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On nuclear energy and its perceived non-sustainability

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Public opinion is divided regarding the use of nuclear power for electricity generation, and there is a generalized feeling about its lack of sustainability. It is considered not sustainable in terms of its environmental impact and its potential health risk in the case of accidents, the fact that the fuel is non-renewable and, to a lesser extent, on the price tag of the project. In this paper, the four main arguments against nuclear power will be analyzed and discussed: the risk perception and safety considerations, the generation of waste and what to do with it, the cost of nuclear installations and the availability of fuel. For each of these problems, potential strategies and/or arguments in favor of nuclear power are presented, and the options and opportunities for Mexico are discussed as well.

Keywords: Energy policy; nuclear power; economics of energy; nuclear fuel; fusion; small nuclear reactors; reprocessing; risk perception.

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1. Introduction

Nuclear power is an energetic option in a singular position: it reduces greenhouse gas emissions considerably, but it is typically not regarded as a sustainable energy source due to factors associated to risk perception by the general public and legacy waste, as well as economic considerations. During the almost 15,000 reactor-years of operational experience, there have been three severe accidents in the nuclear power industry since the start of commercial operation of nuclear reactors in the 1950s: the partial meltdown of a pressurized water reactor (PWR) core at the Three Mile Island power plant in Pennsylvania, USA in 1979; the catastrophic explosion of a russian high-power channel-type reactor (RBMK) graphite core in the Chernobyl power plant in Ukraine in 1986; and the 4 units that went completely dark and suffered a loss of all coolant event at the Fukushima power plant in Japan in 2010. This last event has stopped a trend that before it occurred was regarded as a resurgence of nuclear power [1-3], and has also fueled an important opposition to the use of nuclear power as an energy source.

In the present paper, the four issues that are usually quoted as severe handicaps for a more aggressive implementation of nuclear power (safety and risk perception, cost competitiveness, fuel availability and waste generation) will be addressed and discussed based on a literature review, and the current strategies taken by the nuclear industry to resolve these issues will be presented. A short analysis on the current position of Mexico and its opportunities from the perspective of nuclear power will be presented as well.

2. Safety, risk and its perception

Technological advancement, especially during the last century, has created an interesting paradox: people view themselves more rather than less vulnerable to the dangers and threats posed by technology, despite steady improvements in health, safety, and longevity derived also from technological advancement [4, 5]. Government entities aimed at assessing and managing risk in many different fields have emerged in advanced industrial societies.

Risk is typically defined as the likelihood of an undesirable outcome or harm to the individuals and/or to a collective of individuals. In most *risk assessment* methodologies, two factors are used to attempt a quantification of risk: the probability of occurrence of the events and the magnitude of its consequences (i.e. a measure of undesirability) under a pre-established framework (economic loss, deaths, environmental impact, health impact, etc.). The risk is usually defined by multiplying the two terms, under the assumption of a commutative property: the risk of a low-consequence/high-probability event is equivalent to the risk of a high-consequence/low-probability event. There is, however, a component often ignored which is critical to the acceptance of risk, and this is the subjective component, the *individual* perception of risk. From this point of view, the likelihood and the seriousness of a consequence, and hence the apparent risk, are strongly influenced by personal traits and socio-cultural parameters, a process known as *risk perception* [6]; the study of risk perception addresses the question of why people perceive different hazards differently. It has been found [5, 7] that perceived risk is quantifiable and, more importantly, predictable despite being subjective; it correlates strongly with personal benefit or pleasantness (the more tangible the benefit, the lower the risk perception), the sensation of freedom (when the risk is assumed from personal choice, the lower the risk perception), the feeling of dread it inspires (higher dread feeling, higher risk perception), the degree of tangibility and knowledge (higher risk perception for unknown and/or invisible things). Research in psychometrics has proven that risk perception is highly dependent on intuition, experiential thinking, and emotions [4, 6].

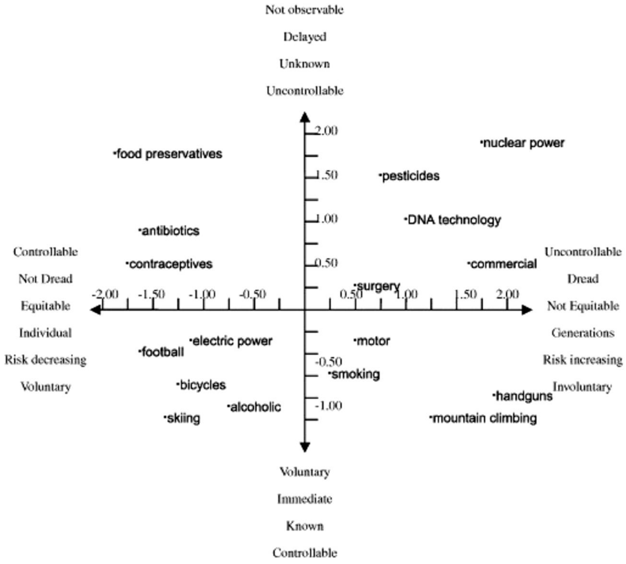

FIGURE 1. Placement of nuclear power on the perception paradigm chart, along with other risk activities and technologies [5].

