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Jacques Després[1234*], Patrick Criqui[12], Silvana Mima[12], Nouredine Hadjsaid[13], Isabelle Noirot[14]

[1] Univ. Grenoble Alpes, F-38000 Grenoble, France ;
[2] CNRS, PACTE, EDDEN, F-38000 Grenoble, France.
[3] CNRS, G2Elab, F-38000 Grenoble, France;
[4] CEA, LITEN, DTBH/SCSH/L2ED, 17 rue des Martyrs, F-38054 Grenoble, France;

Keywords

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Abstract

Energy systems are changing worldwide: new energy policies promote more sustainable energy productions, including Variable Renewable Energy sources (VREs) such as wind or solar. The long-term implications of the variability and relative unpredictability of these non dispatchable energy sources need to be assessed, for example with energy scenarios. Indeed, electricity is not a homogeneous good: its value depends on the time, space and how variable a production is. Long-term energy models are used, VREs integration challenges being a hot topic in energy modelling. An assessment of long-term energy models is necessary to understand how they represent the specific constraints of VREs on the rest of the power system. Therefore a new typology is proposed for comparing both long-term energy models and power sector models. This comparison shows that – despite all the recent modelling efforts – no long-term energy model represents in detail all the impacts of VREs on the power sector. For example, the sequential representation of the electricity storage operation is too precise for many long-term models . Therefore we develop a dedicated new power sector module, EUCAD (European Unit Commitment And Dispatch). The particularity of the work is that it is connected to POLES (Prospective Outlook on Long-term Energy Systems), one of the most technology-detailed long-term energy models. We present the first results of this new detailed electricity module.

1. Introduction

Reducing CO_2 emissions from the energy sector is a key challenge for many countries. This impacts energy policies, with more and more production from Variable Renewable Energy sources (VREs) being deployed, like wind and solar. In order to evaluate the trajectory of an energy system, long-term energy models depict the future of the energy system with all sources, vectors and exchanges of energy between regions or countries. The main parameters being monitored (energy production, costs, etc.) have an endogenous evolution over time [1], even if some macroeconomic and demographic factors are usually exogenous. This approach is useful for taking long-term energy policy decisions, thanks to a coherent long-term vision. The energy flows and the main technologies are described economically, but their technical description remains simple.

The power sector is crucial for long-term scenarios, as it is an important form of energy that can allow the development of renewable energy sources. VREs add some new constraints to the management of

[*] corresponding author:
Jacques Després, CEA, LITEN, 17 rue des Martyrs, F-38054 Grenoble, France. E-mail: jacques.despres@cea.fr.

the power sector (decentralized resources, variable output, uncertainty, lack of controllability). Several mitigation solutions exist: better spatial integration of the electricity grids (interconnections, smarter management of the distribution grid), demand side management, electricity storage or use of so-called "back-up" power plants. Taking into account these challenges requires a precise spatial and temporal representation.

Another category of modelling tools focuses on the power system, with a more accurate physical representation. Their complementarities with long-term energy models are strong: their outputs might help to calibrate the long-term energy modelling tools (e.g. with VREs integration costs, production curtailment, impacts of the electricity storage). On the other hand, long-term energy models provide the economic assumptions to the power sector models (e.g. evolution of the power demand and of the costs and performances of the technologies).

Given these complementarities, an energy modelling tool that integrates the main features of the power system would be of great interest. Our work seeks a better understanding of both long-term energy models and power sector models, as well as their complementarities and possible combinations. We propose a common methodology, concerning both the technical and economical aspects. This typology should help asking the right questions when faced with an energy modelling tool. It gives an overview of a tool and helps formulate the different characteristics of the power sector and compare them with other tools. Qualitative comparing criteria focusing on the power sector components are proposed. One can then focus on specific matters of interest to him (for us, electricity storage).

When analysing long-term energy models, we understand that in most cases the balance between supply and demand in the power sector is considered with a few aggregated time-slices that contain similar hours in the season or the year. On the other hand, modelling the power system has its particularities that cannot be included in aggregated long-term representations (demand and supply must match at any time; voltage level has to be kept within physical limits; current flows have to stay below thermal limits of the components).

