The Value of Load Following Capacity: Will Increasing Renewable Share in Europe's Electricity Reduce Nuclear Reactors' Capacity or Load Factors

A. Bidaud, S. Mima, Jacques Després, Daniel Heuer, Patrick Criqui, Bénédicte Champel, Nouredine Hadjsaid

To cite this version:

A. Bidaud, S. Mima, Jacques Després, Daniel Heuer, Patrick Criqui, et al.. The Value of Load Following Capacity: Will Increasing Renewable Share in Europe's Electricity Reduce Nuclear Reactors' Capacity or Load Factors. International Congress on Advances in Nuclear Power Plants (ICAPP 2016), American Nuclear Society, Apr 2016, San Francisco, United States. pp.503-508. hal-01848285

HAL Id: hal-01848285
https://hal.science/hal-01848285
Submitted on 24 Jul 2018

International Congress on Advances in nuclear
power plants, at San Francisco

THE VALUE OF LOAD FOLLOWING CAPACITY: WILL INCREASING RENEWABLE SHARE IN EUROPE'S ELECTRICITY REDUCE NUCLEAR REACTORS' CAPACITY OR LOAD FACTORS ?

A. Bidaud*, S. Mima**, J. Despres**, D. Heuer*, P.Criqui**, B. Champel***, N. HadjSaid****,

**Laboratoire de Physique Subatomique, LPSC/IN2P3/CNRS, Université Grenoble-Alpes, Grenoble53 Avenue des Martyrs 38026 Grenoble Cedex FRANCE*
Tel: +33 4 76 28 40 45, Fax: +33 4 76 28 40 04, Email: bidaud@lpsc.in2p3.fr
*** Economie du Développement et de l'Energie, PACTE/CNRS, Université Grenoble-Alpes, Grenoble*
**** LITEN, DRT, CEA, Grenoble*
***** G2ELAB, CNRS, Université Grenoble-Alpes, Grenoble*

Nuclear energy cost structure makes it a base load technology. In the cases where variable renewable production has a higher priority on the grid, renewable technologies will reduce load factors of dispatchable technologies. If not able to follow residual load, nuclear reactors could be supplanted by more flexible technologies. In this paper, we study the disregarded load following capacity of nuclear reactors for the nuclear industry in terms of preserved market share.

The hourly variations of Variable Renewable production is almost never simulated in the same tool as the decade long time scale of investment in nuclear capacity. We use the coupling of POLES (Prospective Outlook for Long Term Energy Supply) and EUCAD (European Unit Commitment and Dispatch) for the dynamic simulation of coupled supply and demand of energy, resources and power markets at these very different timescales. We present studies of the evolution of the nuclear fleet and its load factors as a function of some key factors such as load following capacities, availability of other technologies (renewable shares, storage capacities carbon sequestration options), carbon reduction policies.

I. INTRODUCTION

Given the importance of investment cost and the limited cost of its fuel, nuclear power marginal cost is very low. This makes nuclear power a base load technology that has limited economic incentive to reduce its production when electricity prices fall. Daily electricity prices in Europe are now clearly dependent on PV production (with low prices not only at night but also by noon) and on wind power production. Even negative prices are seen during period of reduced demand and high wind. This and the higher priority to access the grid of renewable reduce the production of controllable power plant, in particular fossil ones. With the increasing share of renewable expected in the future, the load factors of controllable production, among which nuclear, will continue to decrease. And so will their revenues if no or limited development of capacity markets is set up to compensate for the services of grid security. The actual market for base load electricity, where nuclear competitiveness is expected to be the highest may completely disappear. Nuclear energy might be forced whether to phase out or to adapt itself and to demonstrate its ability follow load and price variations.

Nuclear reactors have a larger load following capacity than usually said[1], even if technical difficulties (Xe effect, fuel constraints, thermal fatigue etc…) can limit it. Because of the very high contribution of nuclear power in the French energy mix, this capacity is already and will probably be even more used in the future in France. To simulate the evolution of the power system on the long term with a high level of variable renewable production and some storage technologies, one needs to simulate both the short time period at which demand and renewable productions change (typically hours) and longer ones, such as those of investment life times (typically many years). This is exactly what can be done with the combined use of EUCAD[2] (European Unit Commitment and Dispatch) and POLES[3] (Prospective Outlook for Long term Energy Supply).