Nuclear power is a technology with an unusually high risk perception (see Fig. 1): to the general public its benefits are very low, the feeling of dread it inspires (due to the inevitable association with weapons and the consequences of their use) is very high, it is regarded as an unknown and invisible threat, and is also perceived as a source of undesired legacy for future future generations [7]. Mistrust in the institutions behind nuclear power and media hype surrounding the three major nuclear accidents have reinforced, but not generated, these perceptions towards the technology [8]. It is believed that the feeling of dread inspired by nuclear power will be very difficult to eradicate by informative campaigns, so the focus should be on making its benefits more tangible [5]. Following the Fukushima accident, the German government declared a moratorium on its nuclear program and announced its decision to phase it out completely by 2022, with renewable energy sources (solar and wind) substituting that capacity [9]. If Germany fails to demonstrate that an industrialized country can cover its energy needs and curb its CO_2 emissions with an energy portfolio based heavily on renewables, then nuclear power may have the only thing capable of reversing the strong aversion towards it: the very tangible need for it.

Safety refers to the engineering controls devised to protect the public from accidents, and it is a very important aspect of any industrial activity [10]. Due to the dangerous nature of the materials handled in the nuclear power industry, it is one of the most safety-regulated economic activities. International and domestic organisms in each country are charged with the safe operation of nuclear installations around the world.

Safety design has two shortcomings: it makes use of risk assessment methodologies (rather than risk perception) in order to remain objective, and it can only mitigate the risk, but not eliminate it completely [10]. The first shortcoming means that a generalized sense of safety will never be achieved, in particular when the risk perception of the collective is high; the second means that unwanted events will still happen because the imagination of the risk analysts is limited, the number of possible failure scenarios is infinite and the time and resources allocated to safety analysis and implementation are finite [11]. Safety design is charged to experts in the field, whose risk perception more than always differs significantly from that of the general public [12]; this fact, combined with the mistrust in industry and regulatory bodies (which are often confused with or heavily influenced by lobbying bodies) causes the general public to challenge the safety measures in nuclear installations [13].

Safety is not a static concept: what was safe yesterday is not typically safe today, it is a learning process. Safety engineering is enriched by operational experience; all accidents, from minor mishaps to near-misses to severe accidents enrich our knowledge of the process from the safety point of view, and eventually lead to new regulations, design modifications or modified protocols. Some industrial activities have the possibility of undergoing this process with manageable consequences, but not the nuclear industry [14]. Three major accidents and day-to-day mishaps in nuclear power plants [15] highlight that, despite not being desirable, this industrial activity is also immersed in this learning process. Operational experience is useful at incorporating into safety engineering two important aspects often overlooked in an engineering reliability study: human factor and organizational culture [14, 16]. Implementation of adequate training programs, strong codes of professional ethics an external oversight into operation can help mitigate the undesired effect of human and organizational factor on the safety of nuclear installations [17], but with regards to the engineering design the tendency has been to “patch” safety shortcomings of plants designed and built 40 years ago. This is justified by operators stating that major modifications to design would represent a significant investment on a project that was already expensive to begin with, or the adoption of an unproved design that looks “inherently safe” on paper but on which no construction or operational experience exists [16]. A closer and more stringent look should be taken at the license extension process for nuclear installations that may operate reliably, but not be safe enough due to their age and outdated designs [18].

3. The waste issue

One of the main concerns regarding the use of nuclear power is the generation and subsequent disposal of spent fuel. The production of electricity by nuclear means has created radioactive residues which have to be carefully managed and accounted for because they are hazardous to human health [19]. The waste exists in solid, liquid and gaseous forms and is derived from both civilian and military nuclear activity. High level solid radioactive waste is the product of once-through fuel cycle operation (common practice in the United States) and the solidification of liquid waste generated in the fuel reprocessing process. This waste is currently being stored in purpose-built stores pending final disposal deep underground.

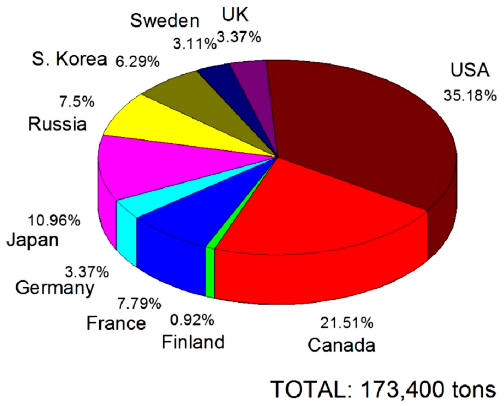

FIGURE 2. Spent fuel inventory from OECD countries with nuclear activity.

With a nuclear worldwide capacity of 375.2 GWe and an energy content of roughly 263 GWeh/ton, the yearly amount of nuclear waste arising from spent fuel is on the order of 10,000 tons, or 4000 m^3 [19]. The accumulated inventories of direct disposal (no reprocessing) spent fuel from the roughly 50 years of nuclear reactors operation is 122,000 tons just for the OECD countries [20], distributed as shown in Fig. 2, with the actual global inventory closer to 230,000 tons in (2003) [21]. The spent fuel generation rate is expected to increase significantly, as emerging economies decide to increase the share of nuclear power in their energy generation mix, doubling the number of reactors in a time horizon of 15 years [22-24].

