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Uranium Resources, Scenarios, Nuclear and Energy Dynamics

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Abstract –*A dynamic simulation of coupled supply and demand of energy, resources and nuclear reactors is done with the global model Prospective Outlook for Long Term Energy Supply (POLES) over this century. In this model, both electricity demand and uranium supply are not independent of the cost of all base load electricity suppliers. Uranium consuming Thermal Neutron Reactors and future generation, free from the uranium market once started, breeder reactors are only one part of the market and are in a global competition, not limited to the other nuclear generation.*

In this paper we present a new model of the impact of uranium scarcity on the development of nuclear reactors. Many scenarios rely on the subjective definition of ultimate uranium resources. We suggest that when uranium will mainly be extracted together with other resources, its cost should not be simply a function of cumulated uranium mined but also of mine yearly outputs. We describe the sensitivities of our model to breeder reactor physical performance indicators. Used fuels can be seen as a liability or as a source of usable material and a scarce resource limiting fast reactor startups in fast development in India or China. We present the impact of synergetic strategies where countries with opposite strategies share used fuels.

I. INTRODUCTION

Dynamic fuel cycle models run by reactor physicists can model the development of many nuclear reactor technologies. In particular they often model scenarios involving uranium consuming reactors and future generation, free from the uranium market once started, breeder reactors. They are able to give detailed calculations of radioactive materials and make assumptions about an exogenous "demand" for nuclear energy and fixed availability of uranium resources. The different nuclear reactor technologies are supposed to be in a competition to try to fill the gap between "nuclear demand" and installed power as a function of their relative costs. The "nuclear demand" is usually assumed to be independent of the actual cost of electricity of the composed nuclear reactor fleet and then of the natural uranium market.

Reciprocally, advanced global energy models such as POLES [1] (Prospective Outlook for Long Term Energy Supply) are able to propose a calculation of prospective electricity market, modeling both supply and demand match as a function of all technology costs (including energy saving costs). In those models production costs are based on addition of investment costs, operation and maintenance and fuel costs. As opposed to nuclear scenario codes such as DANESS [2], TIRELIRE-STRATEGIE [3] or COSI [4], the demand for nuclear energy is not user defined.

Here a presentation of updated global energy economic model with a very simplified physical coupling of two types of reactors is made. Some sensitivity studies to uranium market assumptions and breeder reactor performances are proposed.

I.A. POLES world energy model

The model simulates the energy demand and the supply of 45 countries and 12 regions in the world. It covers 15 sectors of energy demand (primary industries, transportation systems, residential and services), forty technologies of electrical production and hydrogen. Another module, called TECHPOL, supports their economic and technical specificities. For the demand, the behavioral equations take account of the combination of the price effects, the incomes, the technic economic constraints and technological changes. 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 down to a "floor" cost. 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 technology [1].

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 market, which balances international flows of energy. The changes in oil, gas and coal prices are endogenous, and take account of the utilization ratio of the capacities of the Gulf for oil, the reserves compared to the production of gas and oil, and the tendency for this productivity as well as its cost.

The choice between technologies is made in order to optimize the energetic mix according to physical (capacity installable, availability…) and economical parameters (production costs of electricity…). 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 competitivity of each power sources. The load factor of technologies that do not benefit from feed in tariffs is calculated as a function of their respective order of merits Given their low marginal cost, nuclear reactors are expected to work as base load with a fixed load factor of 0.85..

The choice between the two nuclear technologies available in POLES is of course driven by their relative competitiveness, their feasibility and the availability of their fuels. Strategic drivers like energy independence that would allow the Fast Breeder reactor (FBR) development before they reach economic competitiveness are not taken into account. The main strength of POLES is that any of these two nuclear technologies should also be competitive with any other electricity production systems.