The variability and relative unpredictability of non dispatchable VREs has increasing impacts on the electricity market. Indeed, electricity is not a homogeneous good [2]. The best way to assess its value is by comparing this good with the actual need for it, i.e. the electricity demand. The value of electricity depends on the time of production (because demand is not constant), on the production site (because a grid is needed to bring the electricity to the consumer) and how variable a production is (because the dynamics of the demand have to be met at all moments). All electricity productions are not equal: those able to vary quickly upon request (peak fossil production) have a greater value than wind or solar.

This is an important issue in long-term energy models considering scenarios with a lot of wind and solar energies. Therefore we focus on models dealing with the energy system and its power sector sub-system, where wind and solar energy sources are connected.

We present hereafter the methodology we developed for classifying the technical and economical models. In section 3, we apply this methodology to some examples, both long-term energy models and power sector modelling tools. Then, section 4, we explain how we integrated a new electricity module in the long-term energy model POLES and what are the interactions between VREs and the different forms of management of the electricity. Finally, we conclude in the section 5.

2. A new typology for comparing energy modelling tools

In order to analyse the existing models and compare the most interesting modelling characteristics for VREs integration problems, we studied the existing models and their categorizations. We developed our own typology for long-term energy modelling tools and more detailed power sector tools.

A commonly used criterion is the bottom-up or top-down paradigm. Top-down models describe the macro-economic relationships between the components, while bottom-up models describe better the supply and demand sectors, from a technological point of view [3,4]. Some hybrid models try to conciliate both approaches [5], by mixing technological description and macro-economic loops. In this paper, the impact of VREs on the other technologies is considered, and therefore we mainly examine bottom-up models.

Many reviews explore possible categorizations of energy modelling tools [6–12]. Some categories exist more specifically for long-term energy modelling tools (see for example [12]). One should distinguish partial equilibrium models, general equilibrium models (e.g. NEMS, CIMS, IMACLIM), energy-economy-environment models (e.g. GEM-E3, E3MG) and integrated assessment models (e.g. DICE, MESSAGE, WITCH, GCAM). An interesting survey involving 37 energy modelling tools has been carried out in [13], with seven categories used to classify very different tools. The methodology proposed in our work uses some similar criteria, and adds others. Our goal is to allow a comparison between the description levels of several components of the power sector (e.g. the components related to the integration of VREs). The main categories of our typology are the following.

First, the general objectives of the models are described, with several criteria. For a broad categorization of energy modelling tools, one can identify which energy sectors are considered (power sector, heat sector, transport sector, other forms of energy like hydrogen or gas). One should also distinguish simulation and optimization logics. A simulation model (e.g. POLES [14], PRIMES) is recursive: the model is run year after year and the parameters can vary along the simulation. An optimization model (e.g. MARKAL, TIMES) has one or several criteria and parameters being optimized. In this case, it is important to identify these criteria and parameters. Then, while long-term models usually have endogenous evolution of some parameters (but generally not the macro-economic input parameters like GDP or population), the majority of the more detailed sectorial tools are computing an exogenously fixed system.

Next, we can define criteria more specific to the representation of the power sector. Some models adopt a system-wide approach, when the whole system is considered and a social, centralized, aggregated perspective is used. Other models use an agent based approach, as they look at an individual actor, with consideration of its own interests (decentralized logic). Finally, there is a difference between operation models (with a short-term perspective) and investment planning models.

These first set of retained criteria is summarized in table 1.

	Criteria	Value of the criteria
General logic of the model	**Represented energies**	Electricity / Heat / other energies
	Evolution over time	Fixed system / Evolving parameters
	Computation logic	Simulation / Optimization
Electricity: representation choices	**Studied system's approach**	System / Individual
	Choice of dynamics	Operation / Investment planning

Table 1: First set of criteria for energy modelling tools: a broad categorization

The second type of criteria is the spatial and temporal characteristics of the model. It includes the time horizon and the time step of the model. Choosing one of these characteristics sets a limit on the other, because of the computation time (and the time-step must be lower than the time horizon). This is represented in figure 1. The spatial resolution is also important for the technical detail that a model is able to represent (disaggregation of demand and production, electricity grid considerations).