The history of technical and sociopolitical problems associated with spent fuel in the United States is quite illustrative for countries working on open fuel cycles. In the early days of the nuclear industry, utilities were assured that waste would be responsibility of governments, who would undertake fuel reprocessing activities and provide a repository for all waste generated by the industry [25]; this repository, however, never materialized. To make matter worse, fuel reprocessing activities that reduce the amount of waste by separating inert material from the spent fuel were stopped in the US by the Non-Proliferation Act of 1978 [26], a decision derived from the fear that making the technology of plutonium refining (closely related to reprocessing) available to the private sector would inevitably lead to nuclear weapons proliferation. At the time, the administration of President Carter expected all countries to follow suit, but both Great Britain and France, their strongest nuclear allies, decided not to align to such policy and continued their nuclear fuel reprocessing activities domestically.

Under pressure from the utilities not having enough short-term storage and the ever increasing amount of spent fuel derived from the growth of the industry, the US government finally agreed to pass the Nuclear Waste Policy Act (NWPA) in 1982 [27]. The utilities acquired the obligation to contribute to a fund for the development of the long term storage site, and the US government assured them that it would start formal studies for site selection. By 1987, Yucca Mountain, a remote desert location near the nuclear weapons Test Site on the state of Nevada, was selected as the potential site for a geological repository for spent fuel [27], and found to be technically viable 11 years later, almost a year past the deadline established for operation of the repository by the NWPA. A considerable amount of time, money and technical effort went into the qualification and design of the Yucca Mountain site [28], and in 2009, the political decision of cancelling the project was taken, without really offering technical arguments to justify the closing beyond the risk perception of local and federal politicians [29]. Given first the delay on the construction of the site and the final cancellation of the project, the US Department of Energy was involved in multiple legal disputes with utilities arguing breach of statutory and contractual obligations form the part of the government [30, 31]. Given this situation, utilities that are generating nuclear electricity are put in an awkward position: on one hand they argue the safety and acceptability of surface storage of spent fuel for decades into the future, and at the same time they will keep pressing the government to honor its long-past-due obligation to take custody of most of that fuel [32].

The lack of a final repository forces a situation where the nuclear material is scattered at many locations, as evidenced by the US map shown in Figure 3. This presents a security risk associated with terrorism, and also the practice by some utilities of storage schemes far from safe, such as overloaded storage pools without secondary containment. Excess spent fuel in storage pools represents a risk since overloaded storage pools have a risk of achieving accidental criticality [33] or suffer damage due to loss of coolant, such as it happened in the Fukushima plants [34]. It is expected that this will be a severe blow to the nuclear industry, since now the cost burden for long-term storage of fuel in dry cask storage (although lower than wet storage for current prices [35]) will have to be absorbed by the utility, affecting the profitability of new projects.

It is clear that in the case of the US, the government could partially fulfill its initial commitment to the nuclear industry by reactivating reprocessing activity, a move that would greatly reduce the amount of waste and relief some of the pressure of the mounting amount of spent fuel scattered around [36]. If the spent fuel is reprocessed, 94% of the waste mass is recovered as non-waste, and reinserted in the fuel cycle. The remnant part of the waste is composed mainly of minor actinides and fission products, as can be seen from Fig. 4. The radio toxicity of the spent fuel is greatly reduced if the minor actinides are eliminated in either fast reactors [36-38] or in fission-fusion hybrid reactors [39-41], on which the fast neutrons can transmutate or even produce energy from the minor actinides. The hybrid route may have the added benefit of serving as a maturation stage for nuclear fusion technology, which may one day replace fission as the primary nuclear energy source (see the section on fuel availability) [42,43].

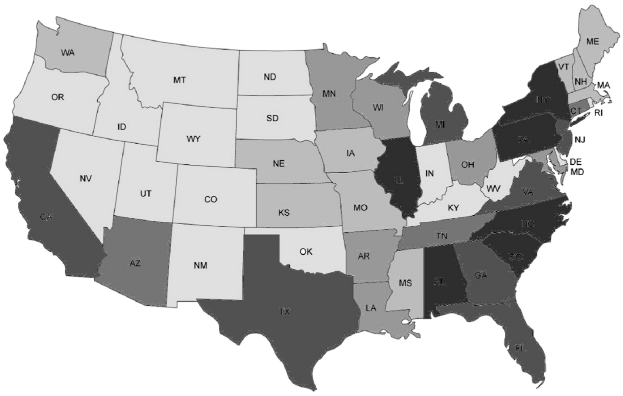

FIGURE 3. Inventory of spent fuel within the United States. Darker color indicates larger amount of fuel.