In this paper we propose to simulate the evolution of the nuclear fleets and their load factors as a function of some key factors such as the availability of other technologies (carbon capture and storage, power storage), as load following capacities, and as a function of carbon reduction policies. We focus on the European and French cases for which nuclear share is higher and for which the impact of new renewable share should be seen first.

I. COUPLING POLES AND EUCAD

POLES is a partial equilibrium energy market prospective tool. The model simulates the energy demand and the supply of 45 countries and 12 regions in the world on a yearly basis up to 2100. It covers 15 sectors of energy demand (primary industries, transportation systems, residential and services), forty technologies of electrical production and hydrogen.

The choice of investment between technologies is made in order to optimize the energetic mix according to physical (capacity installable, availability...) and economical parameters (production costs of electricity...). On the base of POLES, yearly power production capacities and demand projections, the actual utilization factors of capacities are calculated whether with a simplified optimization algorithm in POLES or in a specific external module called EUCAD in the case of Europe.

EUCAD minimizes the total variable costs of electricity of the interconnected European markets. It takes into account the daily variability of renewable productions by applying its optimization algorithm on twelve days (6 of winter and 6 of summers) with very different hourly solar and wind power production profiles. EUCAD and the representative days are described in part ID.

As shown on Fig. 1, the coupling of the two programs allows for the simulation of the evolution of the long-term energy markets with a yearly time step that takes into account the hourly variation of variable renewable productions. This coupling can manage the impact of this variability on load factors of dispatchable power technologies and also demand response and daily storage capacities' evolution such as electric vehicle battery charging.

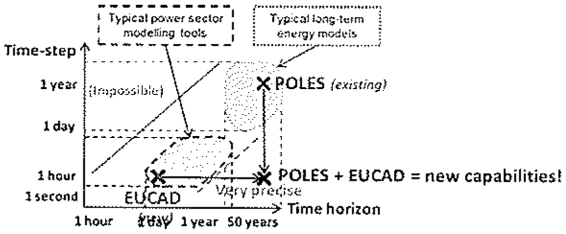

Fig. 1. Typical time scales and time steps simulated in the coupling of EUCAD and POLES

II.A. POLES world energy model

The behavioral equations describing the demand take into account of the combination of the price effects, the incomes, the technic economic constraints and technological changes. Energy demand is build as a sum of energy intensive sectorial demands (housing, industries, electric vehicle battery charging...). Sectorial demands are themselves based on projection of their own evolutions, efficiency gains and fuel switching capacities.

One summer and one winter average daily power demand profiles are simulated from the aggregation of sectorial demands. From those profiles, load, semi load and peak power year are build and used to calculate maximum power capacities presented in figure 2. As a function of simulated variable renewable productions, a residual demand profile is build within the specific module EUCAD for Europe or in POLES for other regions.

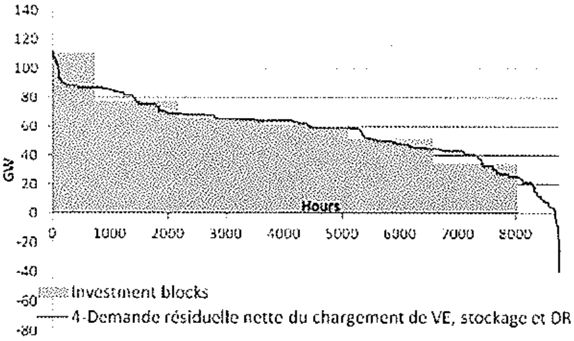

Fig. 2. Residual demand from which Electric vehicules, innovative storages and demand response solutions where sustracted and invesments blocks

The economic and technical specificities (costs, efficiencies, fuel consumptions...) of all technologies whether of demand or production sides are provided by an economic cost database called TECHPOL. It should be noted that in POLES, each technology's cost follows a learning curve that starts from the costs of "First of a Kind" and decreases with their development. For some of them, a "floor" cost is described so that whatever the development of the technology, its cost cannot decrease indefinitely. This evolution is evaluated on the advice of the experts and reflects the impact of the efforts invested in the R & D on the profitability of the technology1.