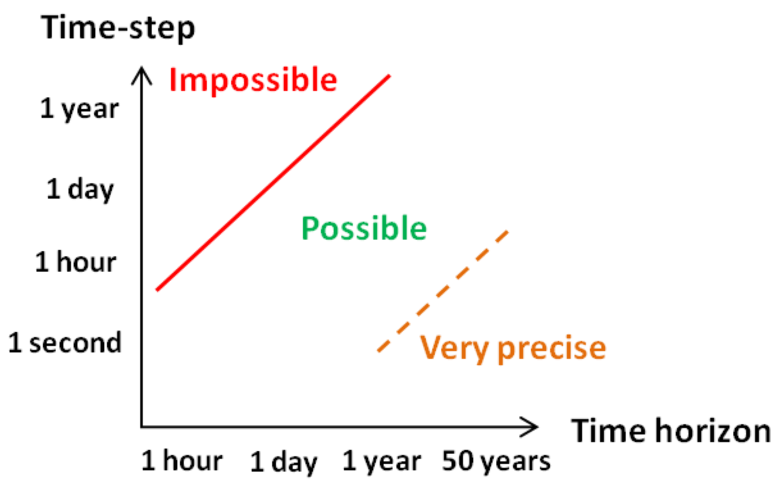

Figure 1: Second set of criteria for energy modelling tools: the temporal characteristics

Finally, the last set of criteria is more flexible; it studies the power sector components in further detail, both on the technical precision and the economical mechanisms. This includes new criteria focusing on the representation of VREs and their integration into the power sector.

The conventional productions can be described one by one or aggregated as one or several theoretical power plants. There are also many possibilities for representing the operation of the power plant (e.g. input-output relation, ramping capabilities, minimum power production). Economically, the dispatch can be more or less precise (heuristics, merit order, some technical constraints, balancing mechanisms, etc.), the investment can be modelled differently, etc. The case of renewable energy sources is different, as the production is not dispatchable and the marginal cost is zero.

Electricity storage has its own technical constraints, like the minimum and maximum state of charge. It is dispatched according to inter-temporal constraints (the state of charge is the relation between the charging and discharging periods). This makes it difficult to represent in long-term models, because they don't usually have an adequate sequential temporal representation. Electricity storage can have several economic values: arbitrage between time-steps, ancillary services, renewable production support, differing infrastructure investments, etc. Cumulating these benefits makes storage more interesting, but it is difficult to model. In [15], Hoffman et al. analyze how several models take the different applications into account.

Electricity demand can have different levels of technical and economical description, in time and space. For example, demand side management can be added. Finally, the electric grid also has several levels of detail in its computation. The economic costs (and benefits) of the grid can be described or not (in the operation and the investment decisions).

All these criteria are rather qualitative, but quantitative data can be attributed to different levels of precision of the technical and economical description [16].

3. Analysis of several energy modelling tools

The typology above applies to any kind of energy modelling tool; in this section we apply it to two of the most detailed long-term energy modelling tools, PRIMES [17] and POLES (Prospective Outlook on Long-term Energy Systems, [14]), and three power sector modelling tools, E2M2 (European Electricity Market Model [18,19]), ELMOD (Electricity Model [20,21]) and EUCAD (European Unit Commitment And Dispatch), the electricity module we developed. Many other models exist, but we chose these five models because they represent well the diversity of modelling choices. For example, one can cite ReEDS [22,23], WILMAR [24] or SWITCH [25,26].

The characteristics of the models are described in table 2.

<table>
<tr><th>Modelling tools</th><th>POLES</th><th>PRIMES</th><th>E2M2</th><th>ELMOD</th><th>EUCAD</th></tr>
<tr><th rowspan="3">General logic of the tool</th><td colspan="2">Electricity, gas, oil, coal, biomass, etc.</td><td colspan="3">Electricity</td></tr>
<tr><td>Simulation</td><td colspan="4">Optimization</td></tr>
<tr><td colspan="2">Evolving parameters</td><td colspan="3">Fixed system</td></tr>
<tr><th rowspan="2">Power sector representation</th><td colspan="5">System approach</td></tr>
<tr><td colspan="2">Operation (simplified),
Investment planning</td><td colspan="3">Operation
No investment</td></tr>
<tr><th>Time horizon</th><td>2050/2100
(every year)</td><td>2050
(every 5 years)</td><td>2050
(every 2 years)</td><td colspan="2">1 year</td></tr>
<tr><th>Time step (occurrences per year)</th><td>2 hours
(2 days per year)</td><td>none
(11 blocks per year)</td><td>4 to 8 hours
(17 blocks per year)</td><td>2 h
(12 days per year)</td><td>Hourly
(18 days per year)</td></tr>
<tr><th>Spatial representation</th><td>57 regions in the world</td><td>Europe</td><td>USA
(multi-scale)</td><td>Germany and Europe</td><td>Europe</td></tr>
</table>

Table 2: General characteristics of the main models studied

Except for POLES, all these models optimize the power sector based on the total cost of the system. Although PRIMES is a simulation model, the electricity module is optimized. On the other hand, POLES has a simulation approach and the choice of electricity production technologies is made through total production costs, maturity factors, price elasticity and maximum potentials. This approach allows some inertia and non-optimalities in the system across time.