4. The cost of nuclear energy

People have in the past referred to the nuclear power option as too costly. The three broad components for the total cost of a nuclear project are the same as those for any other project: capital, finance and operating costs. Capital costs comprise the bare plant cost, the owner's costs (land, infrastructure development, licensing, site evaluation, etc.), cost escalation and inflation. The "overnight capital cost" is often used, which only includes bare plant and owner's cost. Construction cost is overnight cost plus escalation and financing during the period of construction; as a rule, the construction cost of nuclear power plants is significantly higher than that for fossil fuel installations. According to the Energy Information Agency of the US DOE [43], the overnight cost of a nuclear power plant on an existing licensed site is on the order of $5,000.00 USD/kW, based on a 2.2 GW installation, which is in agreement with a different study from the Massachusetts Institute of Technology (MIT) [44]. Given this number, such installation would cost 11,000 MUSD. The annual fixed O&M cost (excluding fuel) for the nuclear installation is estimated as $89.00/kWh [43]; for the 2.2 GW project, the O&M cost is 196 MUSD. A pessimistic approximation for nuclear fuel cost is $10.00 USD/MWh, including waste handling (storage) [45], so the initial fuel charge cost is roughly 2 MUSD. Assuming a lifetime of 40 years for the plant and 33% refueling every two years, the total cost of the project would be 18,855 MUSD; the capital investment still represents more than 50% the cost of the overnight plus O&M, and the fuel expense is marginal 15 MUSD for the life of the plant assuming constant fuel cost.

Some of the factors that drive the nuclear power construction cost up are [46]:

- The need to use special materials and the incorporation of sophisticated safety features and back-up control equipment.
- Construction periods tend to be long. From the technical point of view, a good estimate for construction time of a plant with a proven design is 5 to 6 years [46]. Political (often in the form of regulatory) hurdles, public opposition and/or technical oversights in first-of-a-kind (FOAK) projects can lead to delays that increase the financing cost [47], along with the risk of important economic fluctuations, either on supplies or in financing, during the construction phase.
- Plant decommissioning costs are about 9-15% of the initial capital cost of a nuclear power plant. This cost is typically discounted (incorporated into the operating cost), and represents roughly 0.1-0.2 cent/kWh, no more than 5% of the cost of the electricity produced [44,45].

A discussion of the financing cost for new nuclear installations would be lengthy and take much space, so the reader is referred to an excellent document on the topic prepared by the Nuclear Energy Agency (NEA) of the OECD [48]. Summarizing this document, the financial risk in the investment on nuclear power plants has multiple components:

- The high capital cost and technical complexity of the project, which causes high risks of construction delays, cost overruns, equipment failures and unplanned outages.
- The long period required for investment return and loan repay, which increases the risk from electricity market uncertainties.
- The political and regulatory risk associated with the social opposition to nuclear power.
- The need for clear solutions and financing schemes for radioactive waste management and decommissioning, which only governments can formulate.
- The need for NPPs to operate at high capacity factors, preferably under baseload conditions.

The financing situation for nuclear projects is not very encouraging for most of the energy markets in the world [49], independently of the state of worldwide economics. During the major expansion of nuclear power in the 1970s and 1980s, the historical evidence shows projects which faced construction delays caused by diverse factors, but mainly regulatory and technical showstoppers; these delays resulted in significant cost increases. If this bad historical record is coupled with the lack of recent construction experience, the perceived financial risk is very high from an investment point of view. In addition to technical and regulatory hurdles, nuclear power projects have an additional barrier: despite improved public acceptance in many countries, nuclear remains controversial, and any new nuclear project has a high probability of facing strong opposition among the public, which has the risk of delaying or even halting the project due to social pressure. Investors may even shy away from these projects since their involvement may harm their reputation with some consumer groups [48].

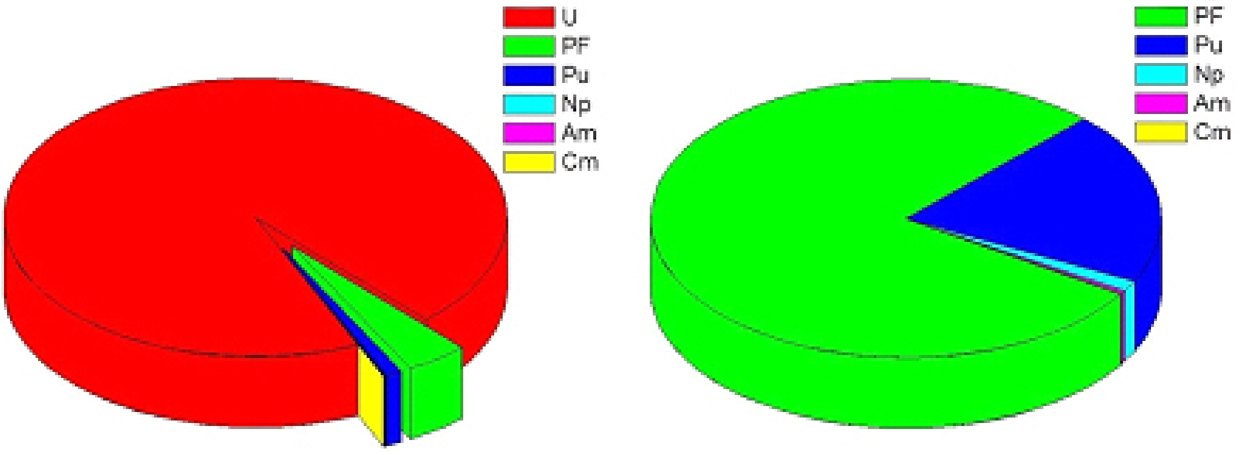

FIGURE 4. Relative content of different actinides in spent fuel considering (left) and ignoring (right) uranium content.