Profiles for supply of oil and gases are projected for key producing countries starting from a simulation of the activity and discovery of new reserves, data of prices, supplies in hand and cumulative production. The integration of demands for importation and the export capacities of the various areas are included in the international module of the energy markets, which balances international flows of energy.

Within each iteration POLES calculates initially the oil price (principal driver), and according to this price projects a request on the hydrocarbons which will depend on the countries, the areas and their GDP and population. Primary power consumption is estimated to satisfy the remainder of the worldwide needs subtracted by the production part of already existing renewable sources. The remaining fraction, to which nuclear energy contributes, is then forwarded to the principle of an optimized choice between capacities, availability, feasibility and production costs of all technologies. This need is converted thereafter into primary energy and an energy mix is defined for that year. The yearly construction is then dependent on the local needs and competitiveness of each power sources.

The main interest for our analysis of POLES is that any of these two nuclear technologies should also be competitive with any other electricity production systems.

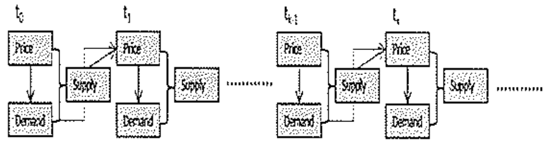

Fig.3 The iteration process simplified

II.B. Europe Unit Commitment And Dispatching (EUCAD)

POLES produces for each country in Europe two 12 times daily demand profiles averaged over 2 hours, one for winter and one for summer seasons. It also produces an image of the installed capacities and an estimation of variable costs for each technology. The production of renewable technologies is subtracted from the seasonal daily profile as a function of the load factors of each typical days. Those profiles are used to simulate the expected load demand as a function of working hours. This gives the figure 2 with the evolution of capacity needed as a function of hours of production each year. This defines blocks of investments of production capacities, ranked as a function of their load factors that are used to calculate the new capacities investments in POLES.

These data and limits in interconnection capacities, load following capacities (minimum production by technology, maximum hour % changes and associated costs…) are then used in EUCAD.

6 typical profiles of daily renewable productions (on-shore wind, off-shore wind and solar) of each season have been extracted for each country simulated. Those profiles where taken using a clustering algorithm[16] applied to a base of 1-hour-steps daily productions taken from data available on grid operator web sites (RTE, Transparency…). When and where data where not available, they where interpolated from neighboring countries[17]. Fig 4. Presents those profiles. One can see that day 1 corresponds to medium high sun, low wind, day 2 corresponds to strong solar and medium wind, day 4 and 5 low sun, low wind with different hourly profiles. Day 6 and 3 have strong winds but low or medium solar.

This produces 2 times 6 residual demand profiles that EUCAD tries to answer with available capacities of production and interconnections. Then a SIMPLEX algorithm is called to do the actual minimization of the variable cost of the whole European power market.

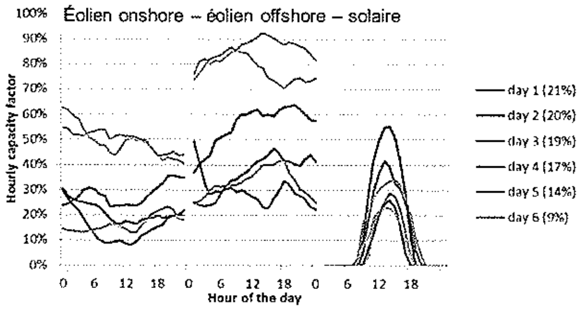

Fig. 4. Hourly Capacity factor of on shore wind power, off-shore wind power and solar power of the 6 clustered winter days

II.C. Nuclear Reactor Models

Only two nuclear reactor types are modeled in POLES. Globally one has the characteristics of a Thermal Neutron Reactor (TR) and the other one has the ones of Fast Breeder Reactors (FBR). Some of the characteristics are given in the Annex or found in Ref 5. All TR needs natural uranium as if using UOX fuels Their used fuel contain about 1% of Plutonium. Fast Breeder Reactors and their associated fuel cycle need a fissile materials inventory of 24 t of equivalent Pu per GWe, obtained from recycled TR fuels to start up. Sensitivities to this inventory were shown in Ref. 15.

