels of renewable sources, the price of electricity decreases (therefore reducing also the market value of renewable energy sources, which are not able to make as much profits as in cases of lower penetration rates), and the capacity factor of conventional plants decrease while their capital costs increase. The optimal share of renewables is derived from balancing those factors, as well as from considering the variability of the renewable sources. Crucially, this assumes that the all externalities (positive and negative) are accurately reflected in costs and prices.

The third presentation, "**Simplified flexibility parameters for evaluating renewable integration**" (section 3.3.3) by Mr. P. Denholm (National Renewable Energy Laboratory), described the suite of models available at NREL (such as ReEDS for capacity planning, or PLEXOS and FESTIV for detailed power system modelling). The modelling analyses carried out at NREL conclude that there is a trade-off between chronology and simplicity. Simplified flexibility parameters reduce model complexity and solving times. Other modelling techniques, such as removing cycling costs from the objective function, may lead to lower running times while preserving the quality of the results and validity of the conclusions. Time series analysis is needed for flexibility assessment, but not necessarily chronological. However, chronological simulation closer to real-time may become increasingly relevant for simulating demand response, energy storage, or prices.

In his presentation, "**Role of storage in decarbonised electricity systems**" (section 3.3.4), Mr. U. Remme (International Energy Agency) described the modelling approaches and results of the latest IEA's Energy Technologies Perspectives exercise carried out with the ETP-TIMES model. This is a 32 time slice global model with 28 regions, coupled to a linear dispatch model. It pays particular attention to the link between the electricity and heat sectors. The main conclusion from comparing different modelling approaches is that the influence of operational constraints depends on the status of the electricity system (more relevant in near-term systems with large amounts of sunk capacity compared to systems with larger amounts of new or replacement capacity needs) existence of capacity and the degree of penetration of variable renewable energy sources. Operational constraints are important in order to have good estimates of curtailment and storage options. Moreover, it is difficult to accurately capture flexibility offered by interconnection in energy system models such as ETP-TIMES, with a low level of spatial resolution, and assuming a copper plate system within the individual model regions.

The presentation "**Integrating renewable energies - estimating needs for flexibility, competition of technologies, and the impact of grid extensions**" (section 3.3.5), by Mr. F. Borggreffe (German Aerospace Centre) introduced DLR's REMix model. This model is based on very detailed estimations of solar, wind, and hydro potentials. It considers demand side management by means of load shifting and load shedding for different types of consumers. The main conclusion from this model is that grid expansion and thermal

storage seem to have the highest potential for increasing flexibility, which would suggest the need to dedicate effort to improving modelling of the heat sector.

The last presentation of this session was given by Mr. G. Giannakidis (Centre for Renewable Energy Sources), who explained the **"Use of residual load curves to study the high penetration of renewables in TIMES-Greece"** (section 3.3.6). This new approach, designed to deal with flexibility in TIMES-like models, relies on ProPSim, a stochastic tool that determines the peak-load and balancing capacities needed based on residual load duration curves. TIMES-Greece generates for each time slice time-series that are fed into ProPSim, which in turn determines minimum storage and dispatchable capacities depending on the characteristics of the residual load curve. These two constraints are then fed back into the model. TIMES-Greece is used in combination with WASP and PSS/E.

Due to the time constraints, it was not possible to accommodate in this session the presentation by Mr. Zakir Hussain Rather (Electricity Research Centre, University College Dublin) on **"Short Term Flexibility Issues in Large Scale Wind Integrated Power System"**. This contribution discussed the issues of flexibility on short time scale in variable generation (VG) dominated power system. Though there has been some level of inherent flexibility developed over the course of time in traditional power systems, requirement of adequate flexibility in large scale VG integrated systems has become significantly more important in order to maintain secure and reliable operation of such systems. Flexibility requirements for large scale VG integrated systems can be broadly divided in two categories: i) short time scale flexibility requirements and ii) longer time scale flexibility requirements. The paradigm shift from conventional generator based power system to VG based system brings various technical challenges at short time scale of operation. Some of the significant short time scale issues can be summarised as:

- Diminishing inertia (synchronous mass) and ROCOF issues.
- Fast Frequency control?
- Voltage Stability/Dynamic Reactive Power/Short circuit power issue.
- Ancillary services/reserves.

Diminishing synchronous mass (Inertia) at higher penetration levels has significant implications on rate of change of frequency (ROCOF). In addition to concerns of reliability of generators, more vulnerability to higher frequency nadirs, higher ROCOF values also pose significant challenges to ROCOF triggered protection philosophy especially at distribution level which accommodates major share of VG. Various operational strategies (operational measures, demand response etc.) and infrastructure investment (new and refurbished synchronous condensers, storage, synthetic inertia from wind turbines/HVDC, strengthening of cross border interconnections) can improve the inertia level of the system. Similarly, system voltage control is becoming significantly challenging due to diminishing reactive power capability. Lack of adequate reactive power reserve especially dynamic reactive power reserve has significant implications during dynamic voltage events in the grid. Better utilisation of local resources like refurbishment of conventional power plants to synchronous condensers, installation of new infrastructure like FACTS devices (SVC), new synchronous condensers and other pragmatic measures can address such issues on short time scale of operation. Various countries (like Ireland, Denmark) are already experiencing short time scale flexibility issues in addition to longer time scale operational challenges. EirGrid and SONI (TSOs, All Ireland System) are considering range of new flexibility/Service products to accommodate higher targets of renewable penetration in secure and reliable manner.

Session 4: modelling flexibility needs in power systems.

This session was opened by Mr. A. Knaut (Institute of Energy Economics, at the University of Cologne, EWI), with the presentation "**Modelling flexibility needs in the European power system with DIMENSION and MORE**" (section 3.4.1). DIMENSION is a linear programming, long-term investment and dispatch model of the power system, while MORE focuses on short-term details. DIMENSION is fed with the EWI Power Plant Database, in which the main features of the power plants are defined as a function of commissioning dates and retrofit information. In order to account for geographical differences in the availability of renewable sources, the model considers weather regions with similar conditions, identified from a cluster analysis of wind speeds and solar radiations. Depending on the questions to be addressed with the model, the time slices may be configured by the users. DIMENSION is able to model flexibility options such as demand side management (by defining constraints representing the technical demand management potentials, availability, and timings at the process level) or flexible CCS units (by changing the rate of CO₂ capture these plants may be able of meeting peak demands at the expense of increasing emissions). A main conclusion from a recent study with DIMENSION is that the system naturally creates enough flexibility to cover peak load. Flexibility is therefore a by-product and is not binding in long term investment models. MORE is a unit commitment model that has a high temporal resolution and block sharp representation of the European power plant mix. Currently EWI is working on the modelling of intra-day markets and long-term uncertainty. Within the interdisciplinary project "Energy Transition and Climate Change", EWI is investigating the linkage between electricity markets and weather modelling.

The second presentation, "**Analyses with the power system model PERSEUS-NET-ESS/TS**" (section 3.4.2) by Ms. S. Babrowski (Karlsruhe Institute of Technology), described the PERSEUS-NET model. This is an LP-MIP, myopic, perfect competition and cost-minimising model of the German power system. It considers more than 400 nodes in the grid and all the plants above 100 MW (while the rest are clustered). The presentation discussed two analyses of: i) the cycling ability of thermal units, and ii) daily electricity storage systems. The analyses were based on the comparison of different model settings (defined by activating/deactivating different constraints, namely: cycling costs, minimum power, minimum up and down times, ramping cost-constraints, and start-up costs) and the use of different simplification techniques. The conclusions from these analyses are that a model taking into account start-up costs and load-change costs is the most appropriate for the consideration of cycling in models that depict whole countries and include many generation units of the same type. As regards storage, the analysis concludes that it becomes profitable when the share of renewable energy goes beyond 50%, and plays a key role easing grid congestion.

The final presentation, by Mr. G. Strbac (Imperial College London) focused on the "**Whole-system approach to assessing the value of flexible technologies and products in supporting cost-effective integration of renewables**" (section 3.4.3). Mr. Strbac began explaining the situation in the UK, where a continuous degradation in the utilisation of conventional assets has been observed due to the penetration of renewable energy sources, a trend that is expected to continue in the future. The features of the generation mix installed in the UK show that flexible technologies are expected to play a relevant role, especially if the electrification of the heat and transport sectors take place as expected. In that case, the value of flexibility could often become higher than the value of energy, and

the power system should evolve from asset redundancy to asset intelligence, that is, a better use of interconnections, demand response, storage, and flexible generation. These issues are being studied with the Whole-electricity System Investment Model (WeSIM). Key research questions addressed by this model are:

- What are the conflicts and synergies between flexible technologies?
- Is the market design efficient and able to cope with increasing shares of renewable generation?
- What are the conditions that may trigger the use of storage?
- What are the relations between operating patterns and technology degradation?

This presentation concluded that in order to analyse and understand flexibility it is necessary to improve the characterisation of the loads. The current "smart" business model is not profitable since it rewards production instead of flexibility, and the producers do not have real incentives to promote lower consumption. It would be desirable to see if the current MS-centric approach could be replaced by a better EU-wide approach.

1.3 Summary of discussions and conclusions

Many modelling teams analyse the transition from the current energy system to future systems with much higher shares of variable renewable energy sources, in order to provide policy-makers with recommendations on how to achieve climate change and energy targets. The models used for providing these recommendations need to address flexibility aspects.

Defining flexibility is a key issue that determines the modelling needs and the research questions that may be addressed. It is important to pay attention to physical and economic aspects, since both are relevant and related for obtaining useful and valid insights.

Since it is often very difficult to know all the current available approaches to address flexibility in energy system models, one of the main conclusions of the workshop is the need to develop some sort of mapping between flexibility needs and state-of-the-art model-based solutions or best practices for modelling it in the context of the evolving energy system. This mapping exercise could build on earlier research done in the FP7 project ATEsT²

There are several methodological approaches to modelling flexibility in energy systems: using heuristics, sector-specific highly detailed models, or combining models, but currently available models do not seem to be able of capturing flexibility issues properly, thus new holistic approaches are needed in energy system modelling. Using a suite of soft-linked tools to address complex questions, rather than relying on a single extremely complex model, would seem the most appropriate course of action. In this context, coupling large-size energy system models to sector-specific models seems to be the prevailing approach for analysing flexibility in real-sized energy systems.

However, model coupling is a complex and demanding undertaking that raises several technical issues. It is thus necessary to identify the critical assumptions affecting model results, providing an indication of what can be simplified and what can be modelled in a coarse manner, without compromising the accuracy and reliability of model results. Relevant in this context is also the issue of the "optimal" level and definition of time slices for energy system models, which needs to be researched in more depth. The participants

² <http://www.cres.gr/atest/>

also stressed the importance of continuing to improve run times through pre-solving, parallelisation, or other techniques. Exchanging experiences in this regard would be useful.

Besides the methodological problems of modelling, gathering data for the models is an issue on its own, and sometimes critical. The two main areas of improvement as regards data are related to the estimation of renewable energy potentials, and to the projection of future demand response and demand profiles. The improvement of these demand profiles is a priority action highlighted by the participants in the workshop, who agreed on preparing a working document on these issues.

Priority actions resulting from the discussions

- ***To undertake a systematic mapping of flexibility needs that have to be addressed and state-of-the-art model-based solutions or best practices for modelling it in the context of the evolving energy system.***
 - Coordinated by Mr. George Giannakidis (CRES),
 - With contributions from MM. Paul Denholm, Kris Poncelet, Joseph Dillon, Asami Miketa (IRENA), Vera Silva (EDF), Dominique Lafond (EDF), and Ignacio Hidalgo (JRC IET).
- ***To improve the representation of future demand response and demand profiles***
 - Coordinated by Mr. Frieder Borggreffe (DLR),
 - With inputs from MM. Goran Strbac (ICL), Zakir Rather (UCD), Paul Denholm (NREL) and Sylvain Quoilin (JRC IET).
- ***To organise (in Spring 2016) a follow-up workshop to review the progress of the two previous actions, and to consider the establishment of a regular forum to exchange and assess energy modelling approaches and exercises related to flexibility problems***
 - JRC

System flexibility may be imposed as well through regulation, but how to include regulation in models remains an open question. It is necessary to improve the representation of market and regulatory aspects so the models provide useful and well founded results.

As regards communication and exchange of information, the participants stressed the importance of using and sharing open source approaches and publicly available data whenever possible, in order to increase transparency and benchmarking models. Another question raised during the discussions was how to improve communication to policy-makers. This is an important issue that has already partially been addressed in several fora and could be further debated in dedicated workshops focused on science for policy-makers. The value of a systematic and comprehensive comparative analysis across models in terms of flexibility assumptions and outputs, along the line of the Energy Modelling Forum format, would be very valuable, even though going beyond the scope of the follow-up actions of the workshop.

Finally, given the relevance of the gas sector, it should be considered in more detail since it may become a significant limitation of the flexibility options available in the power sector. Similar considerations apply to other sectors, such as heat.

2 Introduction and background

Most analyses of the future European energy system conclude that in order to achieve energy and climate change policy goals it will be necessary to ramp up the use of renewable energy sources. The stochastic nature of those energies, together with other sources of short- and long-term uncertainty, have already significant impacts in energy systems operation and planning, and it is expected that future energy systems will be forced to become increasingly flexible in order to cope with these challenges. Therefore, policy makers need to consider issues such as the effects of intermittent energy sources on the reliability and adequacy of the energy system, the impacts of rules governing the curtailment or storage of energy, or how much backup dispatchable capacity may be required to guarantee that energy demand is safely met. Many of these questions are typically addressed by detailed models of the electric power sector with a high level of technological and temporal resolution, but without considering the rest of the energy system, although these issues affect other energy sectors as well. On the other hand, typical system-wide energy models cannot easily introduce such levels of detail without becoming excessively complex, and therefore recent research projects have attempted to couple energy system models with more detailed sectoral energy models and other ad-hoc auxiliary tools.

With this background in mind, the European Commission's Joint Research Centre – Institute for Energy and Transport organised an expert workshop on "Addressing flexibility in energy system models". The workshop was held in Petten, The Netherlands, on 4-5 December 2014, and brought together around 40 experts from modelling teams currently dealing with these problems from different perspectives, ranging from energy system-wide to detailed sectoral energy models, in order to share and compare modelling approaches and results, identifying gaps and potential solutions. The following broad topics were addressed:

- Modelling of the integration of high shares of variable renewable energy sources;
- Modelling of system flexibility needs and products and quantification of the value of ancillary services;
- Description and quantification of the uncertainty and variability of renewable energy sources potentials;
- Linkage of energy system models and sectoral energy models;
- Grid issues; and
- Energy storage.

The discussions took into account modelling and data-related methodological aspects, with their limitations and uncertainties, as well as possible alternatives to be implemented within energy system models. The workshop participants identified specific ideas and recommendations for improving our understanding of how to integrate flexibility in energy system models, as well as methodological approaches to improve the representation of different flexibility-related issues of interest in energy system models.

This JRC Scientific and Policy Report presents the contribution of workshop's participants (Section 3), and summarises the discussions and main conclusions of the workshop (Section 4).

3 Contributions

The workshop was opened by Mr S. Peteves, head of the Energy Technology Policy Outlook Unit at the JRC's Institute for Energy and Transport. After briefly introducing the JRC and the Institute, Mr Peteves highlighted the relevance of the workshop on two fronts: first, future energy systems will be forced to become increasingly flexible to cope with the challenges of integrating higher shares of renewable energy sources; and second, the increasing need for policy makers to consider issues such as how intermittent energy sources affect the reliability and adequacy of the energy system, the impacts of rules governing the curtailment or storage of energy, or how much backup dispatchable capacity may be required to guarantee that energy demand is safely met. With the question of how to address properly these issues in energy system models, the workshop began, organised around four main sessions:

- Introduction to flexibility issues and modelling-related challenges
- Addressing flexibility: linking energy system models and sectoral energy models
- Modelling the integration of high shares of renewable energy sources
- Modelling flexibility needs in power system models

All the abstracts and presentations are available through a dedicated link within the SETIS website³:

3.1 Session 1: introduction to flexibility issues and modelling-related challenges

3.1.1 Addressing flexibility in energy system models

Joseph Dillon, Damian Flynn, Paul Deane, Brian Ó Gallachóir, Eamonn Lannoye, Mark O'Malley, Zakir Rather

University College Dublin (UCD), University College Cork (UCC)

The planned research collaboration between University College Dublin and University College Cork outlined here will provide a unique research capacity that brings together significant research capacity in both power systems engineering and in energy systems modelling within a single partnership. The challenge of addressing flexibility in energy system models is discussed below drawing on the collective experience and expertise of both partners and represents the starting point for the partnership.

Energy systems models provide least cost solutions to meeting future energy needs. They generate full energy system pathways, selecting energy technologies for end use, transformation and energy supply technologies, to meet energy with the option of imposing constraints such as maximum carbon dioxide emissions, minimum renewable energy, maximum energy security etc. The combination of complexity and long optimisation horizon within energy system models poses great numerical challenges. The consequence of these challenges thus far has been to reduce the complexity, in terms of spatial resolution of the system being examined, or in terms of temporal resolution (daily or seasonal temporal resolution instead of hourly resolution) of the energy system model. While this makes the problems more computationally manageable, there are trade-offs in

³ <http://setis.ec.europa.eu/setis-deliverables/setis-workshops-hearings/international-workshop-addressing-flexibility-energy>

terms of precision and solution quality. The reduction in temporal resolution and technical detail has important implications for the electrical power system with levels of variable renewables and in particular in terms of system flexibility. Addressing these challenges requires a broad range of power and energy system expertise and skilful translation from specialised modelling activities to higher level models in combination with the capability to adapt the energy modelling paradigm accordingly and/or to develop brand new paradigms. The issues are discussed in more detail below.