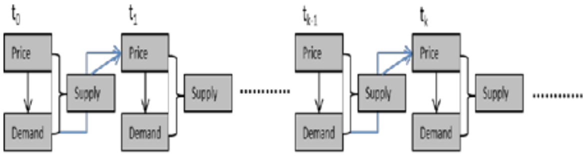

Fig.1 The iteration process simplified

II. NUCLEAR TECHNOLOGY MODELING MODEL

II.A. 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 [5]. All TR needs natural uranium as if using UOX fuels. Please note that no difference in the models as a function of reactor models (ex: AP1000, ABWR, EPR etc…), or fuel types (ex: UOX, MOX…) inside one family can be made and are then completely ignored. Their used fuel contain about 1% of Plutonium. Fast Breeder Reactors need a fissile materials inventory obtained from recycled TR fuels to start up. We will see in III.A that the FBR deployment is very sensitive to this inventory. It will be changed in a large range between 12 and of 24 t of equivalent Pu per GWe. The latest, which gives the most prudent development, being usually the default, might not be the most representative value. The default breeding potential is set to 5% as their MOX fuels are expected to be fully recycled. Discussions about the sensitivity of the results to these assumptions are made in III.A.

Uranium costs and limited availability of resources are discussed in II.B. 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 very indirectly dependent on the assumptions taken on uranium price and resources availability. Dependence on investment costs was discussed in [5]. Results are that FBR development can be delayed if FOAK investment costs are increased but will eventually be equal to the reference case as this development is limited by the availability of Plutonium for FBR start ups and not by their economic performances. If long-term "floor" price are increased, i.e. when large deployment and associated learning curve do not lead to effective cost reductions, then FBR share of the power market can be "permanently" reduced and the potential of used fuel not completely exhausted. In both cases the reduction in FBR share is not compensated by an increase of the other nuclear technology: TR. We hardly ever observe the two technologies as competitors as is expected by classical nuclear energy scenario studies.

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

II.B. Modeling Uranium scarcity

The limits of different reserves categories of IAEA Red book [6] 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 are expected to be developed much faster once the perspective of uranium scarcity would become clearer. 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.

Defining the maximum amount of “Ultimate resources” is very difficult as there is no expected limit to something unknown such as “unknown” resources. The total amount of the most improbable category is much smaller that the amount of uranium probably existing in the deposits described in the UDEPO database [9]. The importance of this limit is very high in nuclear energy simulations. By default we use the sum of identified resources, undiscovered and unconventional resources which would amount to a little less than 25MT of “ultimate resources”. When such a limit to “ultimate” resources is used in the modeling of nuclear energy transition scenarios, the very high uncertainty in its definition is automatically transferred into uncertainties on the startup dates of FBR industrial developments. Fig 2 compares the evolution of TR and FBR installed power when the estimated “Ultimate resources” are doubled. In both cases, the installed power of TR reaches a maximum and then decreases. This maximum happens later and at a higher level when more uranium is available. In classical, nuclear only, scenario tools, a “nuclear” demand must be answered whether by TR or by FBR. If more uranium is made available, more TR can be operated and the share of FBR is usually decreased. In POLES, there is no “nuclear” demand but a demand for electricity that is dependent on available power sources and associated costs. One can see on fig. 1 that in this case, FBR installed power increases with available uranium instead of decreasing. If FBR can produce electricity in a competitive market, they would be built. As in this model, TR are limited by uranium availability, and FBR limited by the availability of fissile material recovered from TR used fuel recycling, FBR tend to have similar behavior than TR and not be in a competition with them. The limitation in uranium reduces TR development that will eventually limit used fuel availability and production of initial inventories of FBR.

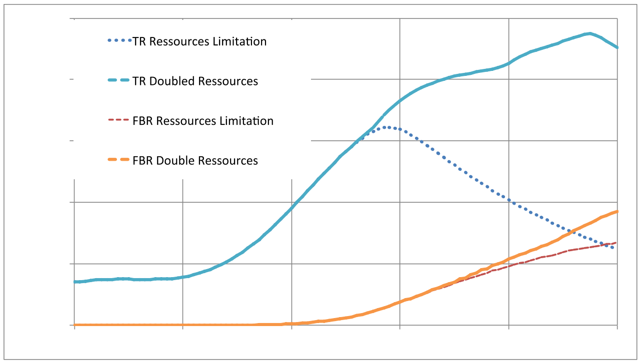

Fig. 2. Comparison of world installed capacities for the 2 technologies (MW left axis) as a function of Ultimate Uranium Resources.