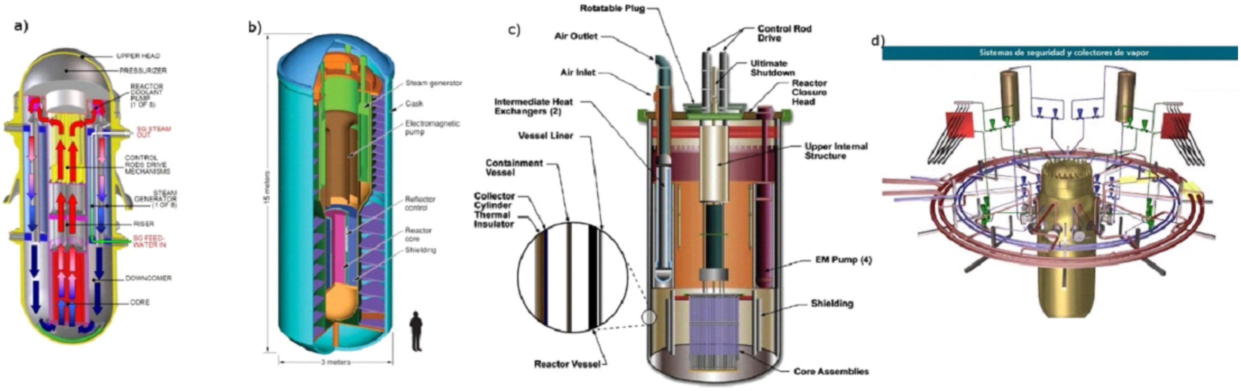

FIGURE 5. Models of some designs of small modular nuclear reactors. a)IRIS (Westinghouse), b)SSTAR (LLNL), c)PRISM (Hitachi), d)CAREM (Argentina) [55].

TABLE I. Cost comparison of various energy technologies (data from [43]).

Technology	Nominal Capacity (MW)	Capacity Factor	Cost (2010 $/kW) Overnight Capital	Fixed O&M	Variable O&M
Advanced Coal	650	0.65	3167	35.97	4.25
Advanced Coal, with CO_2 capture	600	0.65	5099	76.62	9.05
Gasified Coal, with CO_2 capture	520	0.65	5348	69.3	8.04
Binary geothermal	50	0.7	4141	84.27	9.64
Wind, onshore	100	0.3 – 0.4	2438	28.07	0.00
Solar thermal	100	0.15 – 0.25	4692	64.00	0.00
Photovoltaic	150	0.2 – 0.3	4755	16.70	0.00
Biomass (wood) with CO_2 capture	20	0.6	7894	338.79	16.64
Nuclear	2236	0.85	5335	88.75	2.04

The costing of nuclear power has the same problem common to all renewable energy sources: when compared to the option of burning coal or gas, any other options are disqualified on the economic basis; nuclear and renewables are not profitable against fossils unless they have government subsidies. Any expansion of a nuclear power program will require strong and sustained government support in a number of areas, but two of them stand out as critical [50]: establishing the necessary supportive policy, legal and regulatory frameworks; and providing more direct support for financing of nuclear projects. Both France (in the late 1970s) and China (now) have taken the nuclear option seriously, but doing so effectively requires centralized planning of the energy policy, state-backed finance, standardized design and site consolidation, as demonstrated by the case of France [24].

In the general public, there is the vision of nuclear power as a direct competitor with renewables which are considered both clean and cheap [8], without really realizing the shortcomings of renewables in terms of capacity factor, grid compatibility and the need for energy storage infrastructure. Table I shows a comparison between two fossil options (gas and carbon), three renewables (solar thermal, solar photovoltaic and wind) and nuclear energy. The great variety of methodologies and assumptions for estimating costs causes that depending on the author preferences, some or other technology will appear as more economically attractive than other; a case in point is the argument to use total system cost [50] as the economic metric when the study needs to favor nuclear energy; and ignore interconnection and storage expenses, present profitability for low-consumption installations [51] or present externality costs (i.e. social costs) that ignore positive aspects [52] when a case for renewables wants to be presented. During the preparation of the present work, the most thorough, detailed and impartial estimate has been that of the US Energy Information Administration [43], which was used to prepare Table I.