Then, we compare these models along technical and economical criteria. First we describe the constraints that they respect; then for all four optimization models, the components of the objective to minimise (i.e. the total cost) are analyzed. Next, we compare the representation of the production from renewable energy sources (and its impacts on the rest of the system), the electricity storage and the grid in all five models.

Concerning the models' constraints, the basic one is the supply and demand balance. The demand curve can be endogenously produced in several ways. In POLES and PRIMES, the annual electricity demand is the aggregation of all sectorial consumption and depends on macro-economic drivers and on the total average cost of energy. When PRIMES is linked to macro-economic models such as GEM-E3, energy-economy equilibrium can be met year after year. POLES represents two days of typical demand (summer and winter). The other models proceed by aggregating demand into typical time-slices or typical days. ELMOD also uses a price-elasticity of demand.

Then we look at the differences in the components of the electricity prices (which form the total cost of the system, objective to be minimised for the optimization models). On one hand, ELMOD and EUCAD are short-term tools and only optimize the system over one day, therefore not accounting for the fixed costs (investment in capacities or in grid infrastructure, capital costs). One the other hand, PRIMES is more economic and its total cost includes mark-ups indicating market power because some agents may be able to charge prices above marginal costs (market imperfections). E2M2, ELMOD and EUCAD can represent the start-up time and costs and some other inter-temporal constraints, while the other models cannot. However, these models do not consider renewable subsidies, CO_2 taxes or mark-up costs: they are not designed to evaluate public policies.

The potential of renewable production can be modelled through different approaches, usually relying on historical data. The easiest way is to directly use the historical production profile (e.g. SWITCH), but in POLES, PRIMES and ELMOD, a capacity factor is calculated by region and hour of the day, based on a statistical analysis of the historical data. EUCAD uses three different levels of renewable resource across the summer and across the summer (high, medium and low, applied to solar irradiance and wind speeds). The most detailed representation we found was the stochastic approach of E2M2: a probabilistic tree is used to represent the probabilities of variation between a low, a medium and a high wind resource, over three rolling time steps. This approach can thus take into account the uncertainties and variations of the production.

The POLES and PRIMES electricity modules cannot represent well storage because they don't have inter-temporal correlation between their time slices. The PRIMES model takes into account the storage only as a way to lower the variations of demand within a day. For the other tools, there are several ways to represent the value of storage: as a part of the optimization of the unit commitment, as an ancillary service provider or as a way to avoid the curtailment of renewable energy.

The studied modelling tools use three levels of representation of the electric grid. The "copper plate" representation supposes that no grid restrictions exist between all sources and demands. The transport model or net transfer capacities (NTC) uses fixed limitations to the power transfers between regions, and the power flows are directly attributed to the direct lines between the source and the demand centre. The finest representation uses the Kirchhoff's laws and represents the reality of the electric grid, usually linearized as a DC load flow.

The summary of this comparison is presented in table 3. The five models show different methodologies, particularly concerning the specific constraints imposed by VREs.