One of the limitation of those models where nuclear development is only limited by the difficult definition of ultimate resources is that it makes nuclear development mainly dependent on this particular uncertain parameter and less on others such as uranium cost or TR construction costs: whatever those costs, once the uranium peak is passed TR will disappear. It is very unlikely that this unique parameter can have some much impact at any time after the peak.

The “peak uranium” produced by these models is a direct consequence of the assumption that a limit in the total quantity of minable uranium exists. This limit is not very compliant with the crustal uranium distribution with ore grade [6] that shows rapidly growing uranium volumes with decreasing ore grade. The existence of a peak uranium would mean that, at a given unknown grade, the ratio of minable uranium to available uranium should fall dramatically. The growing energy intensity of uranium mining with decreasing ore grade is discussed as a reason for this “cliff effect”. It is unlikely that one would spend more than one unit of energy in uranium mining to extract the equivalent of another unit of electricity in a nuclear power plant. Some recent projections of energy intensity of different mining techniques [7] demonstrate that the ratio of the energy used in the mine to the energy produced in the reactor would probably not exceed 3% during this century. This means that the energy cliff is very unlikely to explain the limit in uranium resources.

II.B.1 Limit in Production Capacity

To overcome the limits of resources limited models, a new model of the impact of uranium scarcity on thermal reactor construction is presented. Recently, a limitation of the flow of uranium has been added to the classical limit in volumes of uranium availability.

UDEPO lists important resources of uranium that 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.

The main idea of our model is to transfer the question of the uncertain existence of "ultimate" uranium resources into their certain existence with an uncertain but higher extraction cost.

II.B.2 New Natural Uranium Models

The new "3D" model for uranium price as a function of both cumulated extracted uranium and annual uranium production is shown on Fig. 3. For low uranium productions, the supply curve is based on the cost categories of AIEA red book used previously. The price is linearly interpolated for volumes setting the limits of cost categories. After some trigger uranium flows, the price of uranium is expected to increase linearly with the annual production rate. The trigger levels are themselves expected to be lower with the increase of uncertainty of available uranium resources. Our review of bibliography [7,8] shows that even thought the resources volumes are very important, the flows of economically recoverable uranium is probably very limited. Then, increasing the production of uranium would imply a very strong increase in the share of uranium sales in the economic model of the mines.

Given the fact that the production will not only depend on co-production, we have sets rather optimistic limits in uranium flows (typically 40kt/y by the time where "undiscovered resources" would be exhausted) and target costs (about 1000$/kgU for a flow of 200kt/y when the 7MT of Reasonably Assured Resources are used) (Fig.2).

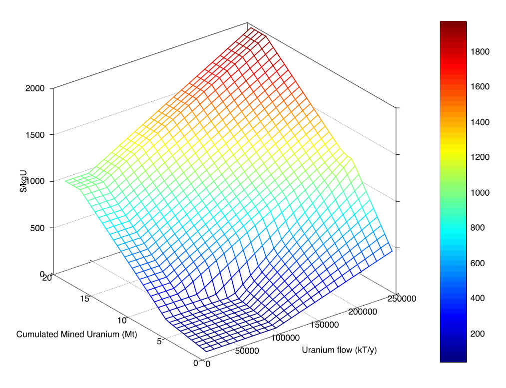

Fig. 3. Uranium Price ($/kgU) as a function of cumulated mined Uranium (Mt of U) and mining rates (kt/y)

II.C. Scenario studies

Fig. 4 shows the comparison of TR and FBR installed power as a function of the uranium market models. For TR, the "peak uranium" cannot be seen anymore. Nevertheless the global consumption of natural uranium in 2100 in both models is very similar and approaches the 25MT of "ultimate resources" discussed previously. The former limitation in uranium expected availability is not so rigid anymore but the result of the balance of supply and demand. Fig. 5 shows that the new model tends to produce higher uranium prices, which would naturally limit the demand for Thermal Reactors without the need of defining a "fear of uranium shortage". The former limit in finite volumes is transferred and simulated by more expensive yearly productions.