3.1.1.1 Modelling of the integration of high shares of variable renewable energy sources

Modelling of the integration of high shares of variable renewable energy sources requires detailed power system modelling [3]. Within actual power system operation and planning, technical constraints (that are generally not considered in energy system models) such as minimum stable generation, ramps rates and minimum up and down times restrict the flexibility of power plant and can affect renewable energy curtailment and conventional plant emissions. Modelling in the absence of these technical constraints can give a false impression of the capability of the system to integrate renewables [4, 5]. It is also important to mention that in the context of energy system modelling, consideration of detailed modelling of each aspect may not be pragmatic given the complexity it will add to the overall system model. Therefore careful engineering trade-off between detailed modelling of different aspects and possibly insignificant compromise of accuracy seems to be a key issue for achieving energy system model with high share of renewables.

3.1.1.2 Modelling of system flexibility needs and products and quantification of the value of ancillary services

Correct system flexibility assessment is data intensive and requires detailed system modelling [6]. Thus, attempts have been made to better capture flexibility in energy system models and increase the temporal resolution of models such as TIMES to hourly resolution [7]; however this approach has limitations. The first is that as demonstrated by [8, 9] hourly resolution is not sufficient to capture important aspects of power system flexibility [10]. Equally it is important to model detailed technical characteristic of individual power plant as the aggregation for power plant capacity in energy system models leads to poor results [11]. Techniques have also been used to improve representation of variable electricity in large energy system models [12] however these techniques, while improving solutions, require exogenously forced parameters to capture the stochastic nature of wind and solar generation. Thus, within existing paradigms and modelling frameworks, it is challenging to capture the necessary level of detail within a large energy system model that is computationally tractable. To address this challenge, bespoke modelling tools [13] have been developed preserve the necessary modelling detail within computational limitations.

3.1.1.3 Linkage of energy system models and sectoral energy models (power system and others)

Multi model frameworks or soft-linking techniques to dedicated power system models, as described in [4] are also used to enhance power system results from energy system models in terms of flexibility. Methodologies have also been developed to link energy system models such as TIMES to housing stock model to better understand the implications of heating technologies choice for the residential sector. These techniques,

while useful have the limitation in that a number of models are required and that it can lead to sub optimal solutions.

3.1.1.4 Description and quantification of the uncertainty and variability of renewable energy sources potentials

Stochastic optimization techniques have been used to study the operational impacts of future high wind penetrations for the island of Ireland [14]. Stochastic unit commitment allows for the characterisation of uncertainty from variable renewable sources and the quantification of the impacts this has on power system operations (costs and emissions) and the increased requirements for flexibility. While stochastic optimisation is implemented in TIMES for the capacity expansion problem [15], the fundamental simplifications of the power system limit its usefulness in the assessment of power system flexibility.

3.1.1.5 Grid issues

In large energy system models such as TIMES, the transmission network is simplified as in [16]. The transmission network has important implications for system flexibility. Transmission congestion can limit the flexibility which can be realized in practice and transmission network will impact the scheduling process of power plant [17]. Depending on the nature of the power system (e.g. small isolated vs. large interconnected) various issues like lack of sufficient inertia, short circuit power, dynamic reactive power support, rate of change of frequency (ROCOF) issues, etc., tend to become bottlenecks in renewable energy integration and need to be modelled appropriately. It is often necessary to translate these complex grid issues which emanate from detailed power systems modelling into simplified constraints which can be implemented in energy system models. An example of this is the System non-Synchronous Penetration limit in Ireland [18]. The planned collaboration will enable the detailed power system modelling underway at UCD to be simplified and inform higher level energy system modelling activities.

3.1.1.6 Energy storage

Energy storage has benefits in terms of quick response times, management of uncertainty, and ability to reduce curtailment and congestion, however it may be difficult to justify economically in many systems until high levels of variable renewables are seen [19]. Energy storage will compete with other flexible resources such as interconnection, more efficient operation of existing thermal fleet of generators and demand side management. Detailed system modelling is required to understand and capture the challenges around energy storage benefits in term of flexibility, ancillary services [9] and uncertainty [20].

3.1.1.7 Conclusion

With the advent of greater computational power, efficient codes, novel numerical approaches, parallel computing and clever algorithmic constructs, there is now an opportunity to revisit the structure and architecture of energy system models and of long term planning models. Both University College Dublin and University College Cork are embarking on this in a pioneering partnership with colleagues in US and Europe [21] with a specific focus on Energy Systems Integration (ESI). The overall goal of this strategic partnership programme is to set up the technical and economic tool box that industries and government will need to build a well-functioning integrated energy system, nationally and internationally. ESI is by its nature multidisciplinary, tackling research question across multiple energy domains at multiple physical scales and time frames. The research

program includes strands that cover the necessary range of topics including control & forecasting, modelling and analysis, economics, finance & the consumer that together make up the energy system. There appears to be strong alignment between the objectives of this ambitious ESI Partnership and the goals of the upcoming workshop and we look forward to participating in this and future activities of the European Commission in this area.

3.1.2 Model coupling across scales

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3.1.2.1 Model coupling

Flexibility “is the ability of a system to cope with the short-term uncertainty of energy system variables” according to [22]. While in the past a high share of thermal power plants guaranteed a sufficient flexibility in the energy system, the increasing share of volatile renewable energy sources (RES) changes this paradigm. Those renewable energy sources create a new source of the above mentioned short-term uncertainties, defined as uncertainties appearing on an hourly time level. Due to this development uncertainties requiring flexibility occur along the complete supply chain in energy systems. They most often turn up due to forecast deviations (i.e. wind feed-in, electricity exchange, end-use demand) independent of the sector of the energy system. To handle those deviations a range of technological options are available, such as demand response, grid and storage expansion, excess capacity, curtailment of RES peak feed-in.

Several approaches to take those uncertainties and possible solutions into account in energy planning already exist. They range from rather simple ones with basic heuristics [23] to more complex ones which incorporate model coupling [24, 4] or specific indicators [25]. In this contribution I focus on coupling of models across scales including the systems perspective which is usually addressed with energy system models.

Typical energy system models are based on time slices. The number of time slices ranges from 6 to several hundreds [26]. While the number and characteristics of time slices are carefully chosen for each respective problem, it isn't possible to take short-term uncertainties like fluctuating electricity supply directly into account with time slices alone. One approach to deal with this challenge is applying more than one model and soft-linking them.

Linking an energy system model with an unit commitment model seems to be an obvious choice to address flexibility issues on the supply side. There are two principal ways to do so: unidirectional or iterative. In unidirectional model coupling the energy system model is employed to determine the power plant portfolio, the electricity demand as well as fuel and carbon prices of the target year and provides them for the unit commitment model. The latter calculates the utilization needed to ensure a secure power system operation [4]. The iterative model coupling additionally passes back full load hours of power plants as well as required storages to the energy system model and iterates this cycle until the results converge [27].

Thus the impact of the power plant utilization on power plant expansion can be integrated into the analysis. However, there is no guarantee that an iterative model coupling converges in a reasonable number of steps. Besides this, an extensive effort is required to adjust both models regarding their input data. Furthermore, integrating both model approaches in one is normally restricted due to limitations in computational capacities.

To address flexibility on the demand side or flexibility of cross-national energy transports other sectoral energy models need to be coupled with an energy system model. In [28] for example the load characteristics of electric vehicles are analysed in a separate model on a

quarter-hourly basis. This detailed sectoral model is coupled with a system model and provides the information needed to integrate the limits of the load shift potential of electric vehicles. Another example is described in [29], where the transport sector's demand response to an integration of road transport into the European emission trading system is coupled with an electricity system model. This coupling allows analysing additional constraints for the electricity system and its flexibility.

There are several additional starting-points to improve the existing approaches. These include for example the impact of a sub-hourly temporal resolution on flexibility requirements, and the impacts of volatile RES on the technical lifetime of thermal power plants. While flexibility has mostly been discussed in a national framework, there are good reasons to address it on the level of the European energy system. Model-based approaches on this level would have to account for the cross-national availability of flexibility and how this flexibility can be utilized.

3.1.3 Challenges of representing flexibility in energy system models

Vera Silva, Gregoire Prime, Timothee Hinchliffe, Dominique Lafond, Francois Rehulka, Miguel Lopez-Botet Zulueta

EDF R&D

3.1.3.1 Introduction

Most analyses of the future European energy system conclude that in order to achieve energy and climate change policy goals, a significant increase in renewable energy in the mix is required. As part of this the proportion of electricity generation from renewable energy is expected to increase from 20% in 2010 to 36% in 2020, 44 % in 2030 and 52% in 2050 [30]. Hydro generation is the largest contributor to renewable electricity in Europe but its potential is for the most part already exploited. This means that a significant part of the development of renewable electricity in the future will be based on variable generation such as wind and PV. These energies, however, like electricity demand, have a variable nature that is not perfectly predictable. As a consequence, short- and long-term variability and uncertainty in the electricity load-generation balancing is likely to increase in the future.

To cope with this increasing variability and uncertainty the electricity system will need to have sufficient flexibility⁴ to maintain the demand-generation balancing at all time. Therefore, energy and power system planning will need to address both the problem of capacity adequacy⁵ and flexibility.

The electricity system has always needed flexibility in order to handle demand and run of the river hydro generation variability and uncertainty as well as generation unplanned outages. The additional variability and uncertainty driven by wind and PV, however, will increase the needs and the solicitation of power system flexibility.

In spite of the fact that flexibility is mostly required at the operational time scales from minutes to day-ahead it needs to be considered from the planning stage. A system that has sufficient capacity to meet peak load is adequate but if this capacity is composed mostly by low flexible plants the system can experience problems for handling demand and generation variability. As a consequence, the representation of flexibility at the energy and power systems planning stage will help to deliver a system that can handle this variability in a cost effective fashion.

3.1.3.2 Electricity system model integration to energy systems models

Nowadays, electricity systems planning tools include a detailed representation of the power system often including the simulation of hourly (or lower) load generation balancing. The stochastic nature of demand and generation availability is commonly incorporated by performing simulations over a large number of climate and generation availability scenarios.

⁴ Flexibility is the ability of a system to adapt its operation to both predictable and unpredictable fluctuating conditions, either on the demand or generation side, at different time scales, within economical boundaries.

⁵ Adequacy is connected with the issues of investment decisions and is used as a measure of long term ability of a system to match demand and supply with an accepted level of risk. This is a measure that internalizes the stochastic fluctuations of the aggregate demand and supply.

Assessing the flexibility needs and adequacy will probably emerge as a new task in power and energy systems planning and different approaches and metrics to support this have been published over the last years. An example with the overall structure of the energy and electricity system planning process including production cost simulation and flexibility assessment is presented in the figure below.

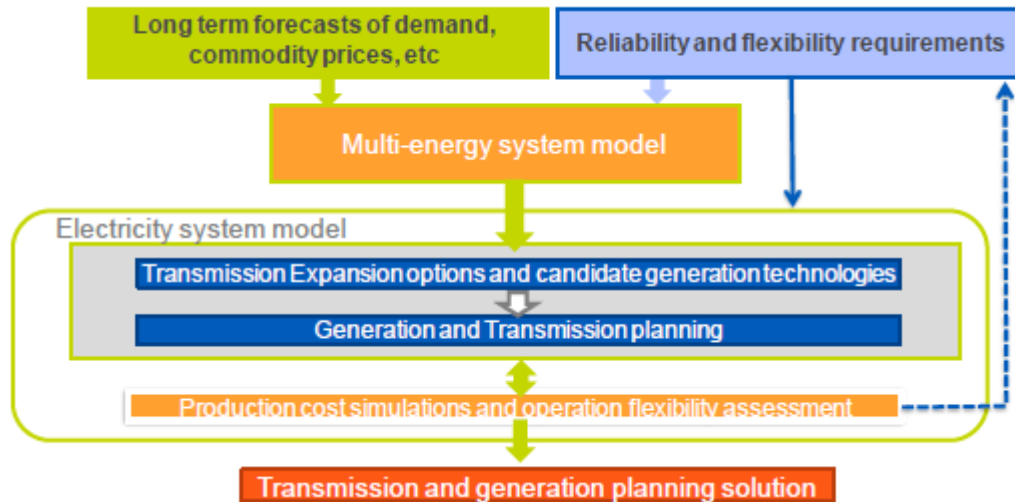


Figure 1: conceptual structure for the integration of the energy and electricity system models

Currently, the electricity system planning does not take into account the interaction with the remaining of the energy system. Furthermore, electricity planning tools that include more detailed simulations of system operation do not provide a multi-year vision of system development as the energy systems planning models do.

Energy system planning models are commonly TIMES type models and have a simplified representation of the power system. In order to obtain a more detailed picture of the energy system development and its interaction with the electricity system, two alternatives can be considered:

- Solving the energy system optimization with a granularity that permits capturing the electricity system flexibility needs (ex; hourly resolution) and including a more detailed representation of the electricity system constraints.
- Coupling of energy system models with power system simulation tools as part of a chain of tools in order to test the performance of the electricity system given the generation mix and network solution obtained from the energy systems model.

Preliminary studies at EDF R&D have shown that pursuing the first alternative by adding additional simulation time steps to a TIMES model (MADONE⁶), adding a peaking constraint and performing a multi-scenario optimization does not permit to obtain optimal investment strategies for the electricity system⁴⁷. Indeed when compared to the solutions for the generation mix obtained using an electricity planning tool, CONTINENTAL model with an investment loop [31, 32], our preliminary results show that peak capacity is overestimated

⁶ MADONE is a model developed by EDF R&D for internal use. It's a TIMES model of the EU27+NO+CH interconnected energy system over the 2005-2050 horizon with, in particular, a detailed representation of the economic potential of wind and solar technologies.

⁷ Conclusions obtained from tests with 288 time steps (corresponding to representative weeks), a peaking constraint to represent the maximum power and with a multi-scenario optimization with 4 scenarios.

and mid merit generation capacity is underestimated. Moreover, adding additional time-steps and further detail of the electricity system leads to an excessive computational burden.

The second alternative, for example based on coupling TIMES type models with electricity systems models seems the more widely used approach. For example in a recent study published by DG Energy a PRIMES model is coupled with PLEXOS to obtain a multi-annual vision of electricity generation investments. PLEXOS is in turn coupled with a power system simulation model DSIM in order to include a more detailed vision of the electricity system hourly dispatch and adjust transmission and generation to obtain the final electricity system expansion solution [32].

EDF R&D is exploring the possibility of coupling the MADONE model with CONTINENTAL model and its investment loop mostly with the objective of obtaining the renewable energy mix and its geographical distribution across Europe. Moreover, this will provide a multi-year vision of renewable development. The adaptation of the remaining electricity system generation mix and interconnections is obtained by the electricity planning tool as a second step by CONTINENTAL Model and its investment loop.

3.1.3.3 EDF R&D chain of tools to integrate near term flexibility into electricity systems planning

The assessment of the need for flexibility and its evolution with the increase of wind and PV installed capacity is a key step of the process of integrating flexibility in energy and electricity systems planning.

The need for enhancing system flexibility with the increase of variable generation is system specific since it depends on many parameters such as the flexibility of the existing mix and the demand variability, etc.

Approaches with different levels of complexity have been proposed to analyse power system flexibility. Examples of these are flexibility visualization charts, offline flexibility indexes and probabilistic tools [33]. Several publications proposed methods to address this problem within the power system context over the last years (see table below).

Table 1: overview of published approaches to perform the flexibility assessment of power systems in the short and long terms

Single optimization problem	Production cost models with investment loop	Production cost model with investment loop + flexibility assessment
Unit construction and commitment [33]	DSIM [3]	Plexos with an offline flexibility loop [3]
Maximizing future flexibility in electric generation portfolios [3]	EMMA, [34]	CONTINENTAL with Investment loop + FLEX ASSESSMENT [31]
MEPO-UC [1]		...

In order to address the problem of obtaining power system expansion solutions and respect both system adequacy and flexibility needs, EDF R&D developed a chain of power systems simulation tools. This chain of tools permits coupling a production cost model (CONTINENTAL Model) with an investment loop and a probabilistic tool that performs a detailed ex post flexibility assessment. This chain of tools is presented in the next figure.