Uranium costs and limited availability of resources are discussed in Ref. 15. They impact TR costs directly. FBR production costs are independent of the uranium market but dependent on the availability of Pu coming from reprocessed TR used fuels. As their startup is dependent on the availability of recycled materials from TR, their development will be only indirectly dependent on the assumptions taken on uranium price and resources availability. Dependence on investment costs was discussed in Ref. 5 and 15.

In POLES, a reduction of any of nuclear reactor technology installed capacity is usually compensated by a mix of demand reduction, increase of thermal power plants (Biomass, coal or gas fuelled) with CO2 Capture and Sequestration, a reduction in demand, and more marginally an increase in new renewables (solar and wind power).

Because of the high number of competing technologies, we hardly ever observe the two technologies as direct competitors as is expected by classical nuclear energy scenario studies.

II.D. Modeling Uranium Scarcity

The limits of different reserves categories of IAEA Red book[3] is often the main reference used for the construction of supply curves in many nuclear energy scenario models. Those supply curves propose an evolution of uranium price as a function of mined resources. The lower cost reserves being probably extracted first, it is expected that higher cost categories of reserves and more uncertain categories of resources would be used later when the price of uranium makes their mining profitable. As they do not need uranium once started, FBR may be developed much faster once the perspective of uranium scarcity would become clearer.

Two different principles of limitating the availability of uranium have been implemented in POLES.

In the first one[5], on top of a classical supply curve, the decision to invest in TR is made dependent on the "visibility" of uranium, ie the ratio of Reserves to Production (R/P). If the ratio is higher than the lifetime of the reactors (40 y by default) then, the risks associated with the unavailability of natural uranium over the expected lifetime of a TR would make the investment in this kind of reactors very unlikely. Investors would probably found them much less preferable than other technologies, in particular FBR whose costs are not related to uranium market.

In the second one, a limitation of the flow of uranium has been added to the classical limit in volumes of uranium availability. The price of uranium can be made dependent not only on previously mined uranium but also as a function of uranium productions as on Fig. 5. This reflects both the difficulty to open new mines at a fast pace but also the price dependence of uranium when produced as a co-product. Important resources of uranium could be turned into minable reserves in particular when extracted as co product of phosphates, coal, black shales, gold, cobalt and other minerals. For instance, 2014 IAEA Red Book declares almost the same volumes (7MT) for identified resources and for resources associated with phosphates. Uranium co extraction is currently done at Olympic Dam in Australia where typically 7% of current world demand is produced. Uranium is or was extracted together with phosphates, gold and more recently with Nickel, Cobalt, and Copper, in Talvivaara in Finland. Those resources are very important when compared to identified reserves. But their extraction at higher rates than the nominal rates allowed by the needs of the co-extracted materials will be very expensive. Then, the cost of uranium would be increasing with the flow of uranium. As soon as the nominal flow of uranium going through the process of extraction of the associated mineral must be increased to sell more uranium, the price should increase.

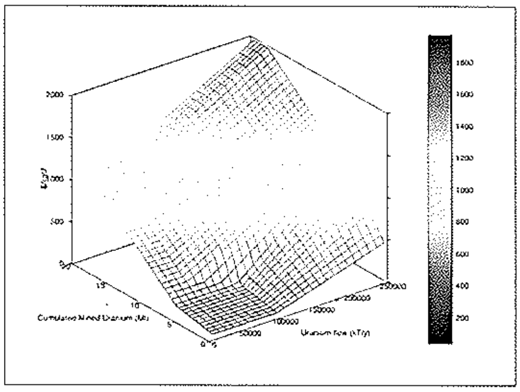

Fig. 5. Evolution of Uranium price ($/KgU) as function of cumulated Mined Uranium (Mt) and Uranium flow (kt/y)

III. SENSITIVITIES OF NUCLEAR INSTALLED CAPACITIES AND LOAD FACTORS

III.A. Scenarios Descriptions

In this part we compare the results of 4 main scenarios. In the first one, no specific climate policy is put into force. All advanced technologies such as Carbon Capture and Sequestration (CCS) and advanced storage (not only Pumped Hydro) are made available.

In the 3 others, a 2°C policy is put into force. The default one will be called "Climate policy". The one in which CCS technology is never mature would be the "No CCS" and the last without nor CCS nor advanced storage would be "No CCS, No storage" case.