FBR development follows somehow the same trend as before. If their over cost when compared to TR is reasonable, their potential market share is expected to be much bigger than the limits on the availability of initial fissile inventory coming from limited recycled materials. The earlier development of TR in the older model makes FBR development slightly faster with the new one.

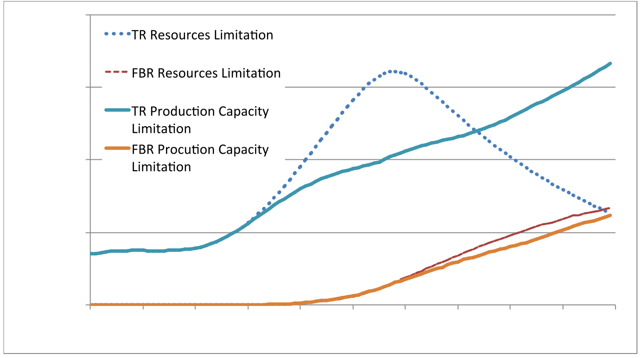

Fig. 4. Comparison of TR and FBR capacities (MW) if using limit in Ultimate resources or new dynamic uranium price formulae

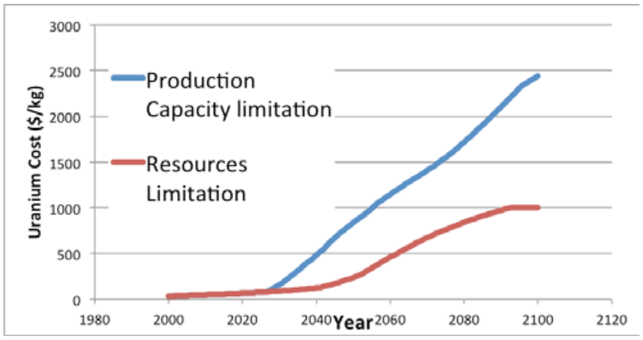

Fig. 5. Comparison of uranium price ($/kgU) if using limit in resources limitation or the limit in production capacity

The new model makes uranium prices higher and very sensitive to our “target” flows and uranium prices. Fig. 6 shows the comparison of TR and FBR installed power as a function of the target prices for uranium prices for high total volumes of cumulated extracted uranium or for very high flows (200kt/y when 7MT of natural uranium would have been extracted). Those high-end prices are reduced from 1000$/kgU to 700$/kgU in the two cases compared in Fig. 5. A reduction in the cost of uranium makes TR more competitive than other electricity generation technologies. FBR share could be reduced and it is very slightly the case at the very beginning of their deployment. But as soon as FBR develop massively in the second half of the century it is the unavailability of fissile material for initial inventories that reduces the speed of their deployment and not their lack of competitivity against TR. Then with the reduction of uranium price, more TR would be operated and more used fuel could be reprocessed and plutonium valued in FBR initial first cores for start up. Here again, an increase of uranium availability would make FBR market share bigger. The two technologies are not in a competition limited to themselves.

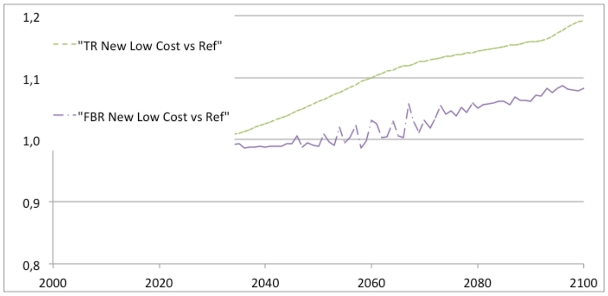

Fig. 5 Changes of TR and FBR installed capacities when using lower “target prices”