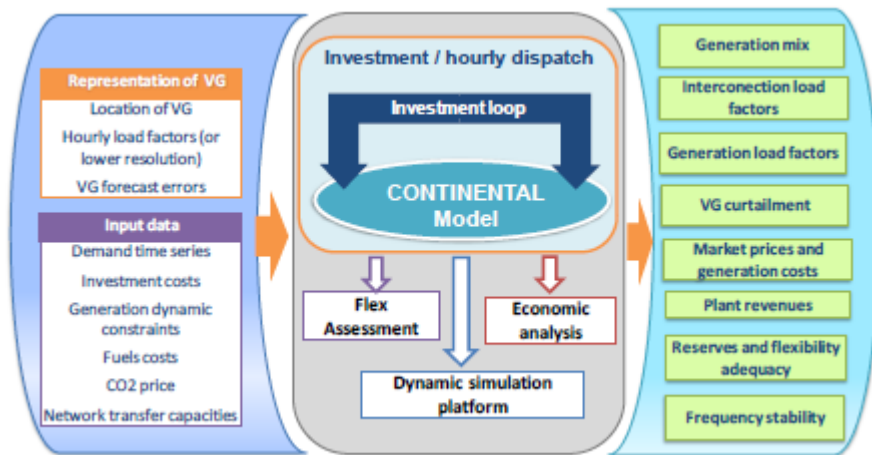


Figure 2: overview of the chain of tools used at EDF R&D to perform long term system development studies including short term flexibility and power system dynamics

In this chain, Flex Assessment is used to assess the ability of the investment and dispatch solutions provided by the planning tool to manage the uncertainty of the demand-generation balancing, for different time-scales [31]⁸ and all simulation time-steps (e.g. hourly). This tool assess whether the electricity system has sufficient flexibility to cope with increasing variability and uncertainty due to the increase of variable generation. With this analysis one can also identify the constraints and lead-times that lead to a flexibility deficit risk. More precisely, the items addressed are:

- Are the generation scheduling provided by these long term tools able to manage the short term unpredictable changes in net load?
- Which generation dynamic constraints (minimal up/down time, ramping up/down rate, etc.) should be included in generation planning tools?
- Is it necessary to include additional flexibility constraints, such as upward and downward ramping requirements in order to ensure flexibility adequacy?

The flexibility indicators obtained from Flex Assessment could be fed into the chain in order to guide the investment optimization to obtain a mix that is adequate and also sufficiently flexible.

This hierarchical approach presents some drawbacks since it can lead to suboptimal solutions. This problem has already been shown by other studies and for example a recent DG Energy study about the integration of renewable energy in Europe [32] presents a rather high peaking plant capacity since the electricity systems model adjusts any flexibility/transmission and adequacy gaps from PLEXOS by adding peak plants.

3.1.3.4 Conclusions

The problem of flexibility adequacy is becoming increasingly relevant and tools capable of handling it are important. This problem, however, should not be confused with [31] system adequacy and needs to be treated separately since it addresses different issues.

Significant work has been done in the identification of the impact of VG on different flexibility aspects but there is no unified view of the problem. Methods and tools with

⁸ The tool is able to consider hydro generation uncertainty, generation forced outages and failure to synchronize, demand, wind and PV forecast errors.

different levels of complexity and different simulation and data requirements have been proposed in the literature.

Among these, offline flexibility indicators are seen as very promising but they do not fully solve the problem since flexibility is a time-specific system characteristic.

Coupling of investment and operation models seems to be the state of the art practice for realistic size systems.

This notion of coupling of different models is currently being extended to multi-energy systems in order to make the problem of integrating power system flexibility needs into energy systems planning solution tractable.

Such hierarchical approaches have the advantage of obtaining a good representation of both the energy and the electricity system whilst rendering the problem tractable. The solutions obtained can be suboptimal with an excessive investment in peaking plants. Further work is thus required in order to improve the representation of the electricity system in the energy model in order to obtain a global solution (obtained from the chain of tools) that is closer to the optimum.

Renewable capacities development is based first of all on the geographic distribution of wind and sun resources which involves a necessary adaptation of the existing electrical and energy system (networks constraints) and drive additional costs. Thus further work would also require that the solutions obtained that respect global flexibility and adequacy requirements, also comply with local constraints of both the electricity and the energy system, still in a cost effective fashion.

3.1.4 The role for a buildings model

Fredrik Martinsson, Markus Wråke

IVL Swedish Environmental Research Institute

3.1.4.1 IVL objectives and activities

IVL is looking for input to our efforts to strengthen our capacity to do detailed modelling of regional and national level energy systems. To date we have focused our quantitative modelling on individual buildings or blocks of buildings, or on aggregated, long term scenarios. The knowledge gained in projects with a stronger focus on individual buildings or city districts (including nearly zero energy renovation and new built) will be used as input to a TIMES buildings model.

A specification for a flexible and detailed representation of the Swedish buildings sector in TIMES was made in a feasibility study by Martinsson et al. [35]. The new specification of the residential and service sector is characterized by a number of building archetypes in order to capture, for example, differences in demand profile over the year (low-energy buildings will have a different demand profile over the year compared with existing building stock), existing heating systems (at least a split between buildings with/without water-based distributions systems) and temperature zone (which will have impacts on demand profile, heat pump efficiency and supply profile of solar-based systems). Demand-side technologies include the possibility to define energy conservation measures (ECM) and possibly on-site energy generation from renewables. We propose to define a limited number of ECM-packages connected to different archetypes. The approach with archetypes has been used in several studies [36, 37].

With the approach of using various archetypes and packages (energy renovation and new built) as input to the model, see Figure 3, it will be possible to capture some of flexibility of the building sector. Building energy simulation runs, using software's as IDA-ICE and VIP-Energy, representing archetypes using different packages will capture the characteristics of the net energy service demand profile on ECM-packages. Parameters such as the optimal size of installed PV could for instance be dependent on the demand side management used in the building.

Costs for ECM-packages will also be given as input to the model. In this way the advantages for the whole energy system of a more flexible building sector can be quantified and be a part of pathways to a sustainable energy system.

3.1.4.2 General key challenges in our work on modelling future flexible energy systems, including the buildings model

Below is a list of challenges that IVL as novel actor on energy system modelling see as important topics to highlight. These aspects are also a part of our work with the buildings model in TIMES. We know that some of these topics are already looked at but could possibly be done in even more detail. An interesting review on modelling methods used in a large Swedish project looking at flexibility in energy system is described in [38]. The approach of using a set of three models, long-term energy scenario, detailed inter annual VRES simulation model and a grid capacity model seems attractive.

- General challenges

- How to integrate detailed analysis of the feasibility of a future energy system in an aggregated, long term scenario. E.g. run the entire modelling period in a higher resolution (time and space), or for selected years?
- If the latter, how to best integrate the results into the long term scenario?
- Uncertainty in variability and availability of supply (inter annual and beyond)
 - How to include a viable spatial resolution for the variable generation of variable on a national level?
 - How to include spatial limitations for roof top PV?
 - Spatial availability of biomass in a long term energy scenario?
 - Most efficient way to include weather statistics – and forecasts of changes in weather patterns – as model input?
 - How to best represent load following constraints in TIMES?
- Uncertainty in demand patterns
 - How to include the potential for demand side management (DSM) and load shedding on a large scale level?
 - What is the best way to include energy storage and multiple building heating systems and the optimization used on a local level in a larger energy system model?
 - Which new data sources are available (smart meters, social media, apps), and how can they be used to inform modelling?
 - How to include the change in energy demand profile due to non-behaviour aspects: energy efficiency measures, energy storage technologies, multiple heating technologies?
- System integration - opportunities and challenges of decentralized energy systems
 - How to model the impact that decentralised variable generation and self-consumption has on investments needed in infrastructure (grid, generation, ICT)?
 - How to include grid capacity limitation, curtailment, congestion and the possibility to use VRES as regulation?
- Communication
 - What is the most efficient way to do sensitivity analysis (Montecarlo analysis, etc.)?
 - What is the best way to communicate uncertainties in the results to decision makers without losing their attention?

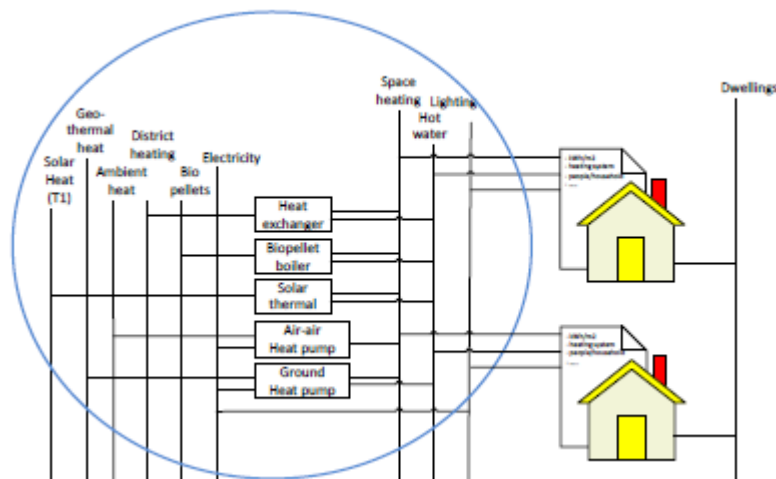


Figure 3: main structure of the residential sector (previous structure in TIMES-SE inside blue line)

3.2 Session 2: addressing flexibility – linking system-wide energy models and sector-specific energy models

3.2.1 Holistic approaches in addressing flexibility in energy system modelling

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3.2.1.1 Introduction

Future energy systems will likely be a complex combination of centralized and decentralized energy production with a wide variety of energy resources and new energy technologies. When variable renewable energy generation, especially from wind power and PV, new technical and market based solutions are required at all levels of the energy system to economically integrate the increasing variability and uncertainty. Electricity consumers are becoming more important but harnessing the flexibility in the demand side is a complicated and multidisciplinary issue. To adequately analyse and mitigate the impact of increasing shares of variable generation in the energy system, the existing energy system analysis and modelling methodologies need to be improved at all levels including frequency and voltage stability studies, unit commitment and economic dispatch tools, regional planning models and global integrated assessment models [3, 5].

A central question to be modelled and analysed is the value of flexibility, i.e. what is the value of flexible generation, flexible demand, and other flexibility options, such as energy storages, and/or combination of these options. The value of flexibility should be considered in different operational time scales, in different geographic regions, and in different market regions. The distribution of the value of flexibility to the different participants in energy systems is also an important question.

In modern open power markets, especially in energy-only markets, the most important market indicator is the spot price but energy market models have difficulty to blend different economical approaches. Social welfare is a tool for assessment of societal desirability of different competing measures and solutions such as flexibility possibilities, for example, whereas spot market models give the reference price for individual investments, where in turn long-term and short-term marginal cost models have a bit different approaches. End-users make their decisions in a totally different environment, based on business economics, and including significant other aspects such as distribution costs and taxes. If we want to assess the value or usability of demand side management (DSM), we have to use several kinds of model approaches to be able to estimate it from all angles, e.g. society, system, utility, network, end-user.

3.2.1.2 VTT's toolbox in addressing flexibility in energy system modelling

A more integrated view of future energy systems is enabled by integration of different simulation and optimization models operating at different time domains and with different sectoral and/or geographic coverage. On the other hand, new technical and market based solutions need to be considered. At VTT, an emphasis has been put on both technology development and energy system model development. We have already integrated generation planning, stochastic unit commitment and dispatch as well as load flow models into one package capable of iterative analysis. The models contain a wide variety of

possible sources of flexibility including many kinds of demand response and storages, more flexible conventional power plants, district heating and transport. The modelling approaches include Balmorel and Wilmar energy system modelling, electricity market modelling with VTT Electricity Market Model (VTT EMM), and power system modelling with PSS [39]. The primary focus is in Nordic and Finnish energy system modelling. The next step will include integration of TIMES VTT modelling, which will ensure more holistic analysis covering the whole energy systems and with larger geographical scope.

Large partial equilibrium energy system models, such as TIMES, facilitate the modelling of many aspects related to variable electricity generation, albeit often in a rather coarse way. For each technology, the estimated capacity credit parameters reflect the ability to meet the peak demand in each time slice. Various energy storage technologies can be modelled both on the seasonal and diurnal levels as well on the inter-period level. The total variation in the residual load (after subtracting non-dispatchable generation) can be taken into account in the required amount of energy storage and additional reserve capacity, by introducing appropriate constraints for each time slice. Ramping constraints and minimum operation levels can also be modelled for each technology. Moreover, the stochastic programming option is available in TIMES, but as it has been implemented via equivalent deterministic problems, applying it for the modelling of variable generation may easily become intractable due to the increase in problem size. Expanding the connections between grids will likely be needed when high amounts of variable generation are introduced in the system. TIMES model provides facilities for the modelling of both inter-regional and intra-regional electricity grids, and linear DC power flows [15, 16]. Smart grids are also likely to make consumers more responsive to higher energy costs, and this can be modelled by adjusting the price elasticities. Possibilities for consumer load shifting can either be simulated by using the time slice storage modelling facilities, or by introducing dedicated demand shifting equations. TIMES VTT modelling exercises have included modelling of energy storages, smart grids and smart energy systems, which have showed that TIMES modelling would benefit from integrated assessments with market models and energy system models with larger variety of possible sources of flexibility, like in Balmorel and Wilmar models [40]

3.2.1.3 Modelling of new technical and market based solutions for flexibility

Large-scale demand response and energy conversion could also be provided by power-to-gas technology. Produced natural gas can then be used for power and heat generation or for transportation. Different business cases can be presented where the economic attractiveness varies. The topic is actively studied at VTT and gas sector is currently integrated into power system models.

Solar thermal energy is not profitable at the moment in Finnish conditions. However, for reasons of self-sufficiency and environmental motivation it is gaining some momentum. In cases of large installations in one area, it may be wise to use the local district heating network, if available, as storage. Such loads should be taken into account by the district heating network operator when scheduling the local CHP plants.

Heat pumps are quickly becoming an important method of heating in many countries and there are policies to encourage their installation. They can both produce renewable energy and act as demand response due to the natural (building mass) and artificial heat storages. There is not much experience of the use of heat pumps for demand response and

therefore also technical solutions need more development. In some cases large heat pumps are suitable for producing district heat and can profitably provide ancillary services.

As the increase in electricity from intermittent renewables is a necessity, we have to have a clear picture of the costs to the system, and the costs include remuneration for new and much needed flexibility. The base assumption would be to increase reserve power such as, for example, gas motors or turbines with or without combine cycles as well as required network quality additions. Managing variable production is not a technological problem, per se, but a minimum cost problem. We want the most economical solution and ways to have the market implement it. The nowadays energy-only market structure itself doesn't offer sufficient remuneration for most flexibility actions, so remunerations have to be sought in auxiliary markets, e.g. primary, secondary or tertiary reserves, related to system operations. However, if we tie certain flexibility to a specified task, e.g. secondary reserves, it will not be available for other types of flexibility needs, e.g. spot or balancing market. We not only need models, we also need market models.

Flexibility can be used for system short-term stability and quality, e.g. frequency control, as well as for system reserves, short or long term balancing of the market, and as an active participant for example on the spot market. All flexibility options are therefore not equally usable, but differ according to inherent functionality. Variable RES give rise to different demands on flexibility, all from local distribution networks to transmission networks, system operations, and market integrations.

3.2.2 Experiences of modelling of intermittent renewable energy

Tom Kober

ECN

The share of renewable energy (RE) of gross final energy consumption in the EU-28 has increased from 2004 by more than two thirds reaching 14 % in 2012 on average [41]. The contribution of RE for electricity supply is even higher with 24 % of the EU-28's gross electricity consumption in 2012. Electricity generation from intermittent RE sources has increased substantially with 70 TWh for solar and 150 TWh for wind in the period 2004 to 2012, which represents for the aggregate of both a growth by factor 5. A future increase of the contribution of RE in Europe, as foreseen by European legislation on energy and environment, imposes various challenges to provide a sustainable energy system. Careful energy planning and decision support for policy makers with appropriate assessment tools will be essential to establish an adequate policy framework. Since modelling of wind and solar electricity production a spatial detailed model approach with a high time resolution is desirable and due to the complexity of the energy system it is hardly possible to capture all aspects of a large-scale integration of intermittent RE in an energy system model at once. Combining models will be essential to use the strength of each particular model and to provide an analysis at reasonable effort. Energy system models cover all entities of the energy system (producers and consumers, markets and policy framework), and hence they are well suited to represent the central assessment tool for a long-term analysis, while being complemented with data from other models/tools, such as power dispatch models, electricity market models and tools for investigating social aspects.

In this regard the linkage of the electricity market model E2M2s with the European TIMES energy system model TIMES PanEU (see [42] and [43]) has proven to provide valuable enhancement of the energy system model with respect to its parameterization of RE technology. E2M2s is a fundamental model for the German electricity market with stochastic treatment of intermittent RE production. It optimizes the future power plant operation for a long-term horizon until 2030 taking into consideration investments in new technology to cover energy demand but also to ensure a stable system operation, including back-up capacity for wind and solar technology for instance. The model entails technology-specific parameters that describe the operational flexibility and costs of units, such as ramp up and ramp down costs. In E2M2s one year is represented with 144 typical hours, hence it allows a much detailed modelling of intermittent RE than TIMES PanEU, which distinguishes 12 times slices per year. Both models were harmonized with respect to the assumptions on fuel prices, technology parameters (costs and performance data) and the production of electricity from RE (on annual level). The models were coupled via a soft link with bi-directional data exchange, which was set-up as follows:

- TIMES PanEU provides the electricity demand for Germany (reduced by non-dispatching production) and net exports to E2M2s
- E2M2s provides system capacity reserve demand and capacity credit for wind and solar technology

The capacity credit was introduced into TIMES PanEU via NCAP_PKCNT parameter, which describes the share of a technology's capacity available in the peak timeslice to cover peak electricity load. The calculations with E2M2s show that the capacity credit for wind energy technology in Germany decline from 10 % in 2010 to 3 % in 2030 if electricity generation from wind almost triples while total electricity generation is rather constant.