Modelling tools	POLES	PRIMES	E2M2	ELMOD	EUCAD
Optimization constraints:					
Demand	Economic function	Economic function	Aggregated	Elastic	Fixed input
Operating reserves	Y	Y	Y	N	Y
Capacity reserves	Y	Y	Y	N	N
Grid	N	N	N	Y	Y
Start-up time	N	N	Y	Y	Y
Costs:					
Fixed (O&M, investment)	Y	Y	Y	N	N
Variable (O&M, fuel)	Y	Y	Y	Y	Y
Variable fuel efficiency	N	N	Y	Y	Y
Start-up	N	N	Y	Y	Y
Reserves, ancillary services	N	N	Y	N	N
Grid	Y	Y	N	N	Y
Renewable and CO_2 taxes	Y	Y	N	Y	N
Capital	Y	Y	Y	N	N
Risk premium, mark-up	N	Y	N	N	N
Renewable energy sources:					
Hydraulic resource	Historical	(Unclear)	(Unclear)	(Unclear)	Historical
Production profile	Statistically determined	Statistically determined	Stochastic	Deterministic	Deterministic
Curtailment possibility	N	N	Y	N	Y
Direct cost impacts of renewables on:					
Operating reserve	N	Y	Y	N	N
Capacity reserve	Y	Y	Y	N	N
Grid costs	None	Y	N	Y	N
Storage economic value:					
Optimization of the system	None	(only load smoothing)	Y	Y	Y
Ancillary services			Y	N	Y
Avoid curtailment			Y	N	Y
Grid:					
Nodes and lines	1 node per country (57)	35 nodes, 240 lines	None (only one country)	Entire Europe	Europe (1 node/country)
Type of computation	None (historical)	DC load flow	Copper plate	DC load flow	Net Transfer Capacities

Table 3: Main characteristics of the main models studied

This analysis highlights the differences in objectives and precision of representation of long-term energy system and power sector tools. Power sector tools have a good description of the technical constraints; their sequential dispatch can incorporate storage options, thanks to inter-temporal constraints. On the other hand, long-term energy models can represent broader economic assumptions and provide economic scenarios, but we clearly see that POLES and PRIMES, the two multi-energy long-term energy models, have a more aggregated description.

4. Coupling a new electricity module, EUCAD, with a long-term model, POLES

This categorization clearly shows that, up to now, energy modelling tools and power system tools respond to different objectives and do not merge the advantages of their approaches. Considering the ever higher share of non-dispatchable VREs in electricity, a new long-term approach is necessary that takes into account the VREs integration challenges. We want to use a precise electricity module in a long-term energy model, with an accurate representation of the value of electricity storage. This means that this electricity module has to include inter-temporal constraints, and that optimization logic is necessary.

Therefore the newly developed optimization model EUCAD, which dispatches all technologies optimally (including storage), is directly coupled with POLES.

4.1 Connecting POLES and the electricity module EUCAD

EUCAD optimizes the electricity unit commitment and dispatch in a fixed European system. It is designed to solve the operation optimization of one day, with an hourly time step.

The inputs are the electricity demand and the power system characteristics of every European country (installed capacities, marginal costs of each technology, other technical constraints). The outputs are the production or storage of each technology and the importations or exportations, for each hour of the day. If necessary, EUCAD can curtail the energy in excess (over-production) or, in case the system cannot supply all of the demand, EUCAD indicates what amount of electricity is not supplied. The social cost of unserved load is considered as a prohibitively expensive production technology.

EUCAD is used as a new electricity dispatch module for POLES, and so it is linked to POLES year-after-year. The hydraulic productions in POLES were divided into run-of-river, lake storage and pumped storage, and they correspond to EUCAD's new modelling of the hydro storage. The rest of the electricity mechanisms (in particular capacity planning) and energy flows other than electricity are still managed within POLES.

In order to take into account the uncertainty and variability of VREs, their production is separated in nine typical days in summer, and nine in winter. For each season (summer and winter), there is a day of strong wind resource (the day corresponding to the first decile of wind power production, from historical data for France 2013 [27]), a median day and a day of low wind resource. The same separation is used for solar resource (high, median and low solar resource days). The two renewable energy sources are considered to be uncorrelated; therefore we combine them in nine "resource days" with different probabilities of realization. EUCAD solves each of these days and weights them to get the seasonal dispatch, which is sent back to POLES in 2-hour blocks (as it is the time step used in POLES). The excess production being curtailed and the energy stored are also sent to POLES.

The economic dispatch is now precisely represented in the long-term model, including ramping constraints and electricity storage. In figure 2 we made a comparison between real French RTE data for the 19th January of 2013 (a randomly chosen day) on the left and the dispatch of EUCAD on the right. The inputs are the consumption, the real renewable resource, water resource used in hydro lakes during this day and nuclear availability on this specific day. On this validation test, the interconnections are set to zero and the actual historic exportations are added to the total demand. The other hypotheses are taken from POLES' database (production costs, installed capacities) and additional EUCAD's hypotheses (ramping capabilities and costs are from [28]).