Most of the studies available in the literature regarding the cost of nuclear power plants, even for last generation systems such as the European Pressurized Reactor (EPR) or the Westinghouse AP1000 model, have concentrated on multi-megawatt installations, which are indeed capital intensive. However, little attention has been given to smaller nuclear reactor designs [53, 54], with capacities in the 50 to 300 MW range, such as those presented in Fig. 5. This has been in part derived from the uncertainty in assessing the economic profitability of a prototype, the lack of regulation and operational experience, among other factors. They present, however, some technical, economic and safety advantages that make them look attractive [55, 56]:

- Due to their smaller size, they are not expected to be as capital intensive or require 5 or more years to get constructed.
- Given the smaller inventory, the assessed risk is reduced (a statement that may not be true for the perceived risk).
- Most designs incorporate the latest advances on passive safety features found in the advanced designs of large reactors.
- They are designed as modular units, allowing installations to grow or shrink as the energy market dictates.
- Modular reactors provide safety and potential nonproliferation benefits, since they will be sealed (no refueling on site) and built below grade for safety and security enhancements, addressing vulnerabilities to both sabotage and natural phenomena.
- Their use would not be restricted to electricity generation, some specific designs would be suited for desalinization, hydrogen production or other industrial operations that require large amounts of heat.

Small reactors have the potential to achieve significant greenhouse gas emission reductions, just like their large counterparts. They could provide alternative base load power currently provided by coal generation plants not suitable for carbon capture implementation. They would be an attractive option for regions where other energetic resources (including solar and wind) are scarce. Small nuclear reactors can accommodate factors which are barriers for multi-gigawatt nuclear installations, such as electricity demand fluctuations and limited transmission capacity. The downside to small nuclear reactors is that it is a technology on its early stages [54]: their design, licensing, and detailed engineering activities are in an early stage. Very limited cost data is available and, as mentioned before, such data is full of the typical FOAK uncertainty in costing.

Small nuclear reactors present an interesting prospect for countries interested in the development of domestic nuclear programs without the intensive capital cost associated with large nuclear installations: there are over 60 different designs in more than 15 countries [56]. This design diversity is an indication of great interest, but such a large number of options creates confusion in the market and dilutes the limited financial and human resources available in the nuclear community [57]. Given the early stage of the technology, first adopters will have the opportunity to participate in the process of establishing regulatory framework, build up the appropriate industrial base for domestic manufacturing with the consequent economic benefits and expand their energetic portfolio. Some designs such as the Westinghouse-supported IRIS small reactor are at a very advanced stage of design and even have submitted applications for an eventual construction license to the US Nuclear Regulatory Commission (NRC) [58].

5. The issue of fuel availability

The OECD publishes an annual review of uranium market outlook; according to the 2011 version of this document [58], the proven and estimated uranium reserves recoverable for a cost under 260 USD/kg are on the order of 5 million tons; if we focus on “cheap uranium” (less than 80 USD/kg), the reserves dwell to 3 million tons. Since according to that same report the consumption of uranium for the fueling of the 440 commercial reactor in operation is 65,000 tonnes per year, giving a net fuel efficiency of 260 GWe/kg, or 0.3 USD/GWe in terms of fuel cost. With this consumption rate, the cheap uranium reserves will last roughly 46 years. If the nuclear reactor fleet increases significantly, fuel consumption will increase and the reserves will last for a shorter period [58]. Given the already difficult position of nuclear power, uranium reserves above 100 USD/kg would severely impact the economic viability of nuclear projects. It has been argued that increases in hydrocarbon and coal fuels would allow access to this difficult to extract reserves and prolong the resources;

however, a detailed analysis of the uranium market [59] reveals that uranium price is directly correlated with fossil fuels and by-products prices of uranium purification such as gold. Due to commodity market interconnections, uranium market trends seem to be hampered or enhanced following worldwide impacting events, i.e. oil crisis, electricity prices, steel shortages, etc.

Given this situation, some authors have suggested that the time extension on electricity availability derived from an expansion of nuclear power does not justify the investment on plants that may run out of fuel before their useful life has been completed [60]. However, there are at least four important strategies that can be aimed at extending fuel nuclear reserves: utilization of the nuclear material in nuclear weapons for mixed oxide (MOX) fuel fabrication, the utilization of fast reactor to breed fissile material from natural uranium, spent fuel reprocessing and the implementation of a thorium fuel cycle.

Two of these strategies are extremely sensitive from the nuclear weapons proliferation point of view: fast breeder reactors and fuel reprocessing. This is due to the fact that both technologies can be used to refine plutonium; reprocessing does this by recovering the plutonium generated in standard reactors and fast breeders generate plutonium from natural uranium. Proponents of the fast breeder have argued that without the capability for enrichment and reprocessing it does not represent a proliferation danger, since the plutonium generated in the fast breeder is mixed with the rest of the fuel and cannot be used to built an efficient nuclear explosive in that state [61]. Rgearding reprocessing, it has been proposed as the way to go for the reduction of nuclear waste inventory, but also to recover material that can be reincorporated into the nuclear fuel cycle. As can be seen from Figure 4, about 1.5% of spent fuel is fissile material (U-235, Pu-239 and Pu-241), which can be reused directly in the fuel cycle. The recovered U-238 from the spent fuel reprocessing can be used as fuel on a breeder reactor. A fuel cycle incorporating uranium enrichment, conventional reactors, fast breeders and reprocessing is depicted in Figure 6.