In part III.B, investment in nuclear reactors is limited to a capacity to answer only base-load and semi-base load demand. Nuclear reactor can enter the competition for the investments only for the investment blocks of the highest duration of production in Fig. 2. The investment blocks opened to a contribution from nuclear reactors are broadening in part III.C. Even though nuclear reactors can contribute to answer demand levels seen only 4000 hours a year, it does not mean that individual reactors will have such limited operation hours. One can see on Fig. 11 that the average load will not be some.

III. B. Limited Load Following Capacities

The evolution of world nuclear capacity as a function of time for our different scenarios is shown of Fig. 6. The implementation of a "climate policy" makes nuclear energy (the sum of the 2 nuclear technology) growing faster in the first part of this century as it replaces a lot of coal power plants. Then whatever the scenario, nuclear may face a plateau that depends on its competitors. If storage is available, nuclear is slightly reduced demonstrating the probable competition with a combination of renewable and storage. If CCS is made available, then nuclear is a little less competitive again. The differences in load factors are less than 1% different between all cases and are not shown here.

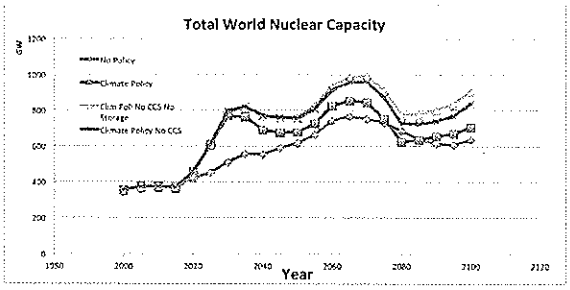

Figure 6. Comparison of world nuclear capacity evolution with time.

Figure 7 shows the same evolution for Europe. One can see than when current nuclear reactors would be dismantled, POLES doesn't replace all of them by new reactors. This is not only due to phase out policies in Germany, Sweden, Switzerland or Belgium. In fact there would be lower demand level for base load electricity and then that a lot of nuclear reactor would be supplemented by semi-base-load technologies even in countries that have not renounced to nuclear, typically France. The choice between the fossil based technologies depends on climate policy and availability of CCS. The

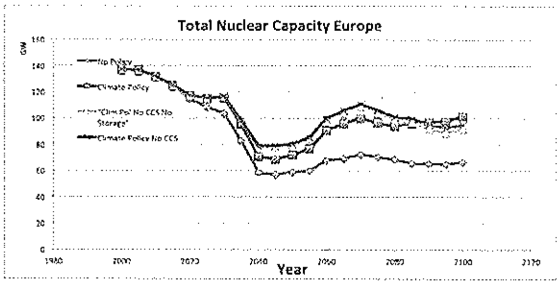

Figure 7. Comparison of European nuclear capacity evolution with time.

The actual dismantling speed is based on the assumption that all reactors have 40 years lifetime exactly, which is probably not representative of the diversity of the reality. Nuclear operators are applying both for life extensions and for shut down earlier than allowed (Mühleberg in Switzerland, Oskarshamn and Ringhals in Sweden, Vermont Yankee in the USA).

Figure 8 shows the evolution of demand and production profiles in France in year 2100 in the case where new storage is made available on a low demand level, summer day. One can see that nuclear energy is used mainly for base load. A very important contribution of wind and solar can be integrated into the grid thanks to strong storage capacities.

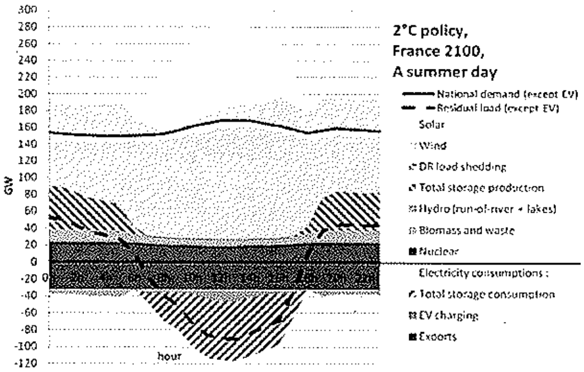

Fig. 8. Demand and production profiles of a French summer day when a climate policy is called, storage capacity available.