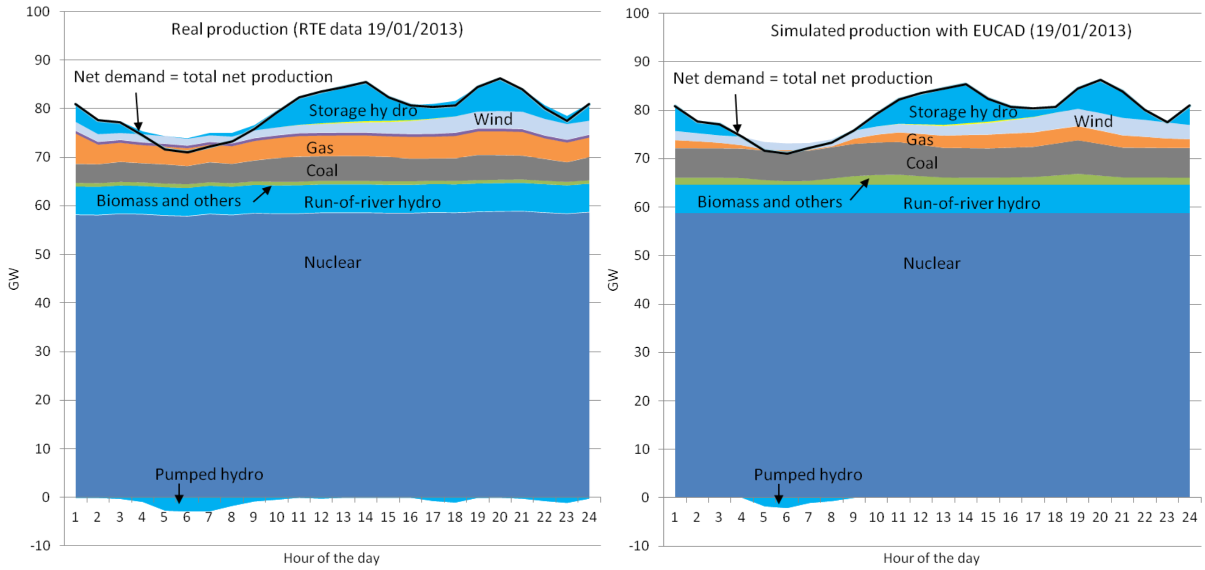

Figure 2: Comparison between real data and simulation from EUCAD (19/01/2013, France)

We see that hydro reservoirs of lakes and pumped hydro contribute a lot to the overall flexibility of the power system. The biggest discrepancy between EUCAD's optimization and the reality is that coal is more used in EUCAD than in the reality; this observation was also found by [29] with a different optimization model (EUPowerDispatch). A possible explanation is that the European air pollution regulation imposes a limited number of hours of production until 2015 for old French polluting coal power plants, which is not taken into account in EUCAD. The real fuel efficiency may be over-estimated; the international coal prices (used in POLES and therefore in EUCAD's production costs) may be an approximation for what EDF (the main French producer) actually pays; the (small) size and actual availability of the coal power plants may have an impact; and finally the redispatching uncertainties are not modelled in EUCAD.

4.2 Interactions between VREs and electricity grid and storage

EUCAD solves the dispatch of the entire Europe. Each of the 24 countries modelled is connected with its neighbours with fixed NTC. This allows a significant reduction in total cost of operation of the system: for a base case POLES scenario, fixing the interconnections to zero increases the total cost by 5.6% in 2030 (plus the social cost of 37 TWh of unserved load for Luxemburg, Switzerland and Norway) and 10.8% in 2050 (plus the cost of 351 GWh of unserved load in Sweden and Hungary). The level of unserved load is linked to the hypotheses for hydro resource in lakes and development.

Electricity storage is dispatched along with the other technologies, as an inter-temporal arbitrage, but it has further constraints: the sum of charging and discharging over one day must be zero, taking into account the round-trip efficiency of the technology. The technologies are mainly the pumped hydro storage, but CAES (Compressed Air Energy Storage), hydrogen and electric vehicles have also been added. In the case of hydraulic power, the description of power production had to be refined into three categories: run-of-river, storage in lakes and pumped storage. The first one is considered non-dispatchable, the second has a water inflow, a resource optimally used over one day, and the third works as a pure storage. A certain level of management of the demand is modelled with the dispatch of the electric vehicles' charging. They have a certain amount of energy to consume from the grid (for transport use, computed in POLES), and can use the rest of the battery as storage for the grid (Vehicle-to-Grid). The hypothesis for their charging (or discharging) hours is described in Figure 3.