Additional to capacity credit parameters for solar and wind energy technology derived from the electricity market model, TIMES PanEU model contains information on how much electricity is to be generated from flexible generation and consumption sources, such as open cycle gas turbines, internal combustion engines without CHP and electricity storages at a certain production of electricity from intermittent RE. This information is introduced via user constraints in order to reflect the limited ability of large coal and nuclear power plants to be operated at lower capacity levels (minimum operating capacity) and comparably low load following rates. Introducing these operational aspects rather exogenously via user constraints kind was valuable, because due to the few time slices (12 in total for one year) the energy system model was not able to capture the associated effects endogenously. As a result of the introduction of these flexibility constraints, the model chooses, based on cost-optimization criteria, flexible generation technologies to support integration of intermittent RE. However, this approach does not feature a model-endogenous assessment of the trade-off between investments in improved flexibility of generation technologies and grid infrastructure investments. In the energy system model transmission grid infrastructure investments is coupled to the installed capacity of wind and solar technologies via cost-potential (capacity) curves with multiple steps.

The experiences for this energy system model reveal, that a linkage to an electricity market model offers various possibilities to improve RE technology parameters in the energy system model and to introduce aspects of system operation for the large-scale integration of intermittent RE in a stylized way via user constraints. This enables the energy system model to consider the most critical cost components for RE integration in the optimization and to assess RE deployment against other low-carbon energy generation technology or climate change mitigation options in other sectors. In conclusion, linking energy system models to dedicated electricity models is necessary to provide robust long-term energy technology systems analysis.

3.2.3 Increasing the level of operational detail in LT energy-system models

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3.2.3.1 Introduction

To limit the computational cost, long-term energy system planning models (e.g., MARKAL/TIMES) traditionally operate at a low temporal resolution and disregard detailed techno-economic operational constraints of the power system and individual power plants. Both model simplifications are shown to have a significant impact on the model results when analysing systems with high shares of intermittent renewables (IRES) [44]. For this reason, different attempts have been made to bridge the gap between planning and operational models, both in terms of the temporal resolution [45, 46] and the level of techno-economic detail [47, 48].

With respect to increasing the level of techno-economic detail in system planning models, distinct approaches either aim to soft-link the planning model to a detailed operational model (e.g., [49]), or to directly increase the level of techno-economic operational detail in the planning model by introducing additional constraints and variables (e.g., [47]). Due to computational limits, the additional constraints directly integrated in planning models are often very stylized. As such, these stylized constraints do not directly represent the physical processes, but rather aim to mimic the impact of these physical constraints on the generation scheduling. Moreover, these stylized representations of operational constraints are rarely verified. A thorough understanding of the electricity system and underlying processes is needed to calibrate these constraints to the specific energy system that is being studied and care is needed transferring these constraints to models for different energy systems.

In this regard, the aim of this work is to obtain and verify a less stylized, robust set of operational constraints for integration in planning models, taking into account computational restrictions. In a second stage, the selected set of operational constraints is integrated in the TIMES framework.

3.2.3.2 Methods

The starting point of this work is the clustered MILP unit commitment (UC) model presented in [50]. This UC model considers detailed operational constraints of power plants (minimum stable generation level, minimum up and down times, limited ramping rates, start-up costs, ramping costs and maintenance requirements) as well as system requirements (demand supply balance, operating reserve requirements).

In a first step, the impact of the different technical constraints on the model results and solving time are identified. This allows prioritizing the integration of different constraints (and corresponding variables). Second, the impact of relaxing integer variables is investigated. Verification of results of different sets of operational constraints and their respective formulation are verified by comparing to the full MILP UC model. The metrics used for verification are the errors on the total cost, the generation shares of the different technologies, the amount of IRES curtailment and the amount of non-served energy. To obtain a robust set and formulation of operational constraints, the analysis is carried out for electricity systems with varying levels of IRES penetration. Finally, following a trade-of

between accuracy and computational cost, a selected set and formulation of operational constraints is implemented in an investment planning model generated with TIMES.

3.2.3.3 Results

Results consist of:

- An analysis of the impact of specific operational constraints on the accuracy and the calculating time
- An analysis of the impact of relaxing specific integer variables on the accuracy and the calculating time
- An analysis of the robustness of different sets and formulations of operational constraints
- An efficient frontier of different sets and formulations of operational constraints (maximum accuracy with respect to a varying limit on the calculating time)

Based on these results, a specific set of operational constraints is selected and integrated into an investment planning model, and the impact of including these additional constraints is analysed.

3.2.3.4 Conclusions

At present, energy system planning models often contain highly stylized representations of operational constraints of power plants and the electricity system. Therefore, these stylized representations should be carefully calibrated to the analysed electricity system, and verification of the applied representation is required, but is often lacking. This work provides and verifies less stylized representations of operational constraints for integration in planning models. In a first step, key operational constraints are identified and the impact of relaxing integer variables is investigated. In a second step, the set and representation of constraints to be integrated in the planning model are determined following a trade-off between accuracy and computational cost. Finally, the impact of integrating this set of operational constraints into an investment planning model generated with the TIMES model generator is analysed.

3.2.4 Flexibility in JRC-EU-TIMES and Dispa-SET 2.0

Wouter Nijs, Andreas Zucker

European Commission, Joint Research Centre - Institute for Energy and Transport

The concluding presentation, "Flexibility in JRC-EU-TIMES and Dispa-SET" by Mr. W Nijs, showed the latest developments at the JRC Institute for Energy and Transport (IET) related to the continuous improvement of the JRC-EU-TIMES model [51] and development of a new version of Dispa-SET, a European-wide unit commitment and dispatch model designed to analyse power system flexibility and storage-related issues [52].

The presentation by Mr. Nijs explained the key characteristics of JRC-EU-TIMES, including some illustrative results (Figure 4 and Figure 5), and explained the approach of representing flexibility needs in this model and the way variable renewable energy sources, such as PV, are treated.

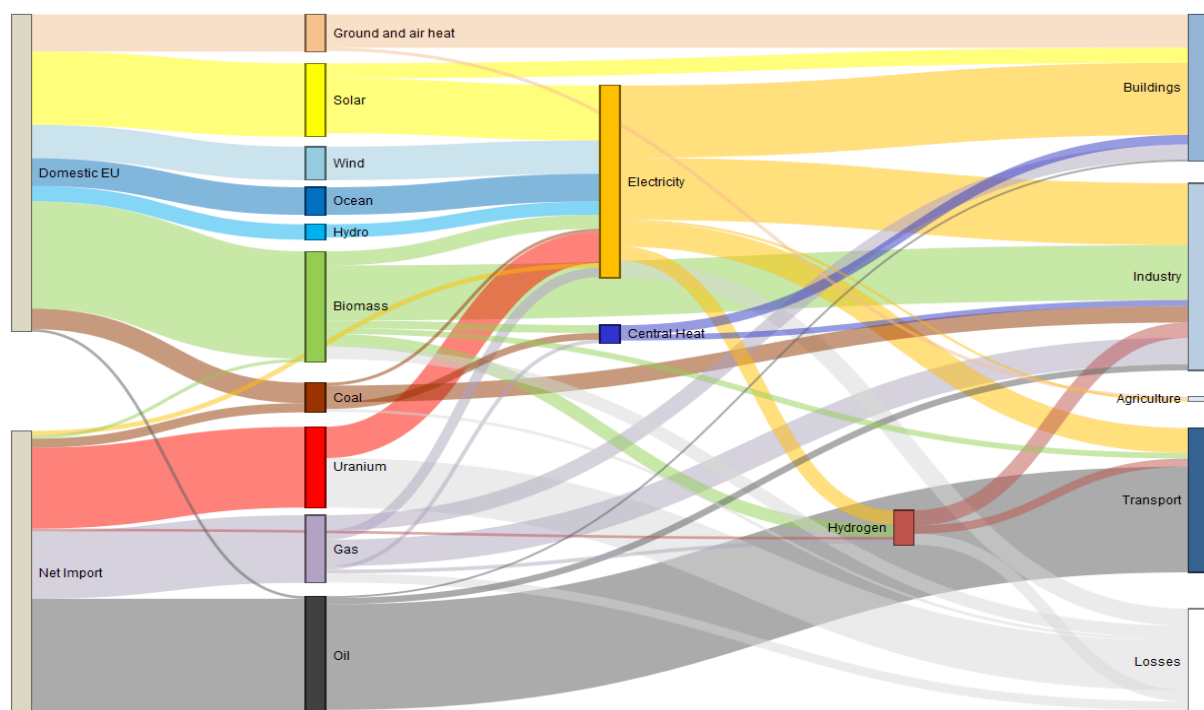


Figure 4: Sankey diagram - illustrative scenario of a low carbon EU energy system in 2050

The JRC-EU-TIMES model covers 70 exogenous demands for energy services across 5 demand sectors (agriculture, residential, commercial, industry, and transport). The model maximises the sum of the surplus of both producers and consumers. In a special case this is equivalent to minimising the total cost. Indeed, when demands for energy services are considered inelastic, thus insensitive to a price change, the JRC-EU-TIMES model minimises all discounted costs over the total modelling horizon period up to 2050.

Many scenarios that target an 80% reduction of the energy related CO₂ emissions have high shares of variable electricity generation. An important driver for this is the drop in projected installation costs of electricity generation from solar, wind and ocean energy. As large energy system models ignore the implications of variability, there is a tendency to "limit" these renewable sources in large energy system models. Very often a renewable potential is derived from other sources.

We presented in the workshop a methodology to improve the representation of high penetration of variable renewable electricity inside TIMES. By representing a possible excess of electricity in an explicit way, we allow the model to trade-off curtailment, storage or direct use in a sector outside the electricity sector. Indeed, a strength of JRC-EU-TIMES is that it can model the interaction between sectors (electricity, heat, transport, industrial fuel use, heating,...). The approach consists in using synthesised flexibility requirements for each time slice of JRC-EU-TIMES to parameterise this variable electricity. Parameterisation is the process of including in the energy system model parametric relations for representing variability with comparable results as an explicit modelling approach. The most important improvement is to force any possible excess variable electricity to be used by flexible demand (mainly heat related electricity appliances), to be curtailed, stored or converted into another carrier (e.g. production of hydrogen by electrolysis). The quantity of 'excess electricity' is derived from the time profiles of variable renewable electricity production and electricity demand.

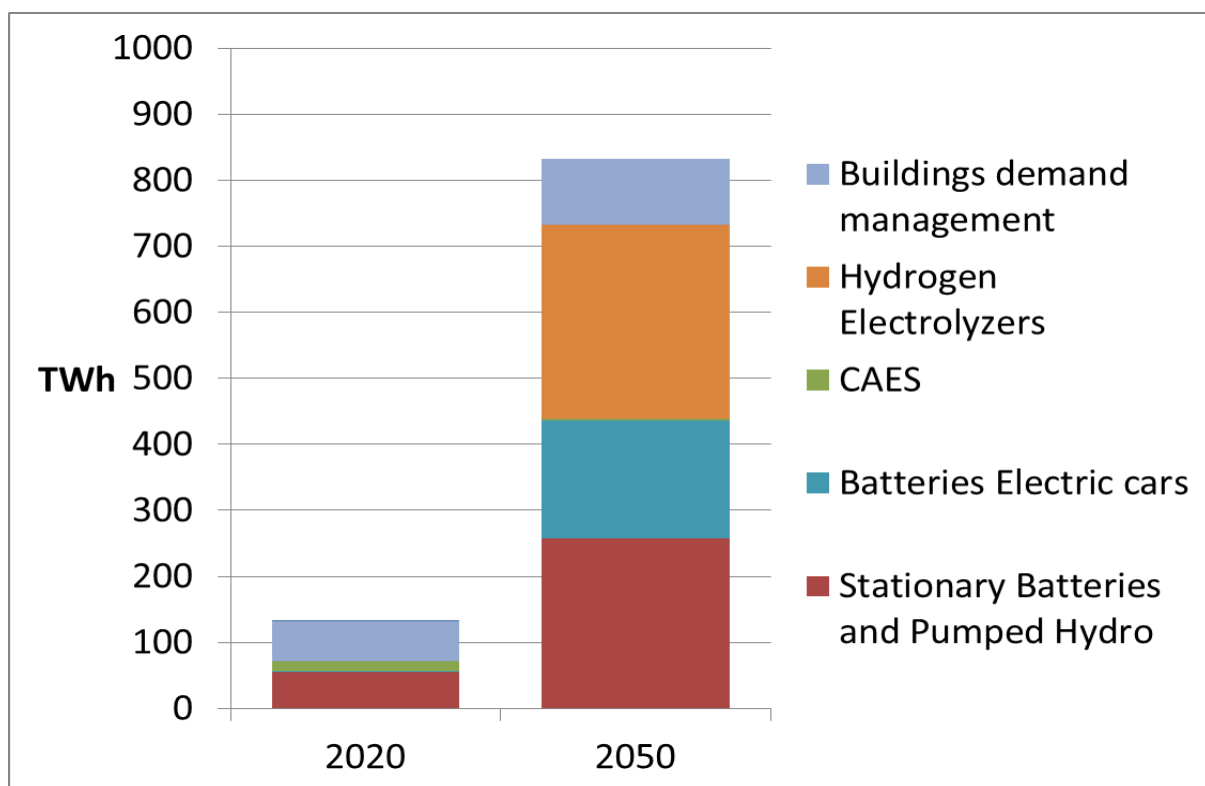


Figure 5: flexibility for storage and demand side management

The Dispa-SET model represents the short-term operation of the European power system with a high level of detail. This allows addressing questions related to the impact of increasing penetration of renewable energy sources as required for supporting European energy policy making. Dispa-SET is a unit commitment and dispatch model formulated as a tight and compact MIP. It minimises total system costs over a daily horizon, across units, markets and periods of fixed, variable (fuel and emissions), start-up, shut-down, transmission costs, and load shedding). The system is subject to hourly demand balances (day ahead, and up and down reserves), bounds on power output (minimum stable generation, previous status, installed capacity and availability factors), ramping constraints, minimum up and down times, and storage-related constraints (bounds on stored levels, pumping, discharge, inter-period storage balances). The model considers NTC-based market coupling, as well as options for emission limits, curtailment of intermittent

generation and load shedding. To illustrate the model capabilities, a simulation has been run using historical data for the case of Belgium. The comparison between the historical data and the simulation indicates a fairly good agreement. One important application of Dispa-SET is to validate the power plant portfolio as determined by JRC EU TIMES model.

The presentation concluded with an explanation of the current activities and the planned extensions of Dispa-SET to be carried out during 2015 and beyond. The next milestone will be the coverage of all EU member states. In the longer-term, some other envisaged improvements would be:

- The linkage with the JRC-EU-TIMES energy system model
- A review of the hydropower model representing non energy water usage water requirements, in particular in Southern Europe (to be translated into boundary conditions)
- The addition of stochastic features
- A review of the representation of reserve needs, distinguishing between different products found in European power systems(secondary and tertiary)
- The addition of a price formation mechanism and of a capacity planning module

3.3 Session 3: modelling the integration of high shares or variable renewable energy sources

3.3.1 Renewable energy options and strategies in energy plans

Asami Miketa

IRENA

3.3.1.1 Rational for the AVRIL project

Within IRENA's mandate to promote accelerated use of renewable energy for sustainable development, one priority area desired by the 138 member states of IRENA and thus reflected in IRENA's current work program is 'mainstreaming renewable energy options and strategies in energy plans'. In particular, there is a strong request to support developing countries to enhance the quality of power sector planning taking into account the renewable energy integration challenges and opportunities. As more developing countries wish to accelerate the deployment of renewable energy sources, policy makers in those countries are increasingly concerned about operational side of variable renewable energy (VRE) integration such as grid stability and curtailment experienced by those power systems that first moved towards higher RE shares. Ambitious renewable penetration targets in the power sector are often challenged by the system operators who are concerned that VRE may endanger the reliability of the power system. Questions then have been raised whether or not these shorter-term concerns need to be reflected in long-term policy making, and more specifically in the tools that support long-term decision making.

The ongoing IRENA project 'Addressing Variable Renewables in Long-term energy planning (AVRIL)' aims at (1) assessing the short-term operational characteristics relevant for the long-term (i.e., 20-30 year time horizon) policy making especially in the context of developing countries, and at (2) identifying pillars of a robust energy planning methodology that may be different from those suited to analyses energy systems primarily composed of conventional thermal plants and large hydro plants. One obstacle in achieving the objectives of AVRIL is different languages used by policy makers, system operators, and energy modellers. Through the dialogue with stakeholders, IRENA addresses the knowledge gaps that may exist hindering the communication among the three groups.