The conversion of nuclear material from weapons into fuel for nuclear power plant has been demonstrated by the Megatons to Megawatts program, an industry-government partnership started in 1995 aimed at converting nuclear materials from Russian intercontinental ballistic missile (ICBM) warheads to fuel for civilian nuclear reactors [62]. This program currently accounts for roughly 10% of the electricity generated in the US, about 13,000 tons since 1995, and is set to expire in 2013 when 500 tons of weapons grade uranium would have been transformed into civilian enriched fuel [63].

The remaining alternative to extend nuclear fuel availability includes the introduction of a completely new fuel cycle based on thorium [64], which is a natural element with a greater abundance (similar to that of lead) than uranium, and with a more homogeneous distribution around the planet. Initial estimates put reserves on the order of 2 million tons, but prospection has not been as intense as in the case of uranium due to the lack of a market; the countries with the most reserves of thorium are India, the United States and Australia [65].

The thorium cycle uses Th-232, a naturally abundant isotope of thorium, which is transmuted into the fissile U-233 isotope by absorption of a neutron. This process is similar to the production of Pu-239 in conventional reactors by the absorption of a neutron by the U-238. Depending on the reactor design and fuel cycle scheme, the U-233 generated from the thorium either fissions in situ or is chemically separated from the used nuclear fuel and formed into new nuclear fuel. Aside of the obvious advantage of being an alternative abundant nuclear fuel, it has also the advantages of being part of a proliferation resistance fuel cycle and reduced plutonium and lower actinide production [66].

6. Perspectives for Mexico on nuclear power

México contributes with roughly 1.6% of greenhouse gases emissions, and occupies 13th place worldwide; per capita CO_2 generation in 2006 was 6.2 tons [67]. Among the commitments assumed by the country to help avoid climate change is the reduction of the 2000 emission levels by 30% in 2020 and 50% by 2050 [67]. These are ambitious goals for a country whose electrical generation energy portfolio relies heavily in gas and coal (75%) and with a strong consumption of primary energy (47%) in the form of liquid hydrocarbon fuels for the transport section [68]. Nuclear energy accounts for 7% of electricity generation with just one dual unit of 1365 MW total power. These two units have been in operation since 1990 and 1995. The government utility (Federal Electricity Commission, CFE) completed an extended power upgrade programme in 2011 on the two reactors, resulting in about a 20% increase in capacity and extended the operating life of the 2 reactors to 40 years, pending regulatory approval [69]. The Mexican government is reportedly considering building new reactors to meet rising demand and to limit greenhouse gas emissions.

Uranium exploration began in 1957 with both ground and aerial prospecting with geological and radiometric methods, and in the period from 1972 to 1980 the activity received a great impulse. Until 1979 exploration was performed by the National Institute of Nuclear Energy, and in 1979 the responsibility for exploration was transferred to URAMEX. The areas explored, in order of importance, are in the states of Chihuahua, Nuevo León, Tamaulipas, Coahuila, Zacatecas, Querétaro and Puebla. Unfortunately, uranium exploration was stopped in May 1983 and URAMEX was dissolved in February 1985 [58], and activities for the exploration, exploitation and benefit of uranium were suspended. In 2008, the Mexican Geological Survey restarted activities on uranium exploration with the analysis, reinterpretation and re-evaluation of existing data, with the aim of developing a database meeting international reporting standards, and additional field work.