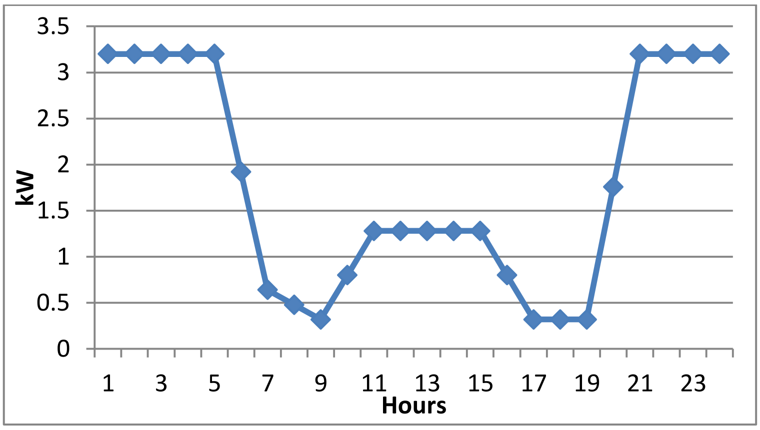

Figure 3: Hypotheses of power connected to the grid for an average vehicle

Hydrogen storage is similar, with an annual demand for hydrogen from electrolysis and an annual consumption of hydrogen by fuel cells (both are input parameters from POLES). However, the economic scenario used has little hydrogen development and this optimization only concerns small volumes, not visible below.

In figure 4 we compare the use of the different energy sources in 2013 and 2030 on typical summer days.

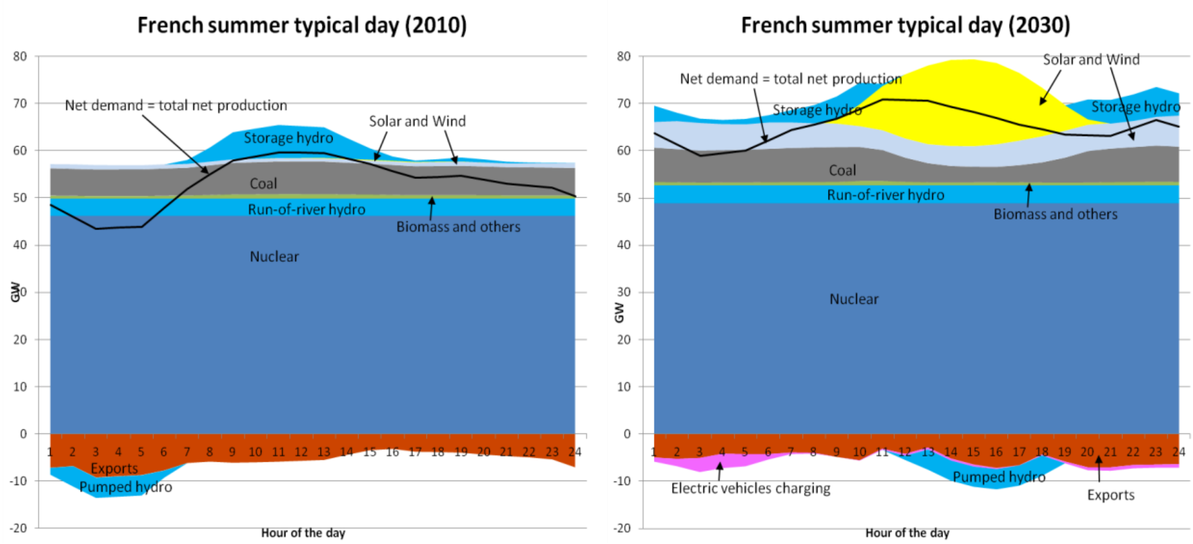

Figure 4: Compared operation of pumped hydro between 2010 and 2030 (based on POLES data and scenario)

In the POLES scenario used for this study, solar and wind energy sources for France rise from 4.7 and 7.5 GW installed in 2013, to 32 and 28 GW respectively in 2030. POLES has a very detailed technology description, so to make the figure lighter we aggregated the different technologies by source of energy. However the separation of hydro power plants shows that hydro storage is used in accordance with the development of VREs: solar power has a strong impact and displaces the pumping hours from night hours (periods of low demand in 2013) to daytime hours (low residual demand in 2030). Between these two situations, there is a transitional period (around 2020) when the use of hydro storage was limited, the residual load being almost constant in normal days of solar production.