III.B Extended Load Following Capacities

III.B.1 Global Impact

With access to increasing investment blocks, depending on its local competitiveness, new nuclear reactors are being built as can be seen on Fig 9. On this Figure, the scenarios "No Policy" and "Climate Policy" are compared with or without extension of Load Following capacity. The specific module for Dispatching is used only in Europe and then on average, the impact in terms of load factors is limited to a reduction of 1%.

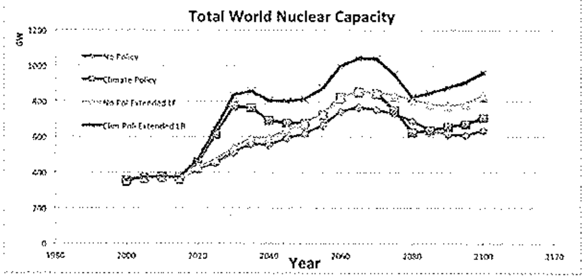

Figure 9. Comparison of World nuclear capacities with or without extended Load Following capacities.

III.B.2 Impact of extended Load Following capacities in Europe.

As in the rest of the world, increasing the opportunities for nuclear reactor to compete in a broader market should increase the installed capacity. Fig.10 shows that the capacity could be increased by up to 30% in the second half of the century.

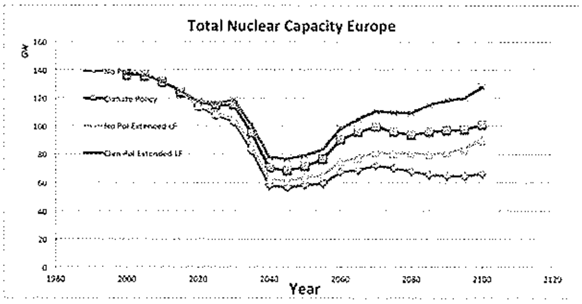

Figure 10. Comparison of European nuclear capacities with or without extended Load Following capacities.

The EUCAD approach is limited to Europe and to years after 2040. So the impact in load factors as a function of the diversity of variable renewable production is almost impossible to capture elsewhere. Fig. 11 shows the evolution of load factors in the cases where the load following capacities are the most wanted which are in the cases where the other flexible low carbon technologies are not available: Carbon Capture and Sequestration and low cost storage. In those cases, the load factors of nuclear power averaged over Europe may change by up to 6%.

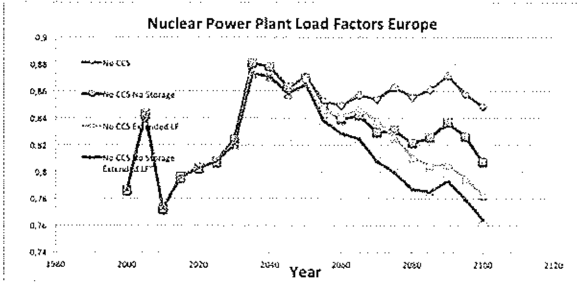

Figure 11. Comparison of European nuclear Load Factors with or without extended Load Following capacities.

III.B.3 Daily profile in case of reduced flexible competition

Figure 9 shows the evolution of demand and production profiles in France in year 2100 in the case where no CCS capacity but extended nuclear load following are made available. On average, France has increased its capacity by 30%. Nevertheless locally, on sunny summer days, nuclear energy is strongly reduced during solar production hours. During strong wind winter days, nuclear energy could also be completely supplanted by wind power. As expected at the time of the investment, the extra capacities might not be used at full power depending on relative variable cost and place in merit order. Nevertheless this will globally improve market share of nuclear as shown in Table 1.