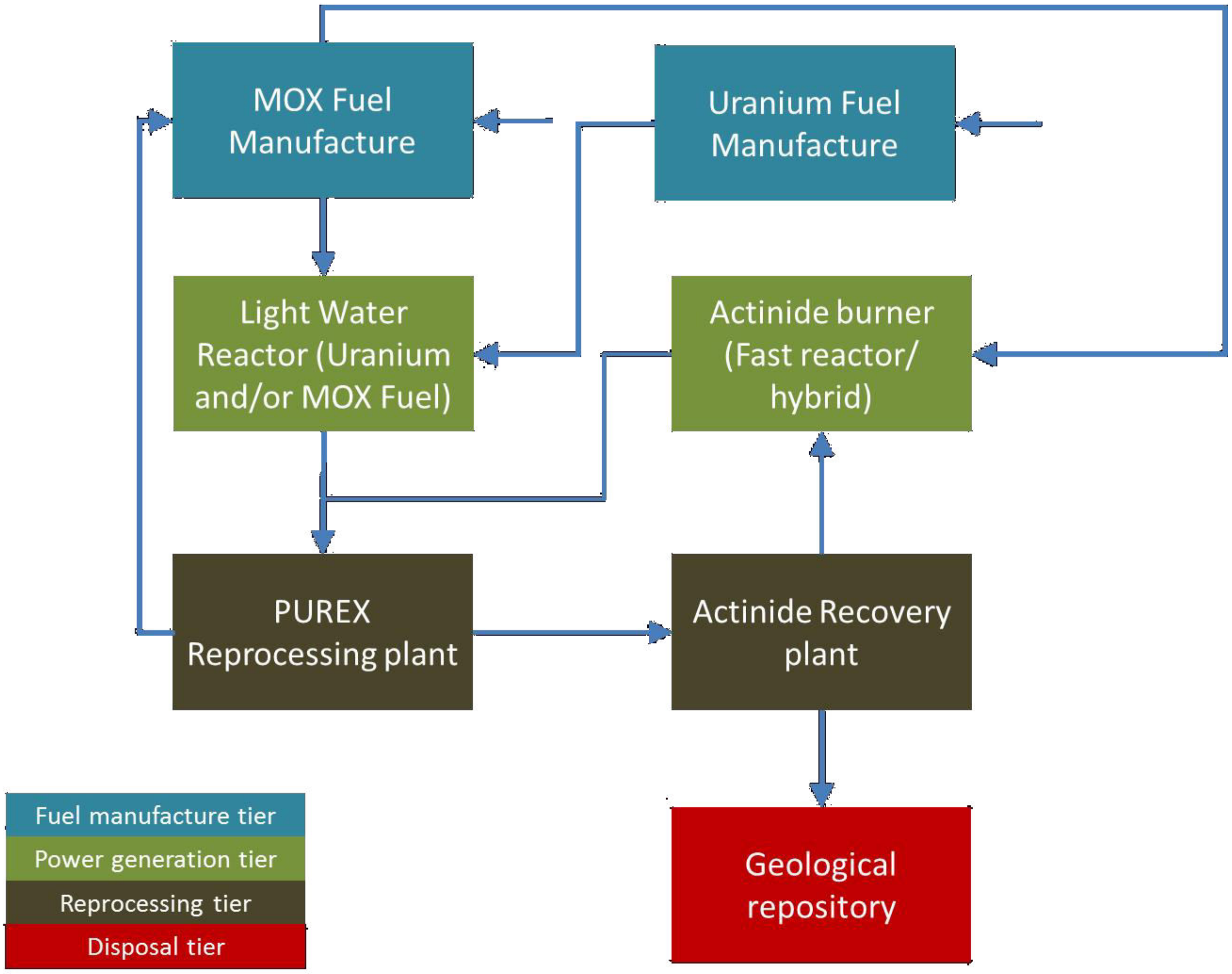

FIGURE 6. A four-tier fuel cycle with the maximum reduction of nuclear waste. Only fission products end up requiring long term disposal.

Among Latin American countries, Mexico is lagging behind Brazil and Argentina. Brazil, just like Mexico, only has one generating station (Angra), but according to the IAEA Brazil has pilot installations (gasification, enrichment and sintering) which would cover an open cycle [70]. Argentina also has only two plants (Atucha I and Embalse) and one incomplete installation (Atucha II). The Argentinians have expressed interest in entering on the small reactor scene with their CAREM design, completely done within the country [71]. Small reactors present a good opportunity for Mexico, given their lower capital investment, the ability to increase capacity in small increments and to boost the local manufacturing industry. The country should take advantage of the central planning in the energy sector, its highly regulated electricity market and the political will after the realization that nuclear energy can help meet the CO_2 reduction commitments acquired by the country. A reinforcement of the human resources capacity will be necessary if the government has serious plans for opening a nuclear option for Mexico's energy portfolio [72].

7. Conclusions

Nuclear power continues to be an option to replace coal and hydrocarbons for base load and dispatchable electricity generation. It is perceived, however, as a technology with very high risk because for the general public the dangers greatly outweigh the benefits and leaves behind legacy waste that is just as risky and dangerous. Since the nuclear danger perception is unlikely to change in the public, the effort to reduce this perception should be focusing on the benefits, such as the reduction of CO_2 emissions and the ability to cover base load demand. To avoid increasing the sense of danger, the safety record of the nuclear industry needs to be even better than it has been up to now; from that point of view, aging plants with outdated designs represent a risk, so any life extension decisions should be carefully evaluated.

Regarding the waste management issue, it will be necessary to minimize the amount by promoting spent fuel reprocessing in countries that continue to use open fuel cycle. Burning of minor actinides present in the spent fuel by means of fast breeder reactors or hybrid fission-fusion systems greatly reduces the radiotoxicity of spent fuel and the storage requirements are greatly reduced.

Conventional nuclear installations continue to be very capital intensive, their construction is faced with delays and the financing is difficult to obtain due to the amount of capital required, the construction time and even public acceptance. The alternative that may potentially represent a more economical route is the small reactors, which unfortunately at this time are in a very early stage of development and will require some time for reaching commercial viability.

Nuclear fuel has the same problem of resource concentration that is observed with oil, with only 15 countries with significant proven reserves recoverable at a low price. The situation is not as severe since half of the proven reserves are present in two stable countries (Australia and Canada) and one near a conflictive geopolitical area (Kazakhstan). The need to develop new fuel cycles, in particular the thorium cycle which makes use of a more abundant material than uranium, continues to be a need in order to make the fuel resource more evenly distributed globally and to extend nuclear power generation into the future, and especially if a significant increase in nuclear installed capacity is expected.

For the case of our country, there are opportunities to adopt nuclear technology and even participate in the generation of new technology via the small nuclear reactors, such as in the case of Argentina. Such a move would diversify our energy portfolio, greatly help in our commitment of emissions reduction without compromising economic development, but to the contrary, giving a boost to the national economy.

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