A vast knowledge exists on the impacts of VRE focus on energy systems of developed countries, especially in European and US context, where VRE deployment already reached high shares [53, 3, 54, 55, 56, 57, 58]. Other countries that start deploying VRE today can learn from these experiences and proceed to a more efficient manner of 'proactive planning', i.e. anticipating impacts of VRE and mitigating or resolving them beforehand. Furthermore, some system-specific properties of developing and transition countries may imply unique integration challenges and opportunities. The rapidly growing energy demand in e.g. China, Brazil or India allows a coordinated extension of grid capacities and flexible thermal plants, in parallel with VRE deployment, to reduce adverse impacts [57].

The three driving questions investigated under the AVRIL project are:

- What are the key impacts of VRE that need to be addressed in long-term energy planning in developing countries?
- How can the relevant VRE properties be addressed in long-term planning models?

- What are the key knowledge gaps?

At an IRENA expert workshop at this year's International Energy Workshop it was discussed that the impacts of VRE occur on different time scales in the range of seconds (system reliability) up to years (for system adequacy issues like estimating capacity credits). Since there is no single model that spans these time scales, it needs a complementing set of models that cover sufficient temporal and spatial resolution and scope. Their interplay need to be carefully worked out. Hard or soft linked models are valid options as well as unidirectional exogenous parameterizations. A typical approach is to start running a long-term capacity expansion model and then insert the resulting capacity mix of a representative year into a highly-resolved dispatch model to verify operational feasibility and economic parameters like operating hours of different plants. These results can then be fed back to derive new long-term results under consideration of operational constraints.

3.3.1.2 Impacts of VRE and planning methodologies

Initial assessment based on a literature review, expert workshops and interviews identified the following four impacts of VRE worth investigating for their relevance to the long-term energy system planning in developing countries:

- Variability requires the system to have backup capacity to meet the required generation adequacy while reducing the utilization of dispatchable plants
- Short-term variability and limited predictability require the system to be flexible to allow generation to continuously follow load (ramping capability, demand response, storage, curtailment)
- Inability to provide inertia or governor response may reduce system stability in the case of contingency
- Spatial dependency requires grid enhancement both in terms of quantity (grid extension) and quality (voltage control system) to provide needed network capacity and stability

Brief discussions that may constitute pillars of a robust energy planning methodology are provided below.

Generation adequacy is addressed by the reserve margin requirement, under which firm capacity needs to be identified. The capacity credit is a metric to define the 'firm' portion of VRE capacity, and it is highly site, technology, and system configuration specific [59]. Given the uncertainty over the location of RE projects, technology choice and system configuration in 20-30 year time horizon, simplified methodology needs to be taken. While some studies [60] provide overviews of capacity credit calculation methodologies from the point of data requirement and applied, and applied one to North African countries, others [61] use alternative GIS based approach.

To represent flexibility of a power system, a finer time resolution of a model may need to be applied to adequately account for the typical daily and seasonal supply variation of RE technologies to be represented in the model, so that the load-following capability of a system and ramping costs can be assessed. It is also worth mentioning that increased time resolution would require data on RE generation profile, ramping capability and associated costs at a same time resolution.

A dispatch model can be used to a snap shot assessment of flexibility-dispatchability of a given system, and to generate stylized operational constraints to be feeding into the capacity expansion model. One of the important recommendations from IRENA expert

workshop at this year's International Energy Workshop was soft-linking of a long-term capacity expansion model (with limited time resolution) and a dispatch model (one hour or higher time resolution). Deane et al. [4] demonstrates such soft-linking approach.

Limited predictability of RE power generation may increase the need for operation reserve, thus may incur extra costs. However, the forecasting methodologies are rapidly improving and cost implication on the future energy system in 20-30 years may be insignificant.

The need for maintaining sufficient inertia and governor response in the system may only be addressed by a separate study to look into a technical limit of inertia-less generators. Inertial response may not be considered crucial problems for VRE integration at the present levels of penetration seen around the world. However, it can be a challenge for small systems [62].

IRENA and DNV-GL currently undertake the assessment of RE related grid enhancement investment costs, sub-divided into conventional grid reinforcement on one hand, and smart grid and retrofit to allow back feeding for distribution network. The case studies for Germany, Morocco, Tonga, UAE, and Kazakhstan are being completed. Transmission investment need is assessed using the geographical information on the load centres and RE sites as well as specific costs for the transmission investment. At the distribution level, costs of network expansion as well as for control and protections are evaluated. The study will reveal the magnitude of the grid related costs associated with the RE integration.

3.3.2 Economic aspects of renewable energy sources

Lion Hirth

Neon, PIK

This paper discusses two related questions: To what extent, and why, is electricity a peculiar economic good? What is special about ‘variable’ renewable electricity sources, such as wind and solar power – and what isn’t?

In several parts of the world, today it is cheaper to generate electricity from wind power than from conventional power sources like coal-fired plants – and many observers expect wind turbine costs to continue to fall. It is widely believed that this cost advantage by itself implies that wind power is competitive (as a private investment option) or efficient (for society). However, this is not the case.

Inferring competitiveness from cost advantage would only be correct if the electricity that wind turbines produce was a perfect substitute of the electricity that coal plants produce – if electricity was a homogenous economic good. But, because it can hardly be stored, its price fluctuates, and hence it matters when electricity is generated. Wind turbines and coal plants produce at different moments in time, hence the value of their output is different. Physically, both technologies produce electrical energy – economically, they produce different goods.

The temporal heterogeneity of electricity – price differences between moments in time – has been acknowledged for a long time [63, 64, 65]. Yet, electricity is heterogeneous along two further dimensions: space – price differences between locations –, and lead-time between contract and delivery – price differences between day-ahead and real-time markets. Electricity from wind turbines and coal-fired plants is not only economically different because it is produced at different moments in time, but also because it is generated at different locations, and under different degrees of uncertainty and flexibility.

Heterogeneity has implications for economic assessments of power plant technologies, such as cost-benefit and competitiveness analyses. Ignoring value differences leads to biased estimates – and several tools that are used in practice for policy advice and decision support implicitly ignore these differences. Take the example of two commonly applied indicators, ‘grid parity’ and ‘levelised costs of electricity’ (LCOE), the discounted lifetime average generation costs per unit of energy (\$/MWh). Policy makers, analysts, and academics regularly compare different generation technologies, such as nuclear, coal, and wind power in terms of LCOE [66, 67, 68, 69, 70, 71, 72, 73, 74, 75]. These studies seem to suggest (at least many readers interpret them in this way) that low LCOE signals competitiveness. This reasoning implicitly assumes the value of output of all generators is identical – which is not the case. A second widely used indicator is ‘grid parity’, the point where generation costs drop below retail electricity prices. Some observers seem to believe that once a technology has reached grid parity, its deployment is economically efficient [76].

Not only these indicators, also multi-sector modelling often implicitly ignores electricity’s heterogeneity. Economists have for many years used calibrated macroeconomic multi-sector models for research and policy advice, starting with Leontief [77]. Today, ‘integrated assessment models’ (IAMs), sometimes based on computable general equilibrium (CGE) models, are an important tool for assessing climate policy and the role of renewables in

mitigating greenhouse gas emissions [67, 78, 79] Such models often represent the electricity sector with one single price, implicitly assuming homogeneity.

Heterogeneity is a feature of electricity as an economic good, and not a feature of a specific generation technology – but it has specific implications for certain groups of technology. Ignoring value differences when comparing technologies makes low-value technologies look better than they actually are. This often favours two classes of generators: conventional base-load generators relative to peak-load generators (base load bias); and, at high penetration rates, variable renewable energy sources (VRE), such as wind and solar power, relative to dispatchable generators (VRE bias). The marginal value (\$/MWh) of wind and solar power falls with their penetration rate and can become quite low at high penetration [80, 81, 82, 83, 84, 85, 86]. After years of rapid growth, VRE shares have reached 15% and more in several European and American power systems [87] [88] [89]. Given that much of this growth is financed with tax money, the valuation of VRE is of major public relevance.

3.3.3 Simplified flexibility parameters for evaluating renewable integration

Paul Denholm

National Renewable Energy Laboratory

3.3.3.1 Introduction

The trade-offs between computational burden and accuracy in electric-sector models are well documented, and become of greater concern with the introduction of variable generation (VG) technologies. Classic simplified approaches to capacity expansion modelling, such as the use of load-duration curves, are well-suited to systems that rely largely on conventional, dispatchable generation technologies such as coal and gas thermal power generators [90]. These approaches perform simple levelised cost of energy comparisons based on capital and operating costs and estimated capacity factors. No chronological simulations are required due to the dispatchable nature of the technologies. However these techniques are less suitable for VG technologies, such as wind and solar photovoltaic (PV). Because of this, there is a general desire to use chronological-based simulation, where one or more years of full simulation are performed in time increments of one hour or less [91]. Chronological simulations can (in theory) be incorporated into the objective function of the capacity expansion model, to estimate the least-cost mix of generation technologies under various operational and policy constraints [92]. In reality, solving a complete chronological dispatch, including unit commitment, dispatch, and power flow, is so computationally complex that incorporating detailed chronological simulations into capacity expansion models is often impractical [93]. Alternatively, chronological simulations can be used to “guide” simplifications often placed into capacity expansion models. For example, a large set of scenarios can be simulated and generate a “surface space” of solutions that determine such parameters as expected unit starts, reserve requirements, capacity credit, and renewable curtailment. The parametric solutions can be used in simplified capacity expansion models.

This approach is still limited by the complexity of state of the art unit-commitment models. Increased computational power has allowed the use of mixed-integer linear programs in electricity markets, increasing solution accuracy which is critically important for accurate market operations. However these models are still typically too complex for analysing hundreds or thousands of scenarios used to guide parametric analyses. For example, a single chronological simulation of the Eastern Interconnection of the United States, with hourly unit commitment, five minute dispatch, and DC optimal power flow, can require more than two months’ time (without parallelization) [94].

3.3.3.2 Simplified flexibility parameters

Because a major source of computational complexity is calculating the unit-commitment process, eliminating this step can greatly improve the ability to evaluate multiple scenarios, or the prospect of including detailed chronological simulations into the objective function of the capacity expansion problem. One proposed approach is to eliminate unit commitment of the existing thermal fleet, and simulate only a reduced-form system dispatch using simplified flexibility parameters for conventional generators. Additional conventional, renewable, or alternative generators (such as demand response or storage) can be modelled in more detail, as the computational complexity is dominated by the existing thermal fleet. This approach has been applied to simulations to estimate curtailment of renewable energy as a function of penetration [94, 95] System flexibility is

determined by two aggregated parameters of existing generation: minimum generation (turn-down) levels and ramp rates.

In this approach, net load (normal load minus wind and solar) is compared to the minimum generation levels and ramp rates of the existing thermal fleet, aggregating plants with similar costs (fuel type and efficiency). The minimum generation levels typically determine the overall system flexibility, and may vary depending on longer-duration unit commitment parameters. For example, an extended period of high wind allows for de-commitment of units that have longer start-up periods, which produces a lower minimum generation point. Initial validation of this approach has been performed using a full unit commitment model [96]. Accuracy of this approach appears to increase under higher renewable scenarios, as longer-start-time units typically retire, and are replaced by more flexible generators with shorter start times and less dependence on accuracy of the unit commitment parameters.

3.3.4 Role of storage in decarbonised electricity systems

Uwe Remme, Luis Munuera

International Energy Agency

The International Energy Agency (IEA) shows in its 2014 edition of Energy Technology Perspectives (ETP 2014) [97] that low-carbon electricity is the core for a sustainable electricity system, by not only reducing carbon dioxide (CO₂) emissions in the power sector, but also by enabling through increased electrification deep CO₂ reductions in industry, transport and buildings [97]. Variable renewable sources (i.e. solar photovoltaics (PV) and wind) are important in decarbonising electricity generation, but also pose challenges by increasing the flexibility needs of the entire electricity system. This paper is based on the 2 degree scenario (2DS) of ETP 2014 and discusses the role of electricity storage in the future electricity system in competition to other flexibility resources, notably demand response through electric vehicles (EVs) and thermal dispatchable generation. The model-based analysis, which links a global, long-term energy system model with a linear electricity dispatch model, illustrates that electricity storage is an important component for the integration of larger shares of variable renewables, but not the sole solution. Especially demand response, e.g. through “smart” charging of electric vehicles, could become an attractive flexibility option, drastically reducing the need for electricity storage.

Keywords: electricity system, variable renewables, electricity storage, demand response, dispatch modelling

3.3.4.1 Introduction

Almost 40% of global primary energy is used today to generate electricity, making electricity a core commodity in the energy system. Oil still dominates the global final energy mix with a share of 40%. Electricity comes only second with a share of 17% in the final energy mix, but its demand is rapidly increasing: worldwide electricity consumption per-capita more than doubled from 1263 kWh/cap in 1974 to 2933 kWh/cap in 2011, outpacing the growth in final oil or gas consumption. Most of this growth in electricity demand takes place in non-OECD countries, which accounted for more than 80% of the global electricity demand growth between 2001 and 2011.

Fossil energy carriers are still the primary fuel of choice to generate electricity, accounting for two-thirds in the global electricity mix. In the 2DS, this situation changes drastically by 2050: the share of renewable sources in the generation mix increases from 20% in 2011 to more than 60% by 2050, a six-fold increase in absolute terms (Figure 6).

Variable renewable sources (wind, solar PV, ocean energy), account for 15% to 50% of total electricity generation in the 2DS in 2050, depending on the region. At the same time, electricity starts to play an important role in the end-use sectors, notably in transport, where the global final electricity share increases from 1% in 2011 to 10% by 2050, and the buildings sector with a corresponding growth from 28% to 44% in its final energy mix. Both trends increase the flexibility needs of the electricity system along generation, distribution and electricity consumption.

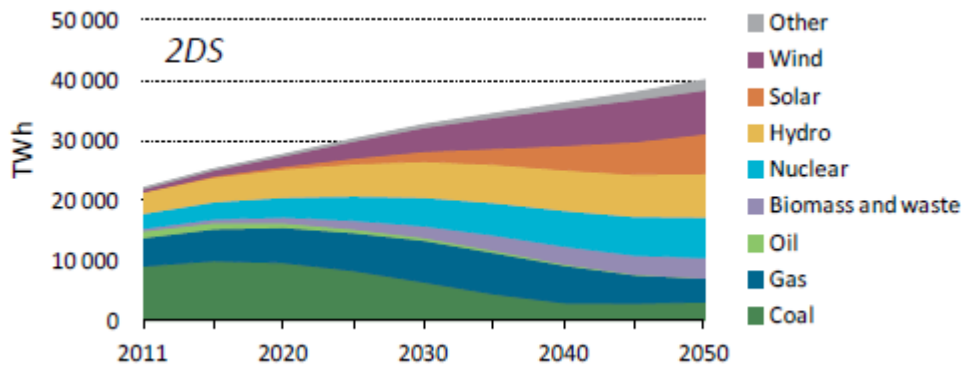


Figure 6: global electricity generation in the 2DS scenario

ETP 2014 analyses key topics of the electricity system in light of these two key trends in the electricity system. On the supply side, solar power and base-load gas-fired electricity generation are discussed, while electrification of transport is analysed as an example for the role of electricity on the demand side. This presentation will focus on the system integration aspect by analysing the role of electricity storage as flexibility option compared to other flexibility measures (demand response, flexible gas-fired generation). The underlying modelling approach is outlined in the next section, followed by a discussion of the analysis results, which are discussed in more detail in ETP 2014 as well as in the Technology Roadmap on Energy Storage [98].

3.3.4.2 Modelling approach

The long-term, global ETP modelling framework consists of three simulation models for the end-use sectors buildings, industry and transport as well as the least-cost supply-side model, ETP-TIMES model, which is based on the TIMES model generator [99] developed by the Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement of the IEA. The ETP-TIMES model depicts the energy conversion sectors from primary to final energy, including electricity generation, for 28 aggregated regions, which are interlinked through trade in fossil fuels, bio-energy and through electricity interconnections. Based on the final energy demand from the end-use sector models, ETP-TIMES determines the energy mix and necessary capacity additions for the various technology options in the conversion sectors up to 2050.

To describe the variation in electricity supply from variable renewables and in electricity demand within a year and throughout a day, the long-term ETP-TIMES model uses four typical days (one for each season), which are divided into eight 3h-timeslices. This granularity in the temporal description allows to some extent to capture the impact of variations in electricity demand and supply, on the long-term investment decisions, but is still too coarse to adequately analyse the flexibility needs within the electricity system.

In recent years, various approaches have been used to better incorporate operational aspects of the electricity system into long-term planning models. One can identify two basic approaches: the first one aims to incorporate operational planning aspects into the long-term models e.g. by drastically increasing the number of time-slices in the long-term planning models [100], whereas the second is based on a soft-linkage of a long-term planning model a dedicated stand-alone dispatch model, which analyses a specific year in a high-time-slice resolution based on investment decisions provided by the long-term model [4]. Both approaches have their merits and justifications. The former approach,

incorporating operational aspects in a long-term planning model, has the advantage of providing a direct and consistent feedback of the variability on the long-term investment decisions within one model. Computational resources limit, however, often the level of detail on the long-term planning side (number of technologies, regions and time periods) or operational side (number of time-slices, type of operational constraints). The latter approach, using a soft-link to a dedicated dispatch model, allows for a detailed consideration of these operational constraints in the analysis, but the feedback loop with the long-term planning model is not straightforward and requires an iterative approach.