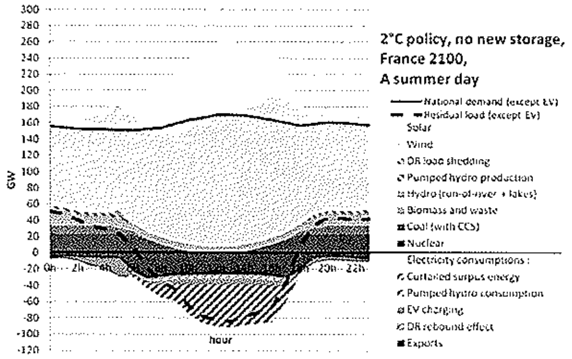

Fig. 12. Demand and production profiles of a French summer day when a climate policy is called

TABLE I. European share of nuclear energy in 2100 (%)

	Base Load	Extended Load Following Capacity
No Policy	6.1	8.3
Climate Policy	8.3	10.4
Climate Policy no CCS	10.4	15.2

IV. CONCLUSIONS

Nuclear energy cost structure makes it particularly suitable for base load production. With the rising share of variable renewables, the need for base load electricity may reduce drastically, in particular if they have a higher access priority to the grid. Thus, if nuclear power cannot adapt to reducing load factors, it could be supplanted by more flexible technologies.

To simulate the evolution of the power markets, one needs to take into account both the long time steps of investments but also the variability of renewable production on an hour-long time step. This is possible thanks to the coupling of POLES and EUCAD.

If nuclear has limited load following capacities, we have shown that it can be partially ousted in some countries in some scenarios. Depending on their availabilities and expected relative costs, the replacing technologies could be a mix of coal (in case of absence of climate policy), gas, and gas with CCS if a climate policy exists and this technology is available.

With extended load following capacities, our simulations shows that despite a reduction in average load factors, nuclear reactors would produce more energy globally thanks to higher installed capacities. One point that may look surprising is that, as renewable, nuclear business model could be improved if large storage technologies exist. Reciprocally, if storages are not available, the load following capacity of nuclear reactors could increase a little the variable renewable share.

These non-intuitive conclusions confirm the need for global scale prospective tools. In particular if those tools must be able to manage both the very long lifetime of investments in power production capacity and grids and the very short period of variability of some sources.

ACKNOWLEDGMENTS

The authors want to thank the institute Carnot-Energie du Futur of Grenoble for supporting the PROSPEN Project and the Défi NEEDS for supporting RUSDYN project.

REFERENCES

1. 1. P. Criqui et al., "Mitigation strategies and energy technology learning: An assessment with the POLES model", *Technological Forecasting and Social Change*, 90, *A*, 119-136 (2014).
2. Zakari et al. *"Interdisciplinary Prospective Analysis of Nuclear Power Technological Transition"*, ICAPP 2011 proceedings (2011).
3. Uranium 2014:Resources, Production and Demand, IAEA (2014)
4. S. Gabriel et al., "A critical assessment of global uranium resources, including uranium in phosphate rocks, and the possible impact of uranium shortages on nuclear power fleets, *Annals of Nuclear Energy*, **58**, 213-220 (2013)
5. A. Monnet et S. Gabriel, *"Uranium from Coal Ashe : Resources Assessment and Outlook on Production Capacities »*, URAM conference, IAEA, Vienna, Austria (2014)
6. World Distribution of Uranium Deposits (UDEPO) with Uranium Deposit Classification, IAEA-TECDOC-1629 (2009)
7. Schneider, E., et al., A top-down assessment of energy, water and land use in uranium mining, milling, and refining, *Energy Econ.*, (2013)
8. Deffeyes, K.S., MacGregor, I.D., *World uranium resources*. Sci. Am. **242**, 66–76, (1980).
9. Technical and Economic Aspects of Load Following with Nuclear Power Plants, OECD/NEA, (2011) https://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf
10. Després, J., Hadjsaïd, N., Criqui, P. & Noirot, I., Modelling the impacts of variable renewable sources on the power sector : Reconsidering the typology of energy modelling tools *Energy*, **80**, 486-495 , (2015).
11. Criqui, P., Mima, S., Menanteau, P. & Kitous, A. Mitigation strategies and energy technology learning : an assessment with the POLES model. *Technological Forecasting and Social Change*, **90** Part A, 119-136, (2015).
12. A. Bidaud et al., Uranium Resources, Scenarios, Nuclear And Energy Dynamics, GLOBAL Conference, Paris, (2015)
13. Nahmmacher P, Schmid E, Hirth L, Knopf B. Carpe diem: *A novel approach to select representative days for long-term power system models with high shares of renewable energy sources*. 2014. https://www.pik-potsdam.de/members/paulnah/nahmmacher-carpediem-wp.pdf
14. J. Despres, PhD Thesis, Université de Grenoble-Alpes (2015).