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TITLE

Expansion of Nuclear Power Technology to New Countries – SMRs, Safety Culture Issues, and the Need for an Improved International Safety Regime

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HIGHLIGHTS

- Many countries currently without nuclear power plants are now considering their use.
- Many of these "newcomer" countries are considering new designs, including SMRs.
- SMRs now being developed offer potential advantages but also face many challenges.
- Deploying NPPs in newcomer countries depends on achieving a strong safety culture.
- Nuclear safety, a global concern, needs a strengthened international safety regime.

ABSTRACT

This article reviews the status and prospects of nuclear power around the world and provides a perspective on the need to strengthen national and international safety regimes and bolster nuclear safety culture globally – one prerequisite for a sustained role of the technology in the future. It discusses the prospects in countries that have never deployed nuclear power before but have expressed an interest in adding it to their future national energy mixes. Many of these "newcomer" countries are considering small modular reactor (SMR) designs which hold promise for fitting better into their local electricity systems. Thus, the article considers the technical attributes of these designs and analyzes the advantages and disadvantages of SMRs with an emphasis on economics, grid compatibility and most importantly, safety. Attributes of a safety culture are discussed from social and cultural aspects, including topics of good governance and the presence of an independent national regulatory authority. Beyond the need for strong national safety regulations, the article also highlights the need to strengthen the international regulatory regime, if nuclear power is to succeed in achieving the highest levels of safety globally. Finally, the qualities of such a regime are discussed.

KEYWORDS

nuclear reactor safety; newcomer nuclear countries; small modular reactors; safety culture; international nuclear institutions

ABBREVIATIONS (these should be inserted in a footnote on the article's first page)

CDF	core damage frequency
CNS	Convention on Nuclear Safety
FSP	fundamental safety principles
IAEA	International Atomic Energy Agency
IDC	interest during construction
LR	large reactor
LWR	light water reactor
MW	megawatt
MWe	megawatt-electric
NFC	nuclear fuel cycle
NPP	nuclear power plant
OC	overnight construction
OECD	Organisation for Economic Cooperation and Development
OSART	Operational Safety Review Team
PSA	probabilistic safety assessment
PWR	pressurized water reactor
SMR	small modular reactor

1. Introduction

Two major international agreements of 2015, the 2030 Agenda for Sustainable Development and the Paris Agreement, explicitly call for fundamental transformation of the world's economies at unprecedented depth and speed. The energy system plays a key role in this transformation, in large part because several social, health and environmental ills are chiefly attributable to the current practices of energy demand and supply. Energy is the primary contributor to the emission of greenhouse gases causing global climate change, and energy system transformation holds the key to a more equitable, cleaner and more secure energy future (IEA, 2016).

Nuclear power can be an integral part of the transformed energy system. On a life cycle basis, it is a low greenhouse-gas-emitting technology comparable to the best performing renewables and essentially does not emit pollutants responsible for poor local air quality and acidification (IEA, 2017; IPCC, 2011; Pehl et al., 2017). The high energy concentration per unit of mass of nuclear fuel means low fuel requirements per unit of electricity or heat, hence low waste volumes to be managed. Several years of fuel can be stored on-site contributing to energy security. Nuclear power is a baseload electricity generator, a feature very much needed in fast growing and industrializing countries.