There is also a substantial difference between days with high or low VREs resource (here a "high VRE day" is a day with a high availability of VREs in all European countries simultaneously). It is interesting to note that, in the figure 5, wind and solar power production have a big impact on coal use and on exportations to other countries.

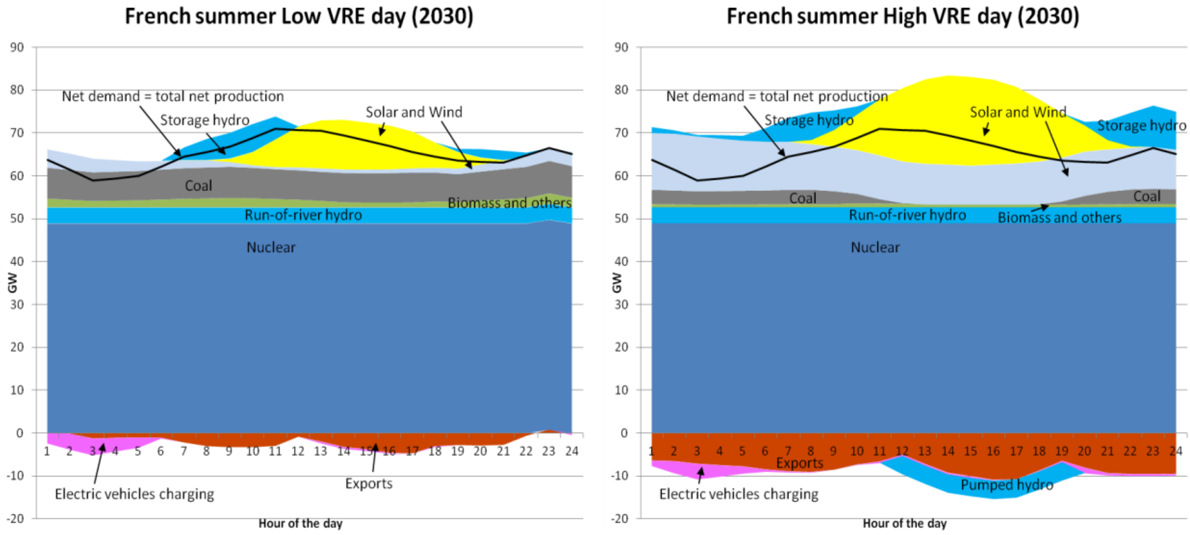

Figure 5: Compared operation in a typical 2030 summer day, with high and low VREs resource

We see that, with low levels of summer consumption, coal (together with biomass) is used as a "back-up": it adapts to the days of low or high renewable input. The same computations for winter days show that it is gas power plants that play this role, coal staying as a base production. Pumped hydro storage is not needed in days with low VRE because the residual load is almost flat across the day, for this country and year of this scenario. Electric vehicles are charged mainly during the night hours although more renewable energy is available during the day.

If EUCAD runs with a stronger deployment of renewable energy sources (57 GW of solar power and 54 GW of wind power in 2050 for France), we see that all gas, oil and biomass technologies are used as back-up for renewable integration. A smaller nuclear installed capacity allows a constant operation and a relatively high number of full load hours for nuclear and coal power.

5. Conclusions

VREs and storage are becoming more and more important in the power system, and should therefore appear with precision in long-term energy modelling tools. Our new approach of technical and economical models allows a comparison of the representations of VREs and their challenges in different types of models, including long-term energy models. The complexity of the VREs integration challenges is too high for a precise representation in long-term models, but specific power sector tools take them into account. The technical and economical characteristics of each component are crucial to capture the interactions between conventional productions, storage, demand and grid. We couple the long-term energy model POLES with a unit commitment and dispatch module, EUCAD, in order to shed light on some integration challenges and the short-term and future role of storage. Combining benefits of power sector tools and long-term energy models is possible, for the first time, thanks to the direct coupling between EUCAD and POLES. It takes advantage of the interactions between the different modelling approaches.

The insights gained from this work into the impacts of VREs will improve the understanding of the effects of sustainable energy policies on power systems and storage development. Renewable development and VREs integration challenges will be further assessed and flexibility options compared.

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