The approach in this analysis falls in principal into the first group by incorporating additional, operational constraints (such as minimum up- and downtimes, ramp-up and –down constraints) in a linear formulation into the long-term TIMES modelling framework (Figure 7). This would allow to run a long-term planning model combined with a detailed representation of operational constraints, but as mentioned before, for computational reasons, this is prohibitive. Instead, the operational constraints in combination with an hourly time resolution for a single year (i.e. 8760 time-slices) have been used to analyse the operation of the electricity system in specific model regions based on investment decisions taken a priori by the long-term ETP-TIMES model. So, the connection between the long-term and short-term planning levels have been realised in this analysis through a soft link. The purpose by focussing this analysis on the operational side, by considering each hour within a year, was to gain experience with the operational constraints. Future work will aim to look closer at the interplay of the operational aspects with the investment decisions for the different flexibility measures, i.e. storage, flexible generation demand response and grid interconnection.

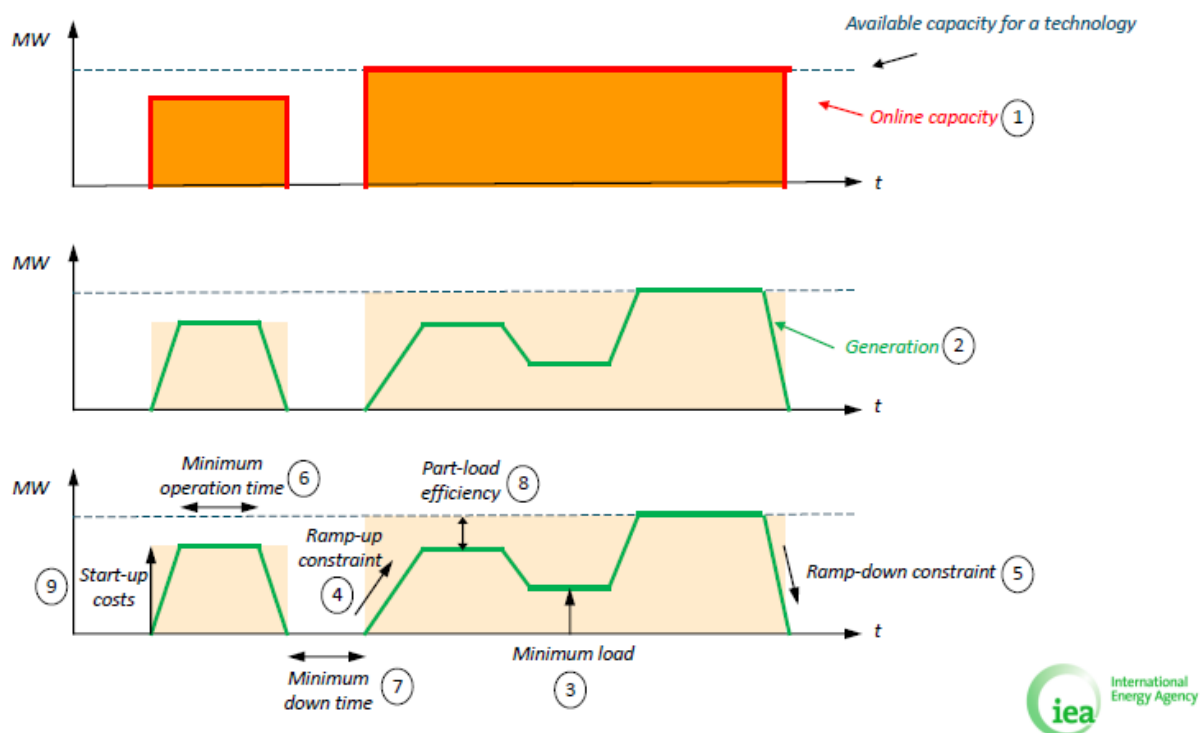


Figure 7: conceptual illustration of the operational constraints in the linear dispatch model

3.3.4.3 Scenario results

The linear dispatch model has been used to analyse the operation of the electricity system for the four regions China, the European Union, India, and the United States in 2050. The share of electricity generation from variable renewable in the four regions varies between 27% and nearly 50% in 2050 (Figure 8). The installed capacities for the various power technologies are provided by the long-term ETP-TIMES model to the dispatch model for the year 2050. The dispatch model then analyses the operation of the electricity system in 2050 with an hourly time resolution, i.e. 8760 time slices. The analysis of the role of electricity storage in the 2DS has been limited to storage technologies providing daily storage services, i.e. with storage durations in the six- to eight-hour range (~300 storage cycles annually). The market for such services is currently dominated by pumped storage hydropower (PSH), but compressed air energy storage (CAES), flow or other batteries could become increasingly competitive in the future. Additional flexibility is provided by sensible heat storage in Concentrated Solar Power (CSP) plants. The impact of electricity grids as a flexibility option by increasing the balancing area has not been explicitly considered in the model, as these aspects are very region-specific and require a higher spatial resolution within the model regions. Therefore, the results should be regarded as indicative on the interaction of the three other flexibility options: storage, flexible generation and demand response.

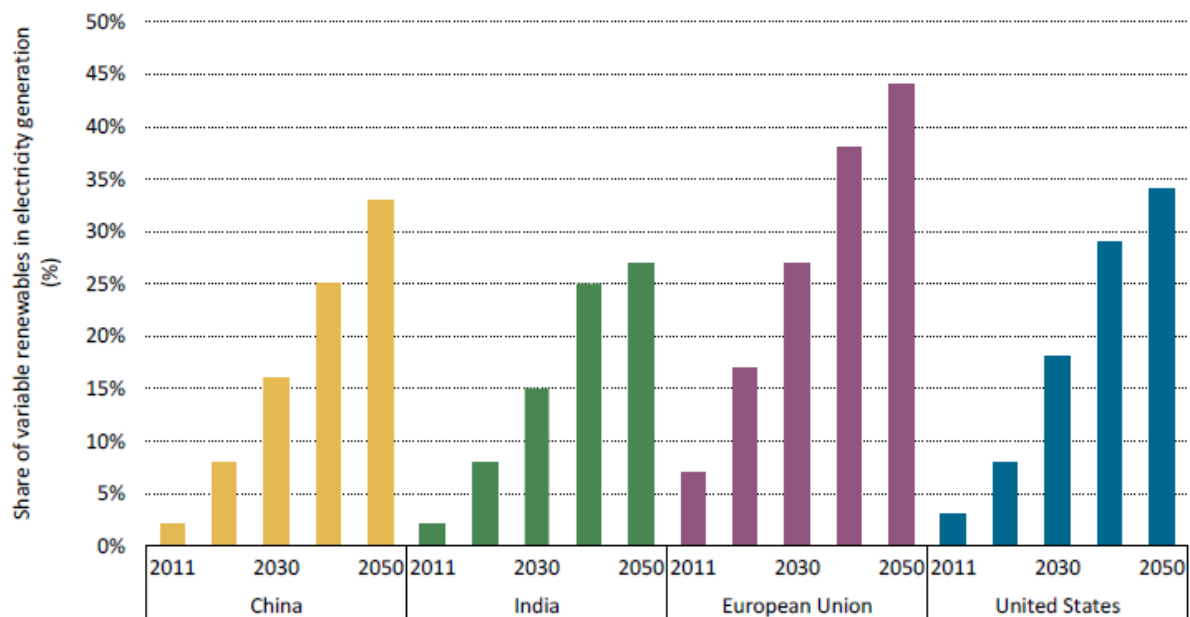


Figure 8: average annual share of variable renewables in electricity generation (%) by region in the 2DS

Whereas the 2DS includes only the first two flexibility options by allowing the model to increase the capacities of storage or flexible gas-fired power plants, a variant analyses the role electrification of transport could play in providing flexibility to the electricity system. Demand response from the anticipated large roll-out of EVs in the 2DS could compete against electricity storage in many applications. The “EV” variant assumes that 25% of the electricity demand from EVs is available for load following at off-peak price periods, so-called grid-to-vehicle (G2V). The possibility of feeding electricity from the vehicle battery back into the grid (V2G) has not been considered in the analysis, as it is likely to have

adverse impacts on battery lifetime [101]. Finally, the "Breakthrough" variant is designed as an estimation of the highest penetration of daily electricity storage in the 2DS scenario. This scenario assumes aggressive cost reductions in electricity storage technologies for arbitrage applications, where these technologies become competitive with the least expensive option currently providing arbitrage services. This result translates to a levelised cost of energy (LCOE) for daily bulk storage of approximately USD 90/MWh. For PSH, these cost reductions are, nevertheless, highly ambitious, since cost reduction potentials in civil engineering costs are limited. Given the recent drastic cost reductions in lithium-ion battery technology (Bloomberg New Energy Finance 2014), and expected up scaling of EV battery manufacture, there is a strong indication that grid-scale batteries sized for arbitrage/load-leveling applications could approach the cost levels envisaged in the 'Breakthrough' scenario significantly earlier than 2050 [102].

Given the hourly demand curve and a set of technology-specific operational constraints, the model determines the optimal hourly generation profile, as illustrated in the lower graph Figure 9 for the 2DS in 2050 over a two-week period in the United States. The upper graph highlights the potential role demand response of EVs could play, by charging them during hours of excess supply of electricity, notably from solar PV during noon hours. Due to good direct solar conditions in the south western part of the United States, the heat storage of CSP plants can further help to balance the electricity system by providing electricity also after evening peak hours after sunset (to depict this behaviour of CSP plants, solar field, heat storage and turbine have been explicitly modelled as individual components).

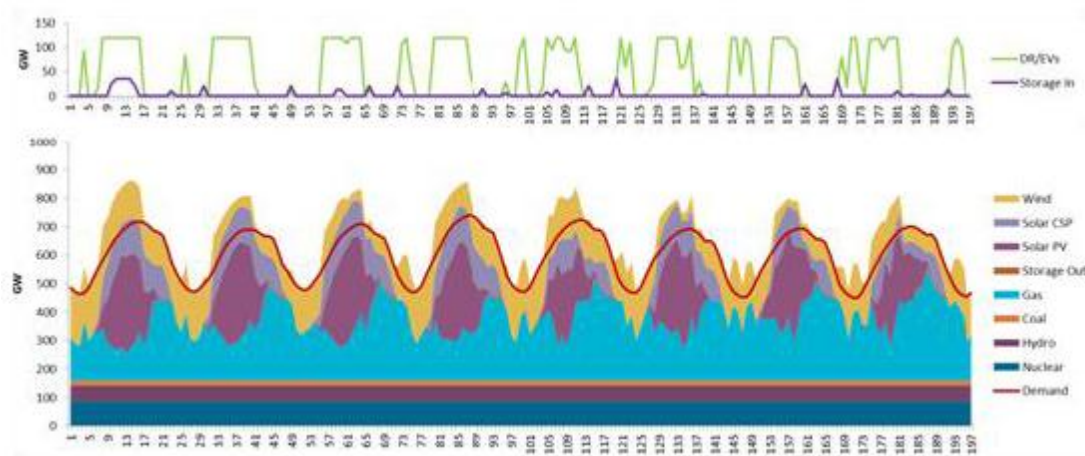


Figure 9: electricity dispatch in the United States over a two-week period in 2050 in the EV variant of the 2DS

Notes: DR/EV: demand response/electric vehicles (charging load shown); PV: photovoltaics; CSP: concentrated solar power.

The analysis for the four regions indicates that electricity storage will play an important role in a future low-carbon electricity system. In the 2DS, an estimated 320 GW of storage would be needed in the four considered regions, which account for 85% of global electricity demand in 2050 (Figure 10).

While storage capacity in the 2DS increases by 2050 by a factor 2 to 3 in China, the US and the EU compared to today, India stands out, with a grows by a factor 12. This rapid increase in India is not only owed to the strong growth in future electricity demand, but also reflects the relative low share of storage capacity of less than 1% in the total Indian

electricity capacity today - despite the relatively high share and potential for hydropower. Storage is, however, not the only solution for increasing the flexibility needs in the system. Demand response, as illustrated in the EV variant, may be an attractive option for providing flexibility, which reduces the need for dedicated electricity storage by around 40-60%. But, its success depends on system-wide management of the vehicle charging through smart grids. In addition, flexible electricity generation technologies, such as open-cycle gas turbines (OCGT) or concentrating solar power (CSP) plants with thermal storage in regions with sunny and clear-sky conditions are further options to increase system flexibility. OCGT is an important technology in all four regions, whereas CSP becomes a relevant flexibility source in India and the US, complementing the also increasing generation from solar PV in these regions. In the “Breakthrough” variant, electricity storage technologies provide all the flexibility requirements in all regions in the 2DS.

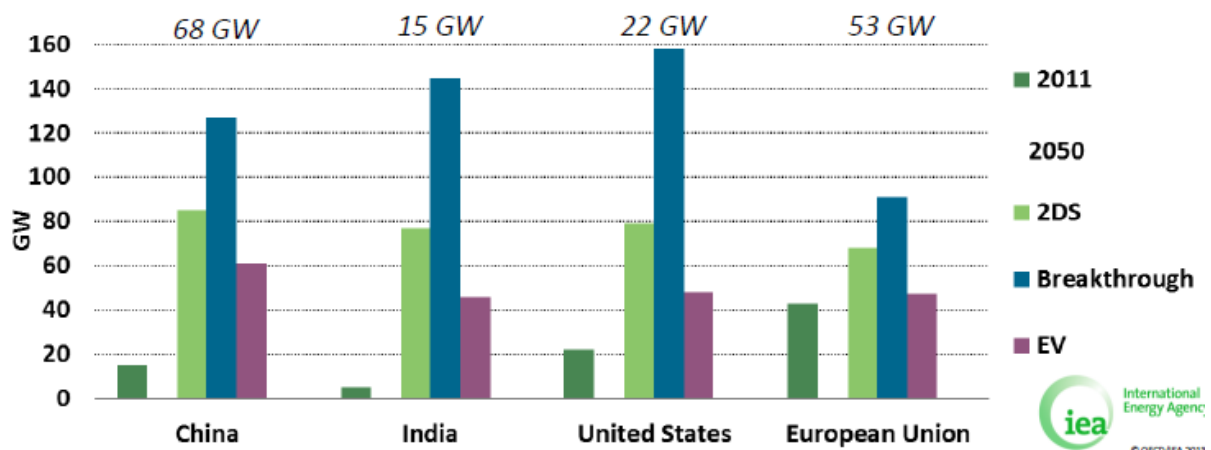


Figure 10: storage capacity for daily electricity storage for four regions in 2050

3.3.5 Integrating renewable energies - estimating needs for flexibility, competition of technologies, and the impact of grid extensions

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German Aerospace Centre, Institute of Technical Thermodynamics

3.3.5.1 Introduction

EU member states aim for significantly increasing the share of electricity production from renewable energy sources to meet long-term decarbonisation targets. The German government defined a goal of 80% for electricity generation from renewable energies by 2050 [103]. Fluctuating renewable energy technologies based on wind, photovoltaic and water will be key technologies to meet these goals. This paper presents results of a three-year study estimating fluctuating renewable feed-in and analysing medium to long-term potentials of most relevant load balancing options in a power supply system with high shares of renewable energies.

The key questions are: How will flexible technologies be used and to what extent competition between these technologies might arise? What characteristics define an efficient electricity mix for the integration of large shares of renewables? The energy systems model REMix [104, 105] developed at the German Aerospace Centre addresses these questions based on a detailed modelling of feed-in from renewable sources and supported by a detailed analysis of potential flexibility options.

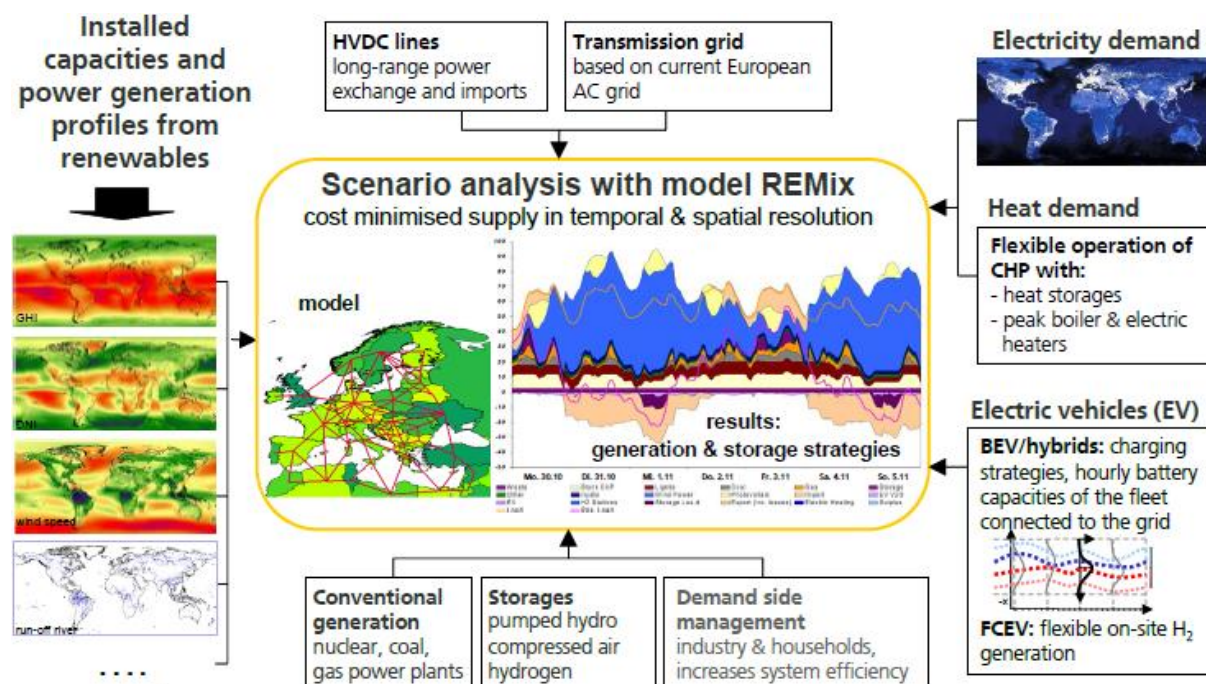


Figure 11: setup of the REMix model

3.3.5.2 Methods

The analysis and estimation of feed-in over time is founded on historic weather data and a in depth GIS analysis. REMix then uses the renewable input data within a linear optimization approach to determine a cost efficient dispatch and to minimize the total system costs. The model is also applied to analyse different scenario variations, investigating the potential role of storages, load management and flexible cogeneration as

well as a grid extension. Load balancing and flexibility options are analysed on an hourly and regional resolution for the years 2020, 2030, and 2050. In this workshop we will present major results and a discussion of underlying assumptions, modelling approaches and required simplifications.