III. SENSITIVITIES TO PHYSICAL PARAMETERS

II.A. Breeding gain and FBR fissile initial inventories

Table 1 shows the changes in TR and FBR installed power in 2100 when FBR breeding gain is increased by 5% (its value is 10% instead of 5%) and when the initial inventory is reduced by 50% from 24T/GWe of equivalent Plutonium to 12T/GWe. A 5% change in breeding can be obtained with a different blanket design such as addition of another row of fertile assemblies or an axial fertile layer and has a small impact of the FBR development rate. A total fissile inventory 24t/GWe is probably in the higher range of the expected values for the different concepts proposed as GEN IV reactors. That is why a sensitivity tests has been done with a value in the lower range. A reduction to 12T/GWe of fissile loading is probably difficult to achieve. It would mean a change of fuel to coolant ratio, which is not easy to do without a reduction of some thermo hydraulics margins. Changing the fuel type is an option. For instance Indian scenarios often rely on a change from oxide to metallic fuel. A change of recycling technology from hydro to pyro processing and the reduction of out of core cooling period could also reduce significantly the needed fissile inventory.

Both these changes have a very strong impact on the FBR development with sensitivities of almost 1 %/% in both cases. One percent increase of breeding gain would increase the FBR installed power by one percent. A reduction of the FBR fissile inventory by a factor 2 would change the FBR installed capacity by a factor of 2.

TR installed power change is very small (less than 1%). Once again, we do not observe competition between the two technologies if both technologies are cheap enough when compared to non-nuclear technologies. If they are competitive then, they are limited only by the availability of fissile materials.

TABLE I

Sensitivities of Installed Power in 2100 to breeding gain and FBR fissile inventory

Parameter	TR Change	FBR
Breeding gain (+5%)	- 0,1 %	+ 4 %
FBR Fissile Inventory (-50 %)	+ 2 %	+120 %

III.B. Synergetic strategy scenarios

The AIEA project ‘Global Architecture of Innovative Nuclear Energy Systems’ (GAINS) has shown that sustainability of Nuclear Energy Systems will be easier to achieve on a global scale if technology users and suppliers collaborate and highlighted the advantages of a transition to a globally sustainable nuclear energy system. The diversity of strategies is very wide and ranges from fast development to nuclear phase-out. Some countries (India, China etc…) may be short of fissile materials to start up FBR when others will be heavily investing in underground repositories for permanently storing their used fuels. The new INPRO Collaborative Project SYNERGIES (Synergistic Nuclear Energy Regional Group Interactions Evaluated for Sustainability) clarifies how collaborations facilitate this transition. The main idea is that the liabilities of what could be wastes in some countries could be turned into valuable materials in another country. We have seen that if FBR can be competitive with other base production electricity technologies (TR being only one of them) their development would be limited by the availability of TR recycled materials. In all figures presented up to now, used fuel inventories where defined and usable only by each country. Fig. 6 shows how TR and FBR installed power are changed when used fuels inventories are shared all regions defined in POLES. One can see that FBR development is slightly faster with such a collaborative approach. The growing rate of FBR is increased by as much as 20% at the beginning of their development and even faster in some countries. As the fast growing countries have access to larger used TR fuels, they can increase the recycling of those fissile contents of those foreign fuels in local FBR initial inventories. By the end of the scenario, the importance of initial inventories in fast growing countries reduces as they have the time to accumulate their own local TR used fuels. The advantage of this strategy is that it allows a faster startup of FBR in the most demanding countries. The other side of the same coin is that the countries that would have had no usage and then, would be forced to store these materials in classical strategies can reduce the cost associated with the final repository thanks to the shared strategy.

Once again, this strategy has no impact on TR development, which demonstrate once again the importance of comparing nuclear reactor costs in a broader competition.

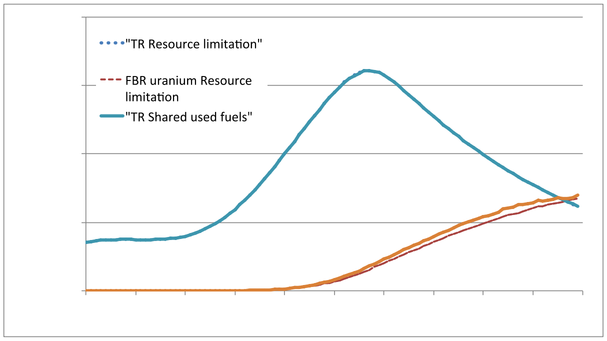

Fig. 6. Change in TR and FBR installed power if used fuels are shared.