Renewables: REMix uses a detailed model to estimate time series for each technology and region (worldwide with focus on Europe/North-Africa). Renewable feed-in is calculated based on weather data for historic wind years, run of river and solar years, as well as available technology and estimated installed capacity. The renewable feed-in for each technology based on 5x5 km pixel is then aggregated to regions. Knowing the technical potential in each region, investments for technologies are estimated based on an annual exploration of the best sites in accordance with the renewable targets.

Grid: Grid extensions compete economically with other flexibility options. Therefore the influence of the transmission grid is analysed, distinguishing two variations of the grid for each scenario: The first approach assumes a conservative grid extension up to 2050, based on the current ENTSO-E grid development plan. The second variation allows for a model endogenous grid extension.

Flexibility options: Different flexibility options are analysed in detail: Heat storage in CHP plants can provide flexibility to the electricity system. Estimations for Demand Side Management show potential in the industry sector, household and commerce sector. Hourly demand side potentials are estimated and specific potential in individual regions are used within REMix. Electric vehicles will have a significant market share in 2050. Some variations of the scenarios assume that batteries in electric vehicles will be used for load management. The following variations of available flexibility options were applied to all scenarios.

Table 2: flexibility options with each extension additional flexibility options become available

0	Reference scenario: no additional flexibility options
+	Flexible CHP based on thermal storage, conventional and electric peak load boiler
++	Additional load management options
	Heat pumps
	Electric vehicles- flexible charging
+++	Additional construction of electricity storages (CAES- Storages)

3.3.5.3 Results

In the full flex scenario (+++) electricity storage systems such as CAES can be build (in certain regions). The results show however that for selected scenarios they are not (economically) feasible. The reason is simple: Demand side management and flexible CHP provide sufficient flexibility.

The results further show, that grid extensions are a powerful flexibility option. All scenarios including the option to extend the grid, significant investments into an extension of the European transmission capacities are observed. The results show, that grid extensions will be used to reduce the shedding of renewable energy supply by around 50%. With regard to integration of renewable energies, benefits from grid extensions outweigh the benefits from all other flexibility options.

Flexible CHP plants have the potential to provide significant flexibility for the integration of renewables. The CHP plants are beneficial for integrating surplus energy in hours of high renewable feed-in. However, flexible CHP does not significantly reduce the demand for additional gas turbines in hours with high electricity demand and low renewable feed-in. Benefits of Demand Side Management technologies (DSM) are opposite to flexible CHP: DSM provides benefits in hours with low renewable feed-in, but shows only small benefits in hours with excess renewable capacities. All in all the results show that CHP and DSM technologies complement each other well.

Long term energy storages such as CAES storages are in this scenario setup economically not feasible. It can be further observed that specific flexibility technologies can be arranged into technology clusters and provide a valuable mix. On the other hand if DSM and flexible CHP are used, they are able to cut the economic potential of other technologies: e.g. CSP imports significantly reduce the requirement for other flexibility technologies.

3.3.6 Use of residual load curves to study the high penetration of renewables in TIMES-Greece

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Centre for Renewable Energy Sources and Saving (CRESS)

3.3.6.1 Modelling the integration of high shares of variable renewable energy sources.

An inclusion of the probabilistic production methodology for renewable electricity in an energy systems model (TIMES-Greece) is presented in paper [106] using the approach of the “Residual Load Duration Curves” (RLDC). The idea of RLDCs is based on the calculation of the load that remains to be covered [107] by dispatchable units (thermal, reservoir hydro) after the contribution of variable renewable energy is subtracted (residual load). In order to do this a stochastic analysis [108] of non-dispatchable energy generation (wind, PV, run off river hydro and small industrial CHP) should be done based on existing generation statistics and possible calculations of the potential of the different RES.

A time series of statistical data for each renewable electricity generation technology should be combined with statistical data of the electricity system load and these can be extrapolated in the future in order to perform a medium to long term analysis of the energy system [108]. This forecast can be used for the calculation of hourly production from RES units in future years. The hourly generation forecast can be used for the calculation of the probability density function (PDF) and the cumulative distribution function (CDF) for each technology of non-dispatchable generation and for the electricity system load. A Residual Load Duration Curve on a monthly basis can then be calculated through the convolution of the system load with the non-dispatchable energy generation (using hourly zones in order to assure small correlation between system load and RES generation).

Using the Residual Load Duration Curve it is possible to define an optimum combination of thermal plants and pump storage hydro plants (or other storage plants) to cover the remaining load with dispatchable power plants. The additional costs related to the curtailment of non-dispatchable electricity or with the installation of extra balancing units can also be taken into account using this approach. The curtailment of non dispatchable electricity, depends on the technical minimum of the existing thermal power plants and can be reduced either by selecting generation technologies with lower technical minimum, or by using sufficient capacity of storage plants. The capacity of the storage reserve required can be calculated based on a maximum value of the probability for energy curtailment (see [106] for details).

This approach has been included in the TIMES model generator [109] and is currently under testing in order to analyse the effect on the results of the model.

3.4 Session 4: modelling flexibility needs in power system models

3.4.1 Modelling flexibility needs in the European power system with DIMENSION and MORE

Andreas Knaut, Dietmar Lindenberger

Institute of Energy Economics at the University of Cologne (EWI)

By 2050, the European Union aims to reduce greenhouse gases by more than 80 %. The EU member states have therefore declared to strongly increase the share of renewable energy sources (RES-E) in the next decades. Given a large deployment of wind and solar capacities, there are two major impacts on electricity systems: First, the electricity system must be flexible enough to cope with the volatile RES-E generation, i.e., ramp up or ramp down supply or demand on short notice. Second, sufficient back-up capacities are needed during times with low feed-in from wind and solar capacities.

Electricity market models help shedding light into the extent of these challenges on a European level. Since all models face the constraint of limited solving time, we approach the modelling of electricity markets with a two-fold consistent modelling framework. The DIMENSION model developed at the Institute of Energy Economics (EWI) is a long-term simulation model for the European electricity market which takes into account different flexibility technologies on the supply and demand side and achieves the cost-minimising mix of different technologies [110]. Concurrently EWI develops the dispatch model MORE that focusses on the detailed simulation of technologic constraints in the electricity market and the interaction of multiple markets.

DIMENSION simulates how the installed capacities of power plants and power storage facilities will develop in Europe in the future. The investment simulation is based on a unique type day methodology that was developed at EWI [111]. Twelve to 32 type days can be used in the simulation that break down one year into characteristic days depending on weekly demand, weather conditions (solar/wind) and regional weather clusters. It is possible to freely select the time resolution. In which technology to invest depends on the full load hours that an additional generation unit is able to achieve. The dispatch is simulated as accurately as possible, in order to reproduce investment decisions appropriately. Alongside the investment in power plants and power storage, the model is also able to invest in cross border interconnectors. Since the electricity market faces a big transition and RES-E technologies are expected to become more and more important, investment into these technologies can also be modelled. Investment in renewables can be stimulated by implementing regional/European quotas or also by high generating costs for conventional power plants e. g. high CO₂-prices. Besides the electricity market, also consumers of heat from cogeneration plants are accounted for in the simulation. This improves the simulation of conventional power plants whose dispatch interacts with the dispatch of cogeneration power plants. Modelling the flexibility needs for the future power system, EWI found out that incentivising investments in efficient generation provides flexibility as an automatic complement [112].

MORE is based on Mixed-Integer-Programming and may be used as a global or rolling-horizon optimization. Total costs of the electricity system are minimized and the optimal dispatch is calculated. Grid restrictions based on PTDF-matrices can be included directly or in a separate re-dispatch calculation. The model is structured such that a large number of scenarios can be calculated with minimal effort in parameterization.

The model covers all connected European markets and North Africa. It takes into account interactions between the spot, balancing and re-dispatch markets. Trade is modelled either via NTC- or flow-based interconnector capacities. Power plants are modelled based on single units or aggregated categories. The combination of block sharp modelling and technical restrictions such as minimal down time, state-dependent efficiencies, start-up restrictions, etc. enables to quantify the value of flexibility in the system. In the rolling-horizon optimization, power plant failures, which cannot be anticipated by the model (unscheduled non-availabilities), can be simulated. Combined heat and power (CHP) units are modelled via a specific heat demand per power plant unit. It is possible to allocate the CHP plants to district heating grids, taking specific characteristics under consideration in the optimization. Storage is endogenously optimized, taking into account natural inflows. For all time-series - especially the feed-in of renewables - profiles can be customized, e.g., based on historical meteorological data and demand. Rules for the curtailment of renewables, e.g., in times of negative prices, can be implemented. In order to assess the value of flexibility between the different options within the electricity system, also demand side management processes of up to 26 different production processes are modelled.

EWI presented the structure of the modelling framework and discussed some results where these models are applied to the European electricity market. The selected results showed how the value of flexibility can be addressed in electricity market models.

3.4.2 Analyses with the power system model PERSEUS-NET-ESS/TS

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Karlsruhe Institute of Technology (KIT), Institute for Industrial Production (IIP),
Chair of Energy Economics

3.4.2.1 The need for daily electricity storage systems in the future German power system considering grid restrictions

Due to the growing volatile feed-in of electricity based on renewables, electricity storage systems will be essential in the future energy sector. Because of the volatile feed-in, electricity will have to be shifted temporally. Additionally, load centres and regions of potentially high wind-based electricity production are located far away from each other in Germany, resulting in the need to transport electricity from the north to the south. According to the targets defined by the German government, more than 65 % of electricity generation in 2040 is to be based on renewables. A strategic allocation of storage systems might help to improve the utilization of grid capacities and integrate renewables at the same time. To analyse this, we implemented the possibility to commission storage systems throughout Germany in the myopic power system model PERSEUS-NET-ESS [113]. This investment and dispatch model includes a DC approach of the German transmission grid and, thus, calculates not only the installed capacities, but also their optimal allocation. Besides storage systems, gas turbines or load shift potentials can be used for the integration of renewables. We use PERSEUSNET-ESS to evaluate the alternatives taking the grid restrictions into account.

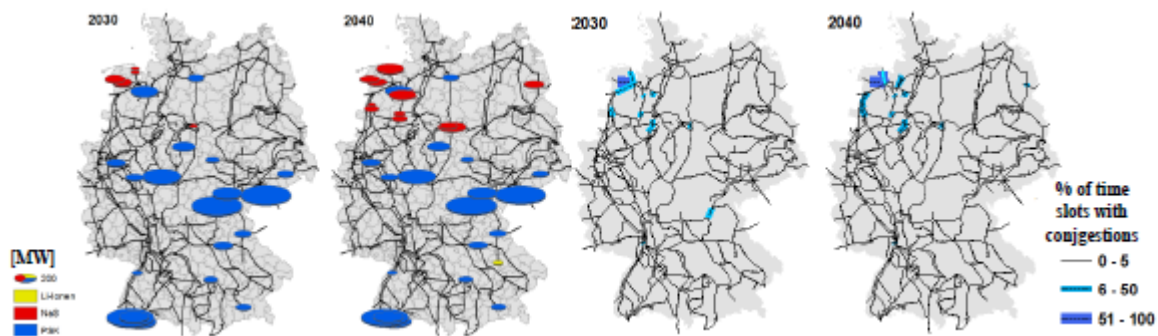


Figure 12: installed storage capacity and grid congestions in Germany by 2040 (Scenario REF)

Depending on the considered scenario assumptions, results indicate that it is beneficial to commission about 0.2-4.1 GW of battery storage systems until 2040. Main influencing factors are the assumed investments for battery storage systems as well as possible grid congestions. In all scenarios, the main part of the endogenously commissioned capacity is to be deployed in northern Germany close to the sea, where electricity from off-shore wind parks will be fed into the grid (Figure 12). At the same time, the storage systems will mainly be located close to congested grid lines. For the case of battery storage systems being too expensive in the model, gas turbines are commissioned instead. One of the scenarios also considers the load shift potential due to electric mobility [114]. It can substitute almost all of the commissioned storage systems and at the same time reduce the total generation capacity needed.

3.4.2.2 Comparison of different modelling techniques for describing the cycling behaviour of thermal generation units

The importance of conducting quick load changes increases for the remaining thermal units in power systems as the share of volatile renewable feed-in rises. An adequate representation of the cycling abilities of thermal units is therefore important in energy system modelling. Subsequently, we analyse the differences between five model techniques used in the literature to describe the cycling ability of thermal generation units. We apply them within the optimizing power system model PERSEUS-NETTS [115]. The model calculates the dispatch of German generation units for 2012 while restrictions of the transmission grid are considered.

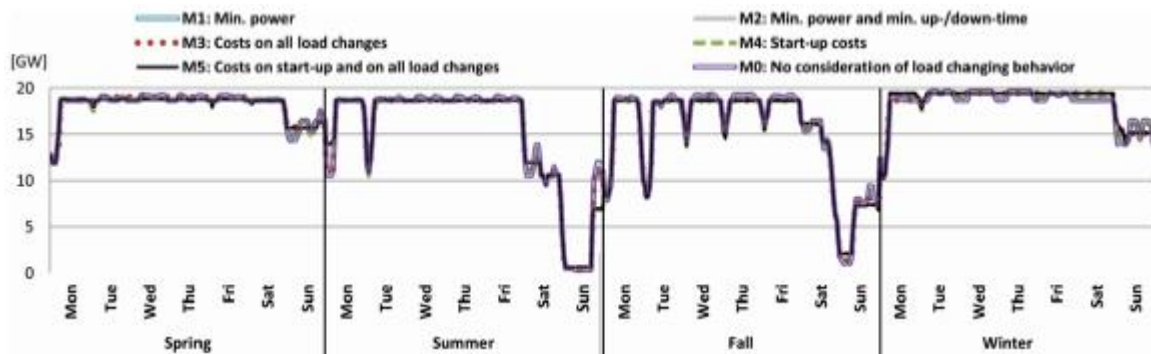


Figure 13: cumulated dispatch of all German coal units

Differences in the cumulated dispatch of coal, lignite, and gas combined-cycle units in Germany due to the different modelling techniques are analysed based on the PERSEUS-NET-ESS results as well as the resulting dispatch of two specific generation units. While the cumulated dispatch for Germany does not show any major differences for coal (Figure 13) and lignite units, the dispatch of gas units differs for the approaches that apply either start-up or load changing costs in contrast to approaches where only technical restrictions are applied, as for example the minimum power. With the application of either start-up or load changing costs, load peaks seem to be rather followed by gas turbines than by gas combined cycle units. At the same time, the dispatch of specific generation units may differ significantly (Figure 14). Modelling approaches that apply costs seem to reduce the on/off cycling stronger than approaches where only technical restrictions are applied.

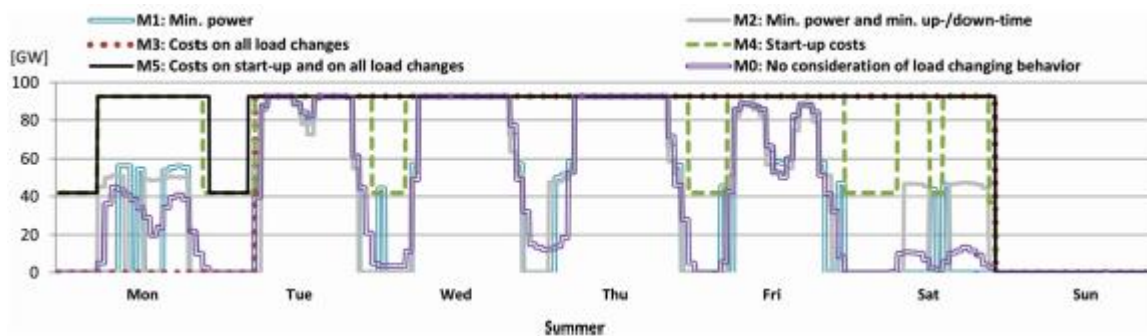


Figure 14: dispatch of a specific coal generation unit during the considered winter week

3.4.3 Whole-system approach to assessing the value of flexible technologies and products in supporting cost effective integration of renewables

Goran Strbac

Imperial College London

A range of modelling approaches and tools, developed by the energy systems modelling team at Imperial has been used to inform industry, governments and regulatory bodies regarding the role and value of enabling technologies in facilitating cost effective transition to a low carbon future including the changes that are needed in the market design and corresponding commercial arrangements.

In the specific areas of modelling of the integration of high shares of variable renewable energy sources and system flexibility needs and products, including the quantification of the value of ancillary services, several modelling tools are applied. Advanced Stochastic Unit Commitment [116, 117] has been developed to assess the ability of future systems to integrate renewables that endogenously optimises the allocation of all reserve and frequency regulation services. This has been applied for assessing the benefits of integrating Balancing Services Markets in the EU [118] and to inform the industry and regulators regarding the importance of enhancing the flexibility of generation, application of storage and DSR and importance of interconnection is facilitating exchange of flexibility services. This modelling demonstrated that value and volume of ancillary services will increase very significantly and that the present market design undervalues the flexibility services. In addition, this stochastic modelling framework has been applied to assess the consequences of the degradation of system inertia in systems with significant penetration of wind and solar generation [119].

Furthermore, when considering development of future low carbon electricity systems, including application of a range of flexible technologies such as demand side response, distributed/bulk energy storage, flexible network technologies and emerging designs of flexible generation, it is important to consider (a) Different time horizons, real-time demand-supply balancing on a second-by-second time scale to long-term investment-related time horizon, particularly to assess alternative smart technologies can impact system investment and operation cost, including security of supply and carbon performance, all considered simultaneously; (b) Different assets in the electricity system: generation assets (from large-scale to distributed small-scale), transmission network (national and interconnections), and local distribution network operating at various voltage levels. For this purpose, Whole-electricity System Investment Model (WeSIM) that simultaneously balances long-term investment decisions against short-term operation decisions, across generation, transmission and distribution systems, in an integrated fashion, has been developed [120], with the ability to quantify trade-offs of using alternative flexibility measures, such as DSR, new network technologies and distributed energy storage, for real-time balancing and transmission and distribution network and/or generation reinforcement management. The model also captures potential conflicts and synergies between different applications of distributed resources (e.g. DSR or energy storage) in supporting intermittency management at the national level and reducing necessary reinforcements in the local distribution networks. This modelling framework was applied to inform the renewable integration challenges in EU electricity system [33] and the benefits of evolving from member-state centric approach to EU wide approach to decarbonising the electricity system [121] and quantifying the benefits of storage [122]. In

studies conducted for the UK Government this methodology revealed the importance of flexibility and competitiveness of alternative smart flexible technologies (DSR, storage, flexible generation etc.) [123, 124].

In order to deal with uncertainty in timing, location, amount of renewable generation deployment, stochastic models for quantifying the option of value of flexibility have been developed [125] and applied for considering strategic versus incremental development of North Sea Grid infrastructure [33] Furthermore, changes in network design standards will play a very important in delivering cost effective transmission grid to support integration of renewables.

Furthermore, our modelling also demonstrated that there will be very considerable interactions between different energy sectors, in particular electricity, heat and gas and that this may present substantial opportunities for energy storage and thereby support a more cost effective integration of intermittent and inflexible low carbon electricity generation [126, 127].

Significant changes in the commercial framework will be needed to support efficient operation and investment in the context of whole-electricity system paradigm. Given the growing requirement for flexibility, there is a need for new market modelling techniques to be developed, to optimally allocate available supply and demand side resources including network capacity, to ancillary services and energy markets, considering participation of both traditional and new players. The roll-out of smart metering is expected to enable millions of small-scale participants to participate in electricity markets and provide system management services [128].

4 Discussions and conclusions

The Energy Union is among the top priorities of the new European Commission. The energy transition must be supported with models, and therefore collaboration of modelling teams on methodologies and data is desired. Many energy modelling teams need to analyse the transition from the current energy system to future systems with much higher shares of renewable energy sources, in order to provide policy-makers with recommendations on how to achieve climate change and energy targets. The models used for addressing these questions need to address flexibility aspects. Model-based analyses may be used as well to provide inputs to the establishment and implementation of the Integrated Roadmap of the SET-Plan, with a new status document just published in December 2014⁹.

Defining flexibility is a key issue that determines the modelling needs and the research questions that may be addressed. It is important to pay attention to physical and economic aspects, since both are relevant and related for obtaining useful and valid insights.

Since it is often very difficult to know all the current available approaches to address flexibility in energy system models, one of the main conclusions of the workshop is the need to undertake a systematic mapping of flexibility needs that have to be addressed and state-of-the-art model-based solutions or best practices for modelling it in the context of the evolving energy system. The team developing this matrix will be coordinated by Mr. George Giannakidis (CRES), and will include MM. Paul Denholm, Kris Poncelet, Joseph Dillon, Asami Miketa (IRENA), Vera Silva (EDF), Dominique Lafond (EDF), and Ignacio Hidalgo (JRC IET). The matrix (which could evolve into a proper literature review) would build upon the results of the ATEsT project¹⁰ and IEA's Task Force 25 "Design and operation of power systems with large amounts of wind power"¹¹. The matrix should consider several dimensions affecting short-term operations and long-term capacity planning, prioritising the most relevant drivers on flexibility to be targeted and included in the models also in the light of the policy questions that the models are required to address, including:

- Policy questions to be studied (such as: what type of uncertainty and volatility arises by the penetration of intermittent energy sources and what kind of flexibility is required to meet the problems imposed on the electricity system?, how will flexible technologies be used and to which extent may competition arise between these technologies?, or what characteristics define an efficient electricity mix for the integration of large shares of renewables?)
- Main purpose of the analysis (social, economic, environmental, technological),
- Intended user (public, research, businesses),
- Time frame (short-term operation vs. long-term capacity planning),
- Most important factors, assumptions, and flexibility drivers to be targeted and included in the models.

The workshop participants agreed to follow this up in more detailed discussions. In the future, it could be very convenient to set up a more permanent forum to exchange modelling approaches and assess modelling exercises, for instance within the follow up of the implementation of the SET-Plan Integrated Roadmap.

⁹ <http://setis.ec.europa.eu/set-plan-implementation/towards-integrated-roadmap-and-action-plan>

¹⁰ <http://www.cres.gr/atest/>

¹¹ http://www.ieawind.org/task_25.html.

There are several methodological approaches to modelling flexibility in energy systems: using heuristics, sector-specific highly detailed models, or combining models, but currently available models do not seem to be able of capturing flexibility issues properly, thus new holistic approaches are needed in energy system modelling. TIMES-like models are able to establish a correct and useful cost hierarchy, but that does not provide information about issues such as technical viability, user acceptance, or profitability of future options. Moreover, in TIMES-like models, increasing the number of time slices alone addresses only the variability itself but does not generally¹² address the operational constraints and thus, those models are in many cases not enough to address flexibility. Also that option increases significantly the complexity and running time of the model. Therefore, coupling large-size energy system model to sector-specific models, rather than relying on one, extremely complex model, seems to be the most adequate approach currently available for analysing flexibility in real-sized energy systems. However, model coupling is a complex and demanding undertaking that raises several technical and conceptual issues (such as which parameters or indicators are exchanged between the coupled models). The following guiding principles for addressing flexibility in energy system models were identified:

- Model simplifications have to be carefully considered in order to achieve the right trade-off between usefulness and computational complexity. This requires the identification of the critical assumptions affecting model results, thus providing an indication of what can be simplified and what can be modelled in a coarse manner, without compromising the accuracy and reliability of model results.
- The definition of the appropriate level of temporal and geographical resolution, as well as the use of parallelisation, flexibility parameters, technology and unit clustering techniques (which reduce running times significantly), and the selection of the constraints to be included or not in the model, are the most important options available to modellers.
- As regards the duration of the time slices, in most cases going below one hour is not necessary or not worthy given the small increment obtained in the quality of the results. However, finer time resolution would allow better assessments of the value of flexibility. There exists a wide range of time slices employed in various energy models. This topic may merit a proper literature review.
- Flexibility options may be constrained by availability of resources such as water in the short-term (for cooling) and critical materials in the long-term (for renewables). These aspects need to be more systematically addressed in energy models.
- Advance features such as water-energy modelling needs hydrological modelling (precipitation and catchment).
- In any case, after implementing simplifications in any model, the resulting scenarios should be validated (for instance by benchmarking or comparing with other models) in order to check whether the model is really fit for purpose. Also crucial for validation, sensitivity analyses are needed in order to understand how initial assumptions and boundary conditions influence the results of the models, especially the influence of meteorological data, the hypotheses on the development of renewable energies, and the assumptions of technology development and availability.

¹² Extensions have been, or are being, developed in TIMES to model operational constraints, and probably they are available in other models based on similar approaches.

Besides the methodological problems, gathering data for the models is an issue on its own, and sometimes critical. The challenge of incorporating a large number of different technology options alongside with detailed technical constraints in energy system models requires huge amounts of information, but in many cases there is a large shortage of data, and assumptions taken to fill data gaps are subject to high uncertainty. The two main areas of improvement concerning data are related to the estimation of renewable energy potentials, and to the projection of future demand response and demand profiles. Follow-up discussions regarding improving future demand response and demand profiles were agreed by the participants of the workshop. This activity will be coordinated by Mr. Frieder Borggreffe (DLR), with inputs from MM. Goran Strbac (ICL), Zakir Rather (UCD), Paul Denholm (NREL) and Sylvain Quoilin (JRC IET).

System flexibility may be imposed as well through regulation (e.g. enforcing ramping capabilities, putting all the burden of balancing on renewable generators). It is necessary to improve the representation of market and regulatory aspects so the models provide useful and well founded results. Models should be able of representing the market signals that anticipate the lack of flexibility, such as the high prices in balancing markets as flexibility options become scarce. Scarcity can trigger investments in or the retrofitting of existing plants. Retrofitting is an important option to increase flexibility in the energy system, but modelling retrofitting is a challenge in many models and should be the object of active research.

As regards communication and exchange of information, the participants stressed the importance of defining appropriate indicators, as well as the importance of using and sharing open source approaches and publicly available data whenever possible. Some sort of standardisation of some model elements (such as naming or reporting conventions and data) could improve significantly these exchanges, helping to communicate the results. However, maintaining a plurality of model is important, as it allows tailoring models to specific policy questions, as well as benchmarking results for improved robustness.

Another question raised during the discussions was how to improve communication to policy-makers. This is an important issue that has already partially been addressed in several fora and could be further debated in dedicated workshops focused on science for policy-makers, a topic that the European Commission is already active in¹³. One possible basis for improving communication on model-based analyses could be the guidelines with best practices for communicating scientific results to policy-makers already published by the Commission:

- Communicating research for evidence-based policymaking: A practical guide for researchers in socio-economic sciences and humanities¹⁴
- Scientific evidence for policy-making¹⁵

Finally, the flexibility of the gas system has not been addressed in this workshop, although most of the models considered rely on assumptions about it. Given the relevance of the gas sector, it should be considered in more detail since it may have a significant impact on the flexibility options available in the power sector. Similar considerations apply to other sectors, such as heat.

¹³ <http://ec.europa.eu/digital-agenda/futurium/en/content/increasing-weight-science-policy-making-call-action>

¹⁴ http://ec.europa.eu/research/social-sciences/pdf/guide-communicating-research_en.pdf

¹⁵ http://ec.europa.eu/research/conferences/2009/rtd-2009/documentation/science_economy_and_society/scientific_evidence_for_policy-making.pdf

5 Annex I: list of participants

The following table lists the external experts that participated in the workshop:

Table 3: list of participants

Name	Affiliation
BABROWSKI, Sonja	KIT (Karlsruhe Institute of Technology)
BORGGREFE, Frieder	DLR (German Aerospace Centre)
DEANE, Paul	UCC (University College Cork)
DENHOLM, Paul	NREL (National Renewable Energy Laboratory)
DILLON, Joseph	UCD (University College Dublin)
GIANNAKIDIS, George	CRES (Centre for Renewable Energy Sources)
HEINRICHS, Heidi	FZJ (Forschungszentrum Jülich)
HIRTH, Lion	PIK (Postdam Institute for Climate Research)
KNAUT, Andreas	EWI (Institute of Energy Economics Un. Koln)
KOBER, Tom	ECN (Energy Research Centre of the Netherlands)
KOLJONEN, Tiina	VTT (Finnish Technical Research Centre)
LAFOND, Dominique	EdF (Electricite de France)
LÓPEZ BOTET ZULUETA, Miguel	EdF (Electricite de France)
MARTINSSON, Frederik	IVL (Swedish Environmental Research Institute)
MIKETA, Asami	IRENA (International Renewable Energy Agency)
PONCELET, Kris	KUL (University of Leuven), EnergyVille
RATHER, Zakir	UCD (University College Dublin)
REMME, Uwe	IEA (International Energy Agency)
SILVA, Vera	EdF (Electricite de France)
STRBAC, Goran	ICL (Imperial College London)

The workshop was attended as well by several participants from European Commission's JRC-IET (Luigi DEBARBERIS, Elena DONNARI, Tilemahos EFTHIMIADIS, Iratxe GONZÁLEZ APARICIO, Ignacio HIDALGO GONZÁLEZ, Wouter NIJS, Bogdan OPRESCU, Efstathios PETEVES, Sylvain QUOILIN, Pablo RUIZ CASTELLO, Alessandra SGOBBI, Amanda SPISTO, Christian THIEL, Julija VASILJEVSKA, and Andreas ZUCKER), and DG ENER (Jonathan BONADIO and Kostis SAKELLARIS).

The editors would like to thank in particular Ms Neslihan CINAR and Ms. Elizabeth HOOGLAND for their support in organising the workshop.

6 Annex II: agenda

December 4 th 2014		
Introduction to flexibility issues and modelling-related challenges	09:00	01: Introduction to the workshop
	09:30	S. Peteves, head of unit, JRC ET
	09:30	02: Addressing flexibility in energy system models
	10:00	J. Dillon et al., UCD/UCC/EPRI
	10:00	03: Model coupling across scales
	10:30	H. Heinrichs, FZJ/IEK-STE
	10:30	Coffee break
	11:00	
11:00	04: Challenges of representing flexibility in energy system models	
	V. Silva et al., EDF	
11:30	05: Modelling urban energy systems – a tentative approach	
	F. Martinsson, IVL	
12:00		
	Discussion	
13:00		
	Lunch break	
Addressing flexibility: linking energy system models and sectoral energy models	14:00	06: Holistic approaches in addressing flexibility in energy system modelling
	14:30	T. Koljonen, VTT
	14:30	07: Experiences of modelling of intermittent renewable energy
	15:00	T. Kober, ECN
	15:00	Coffee break
	15:30	
	15:30	08: Increasing the level of operational detail in LT energy-system models
16:00	K. Poncelet, KUL/VITO	
16:00	09: Flexibility in JRC-EU-TIMES and Dispa-SET 2.0	
	W. Nijs et al., JRC IET	
16:30		
	Discussion	
17:30		

December 5 th 2014		
Modelling the integration of high shares of variable renewable energy sources	09:00 09:30	10: Renewable energy options and strategies in energy plans A. Miketa, IRENA
	09:30 10:00	11: Economic aspects of renewable energy sources L. Hirth, PIK
	10:00 10:30	12: Simplified flexibility parameters for evaluating renewable integration P. Denholm, NREL
	10:30 11:00	Coffee break
	11:00 11:30	13: Role of storage in decarbonised electricity systems U. Remme et al., IEA
	11:30 12:00	14: Integrating renewable energies - estimating needs for flexibility, competition of technologies, and the impact of grid extensions F. Borggreffe et al., DLR
	12:00 13:00	Discussion
	13:00 14:00	Lunch break
Modelling flexibility needs in power system models	14:00 14:30	15: Modelling flexibility needs in the European power system with DIMENSION and MORE A. Knaut, EWI
	14:30 15:00	16: Analyses with the power system model PERSEUS-NET-ESS/TS S. Babrowski et al., KIT/IIP
	15:00 15:30	Coffee break
	15:30 16:00	17: Whole-system approach to assessing the value of flexible technologies and products in supporting cost effective integration of renewables G. Strbac, ICL
	16:00 16:30	18: Use of residual load curves to study the high penetration of renewables in TIMES-Greece G. Giannakidis, CRES
Closure	16:30 17:30	Conclusions of the workshop

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EUR 27183 EN – Joint Research Centre – Institute for Energy and Transport

Title: **Addressing flexibility in energy system models**

Authors: Ignacio HIDALGO GONZÁLEZ, Pablo RUIZ CASTELLO, Alessandra SGOBBI, Wouter NIJS, Sylvain QUOILIN, Andreas ZUCKER and Christian THIEL

Luxembourg: Publications Office of the European Union

2015 – 73 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online), ISSN 1018-5593 (print)

ISBN 978-92-79-47235-0 (PDF)

ISBN 978-92-79-47236-7 (print)

doi: 10.2790/925

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ISBN 978-92-79-47235-0