IV. CONCLUSIONS

Results of using a general energy prospective simulation tools instead of a nuclear energy modeling tools show that nuclear technologies is surprising as the two technologies are usually not in a competition. If both generations of nuclear reactors can be competitive with other sources, we see that in many countries their development would probably be limited by the availability of natural and recycled materials. Depending on the locally available alternative (hydro, coal) and local regulatory framework (safety and waste management for nuclear reactors but also environmental constraints such as CO2 targets), both nuclear technologies could be developed. The update of POLES uranium market model is not changing the most surprising parts of the models. The advantage of the new model is that it avoids the difficult question of defining “ultimate resources”. The drawback is that it needs a description not only of the uranium resources’ volumes but also the link between the cost and the potential production capacities of these resources. It is believed that huge resources exist where uranium can be extracted as a co-production but that these resources cannot be extracted at very high speed economically as the need for the co-product may be too small to justify to haste its extraction.

Sensitivities to the new uranium market, to the main physical parameters of FBR models were shown. They demonstrate the potential for a new insight of nuclear technology transition carried by a general energy model such as POLES. This model can also estimate the impact of a strategy based on collaboration such as those envisioned in the AIEA project SYNERGIES.

ACKNOWLEDGMENTS

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NOMENCLATURE

FBR Fast Breeder Reactor
TR Thermal Reactor
POLES Prospective Outlook for Long term Energy Systems

ANNEX

We consider very simple models of generic Thermal Neutron Reactor technology and Fast Breeder Reactors. The use of generic names in POLES hides the diversity of both current and future designs.

The fuel used in TR will be very comparable with the UOX used in current reactors. No MOX or recycled uranium strategy is implemented ye. Some characteristics of POLES generic TR are:

- Average Burn up: 40 GW_d/t
- Average Load factor: 85%
- Uranium consumption: 210 t/ GWe.y or 28kg/GWhe.

- Overnight construction costs depend on the country and decrease because of learning curves from typically 3$/W to 2,3$/W
- Levelized Cost of Electricity (COE): evolves from 0.06 $/kwh$_e$ at the beginning of the scenario to 0,1 $ kwh$_e$ at the end as the increase in Uranium price cannot be ompensated .

The various designs of Fast neutron Breeder Reactors (FBR), for instance the differences between GEN IV reactors cannot be simulated easily in POLES. We were looking for technologies that allow regeneration of the fissile isotopes. So our generic FBR reactor may hide different technologies such as Na, or Pb cooled. Even Thorium Molten Salt Reactors could be there as far as they allow regeneration and need recycled materials to be started. FBR will probably be and remain more expensive to build than current reactors, and have a rather big initial inventory of fissile isotope. The reduced experience in the operation of such reactors is often expected to decrease the load factor and increase the Operation and Maintenance costs. We expect that on the long term one the experience can be accumulated and our default assumption is to have the same O&M costs for TR and FBR. Changing these values may change the absolute values of TR and FBR capacities but they would not change the dynamical effects discussed here and the importance of the global competition. FBR will probably have a more efficient fuel cycle in terms of natural uranium use and minor actinide production. The FBR fabrication and recycling cost expressed in $/kg of fuels are higher than those of TR. Nevertheless, the higher burn ups and plant efficiency, and the absence of enrichment cost are assumed to close the gap between the two fuel cycle costs not including uranium costs. Here are the characteristics of POLES generic GEN IV reactors:

- Average Burn up: 100GW$_d$/t
- Initial fissile inventory needed for both the reactor and its associated fuel cycle: 12t/GWe or 24t/GWe
- Average Load factor: 85% is probably ambitious for FBR and not enough for TR.
- Overnight construction costs: 30% more than those of TR in average.
- Cost of Electricity (COE): decreases from 0,2$/kWh to 0,05 $/kwh$_e$ thanks to learning curves.

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