While the case for the expansion of nuclear energy in a carbon-constrained future is strong, if not compelling (IPCC, 2014; UNGA, 2015; UNFCCC, 2015), nuclear power continues to face problems in OECD countries due to several economic and socio-political factors. From an economic perspective, new nuclear power plants are expensive to build but generally inexpensive to operate with stable and predictable generating costs over extended periods of time (Forsberg et.al, 2017; Rogner, 2012; USNRC, 2017). However, the 'bulkiness' of the investment and the economic risks associated with it are no longer compatible with competitive liberalized markets without government support. Construction delays and cost overruns have troubled the industry to the point of insolvency. The recent massive reduction in the cost of intermittent or variable renewable electricity generation combined with the externalization of the cost of their system integration narrows the economic space for new but also for existing nuclear power capacities. Cheap natural gas especially shale gas in North America and low-cost, high efficiency combined gas cycle technology is a better match to the variability of demand and variable renewable generation than base-load nuclear power plants. The emergence of low-cost natural gas liquefaction has turned gas into a much more global fuel than pipeline gas. In many OECD countries, low growth, and in some cases stagnation of electricity demand limit the need for capacity expansion, and capacity replacements tend to be of smaller unit sizes than their predecessors. In short, in the absence of a recognition and adequate compensation of several beneficial traits of nuclear power – from its 24/7 capacity availability (Bade, 2017) to its potential to mitigate climate change and other health and environmental benefits (EU, 2016) - the prospects of the technology remain restrained in the OECD. Neither the global climate accord (Paris Agreement) nor the 2030 Agenda for Sustainable Development mention nuclear energy (UNGAS 2015; UNFCCC, 2015).

One of the compelling socio-political issues is public opposition and anti- nuclear politics, especially on the rise whenever there is a nuclear accident causing an incremental increase in the negative reaction among the public. The 2011 Fukushima Daiichi accident in Japan resulted in a heightened safety concern regarding nuclear power, that has continued throughout several countries. The Republic of Korea is the latest OECD country to debate actively a policy of a nuclear phase-out following decisions to do so undertaken earlier by Germany, Switzerland and Belgium. Work on two reactors, about 30% complete, was suspended in July 2017 after President Moon Jae-in ordered a halt, but a government-appointed panel recommended completion of the construction, although the panel's majority expressed support for a reduction of Korea's reliance on nuclear energy (WNN, 2017a). Other countries (e.g., France, Sweden) have capped directly or indirectly the market share of nuclear power.

However, the prospects for nuclear power remain bright in non-OECD countries, mainly in Asia, not only in countries that are already operating nuclear power plants (IAEA, 2017a), but also in more than two dozen so-called "newcomer" countries elsewhere around the world (IAEA, 2017b). Newcomer countries are countries that have never had an operational nuclear power plant but now have expressed interest in adding nuclear energy to their national electricity supply mixes. There is a wide spectrum of interest in these countries, from "simply exploring the issues" to "seriously preparing the introduction" of national nuclear power programs to "actually constructing" their first nuclear power plant(s), construction of which is underway now in four newcomer countries.

The prospects for expansion of nuclear power plant (NPP) technology into countries that have no nuclear power plants today must be carefully assessed and planned, especially in relation to economic, social, and safety issues. The development and maintenance of a highly competent and independent national regulatory system, complemented and supported by a strengthened international nuclear safety regime, are very important in determining whether nuclear power can be successfully and safely deployed in such countries. Although achieving strong safety culture is of major importance in countries that already operate nuclear power plants, for newcomer countries achieving some of the needed safety attributes can often be difficult, especially if their importance is not adequately recognized throughout society and the political establishment.

Small modular reactors (SMRs) have been advanced as new technical alternatives to the traditional large reactors, primarily because of their potential for significantly improved safety performance, smaller unit sizes hence lower up-front capital requirements and affordability, grid considerations, and better match to demand and market uncertainty (Locatelli et.al, 2014; NNL, 2014; USDOE, 2018). While their initial deployment is likely to occur in countries with existing nuclear-power programs, these characteristics have made them also an attractive option for many of the "newcomer" countries, even though the commercial availability of SMRs in the world marketplace is still several years in the future.

Thus, this paper discusses the role of newcomer countries within the nuclear landscape, their potential challenges, concentrating on nuclear safety issues, where by "safety" we mean the likelihood of an accident in a nuclear plant or nuclear fuel complex facility that would cause major damage to the facility with major releases of radioactivity offsite. Successful nuclear power programs have generally been cultivating and empowering highly qualified regulatory bodies as well as giving continuous attention to safety-culture issues. Safety-culture deficiencies have often been at the root of safety matters (Morrow et.al, 2014). The issue of nuclear security, either illicit acquisition of nuclear material or a malicious attack on a nuclear facility that would cause widespread damage and subsequent release of radioactive material that could pose an impact on either human health, the environment, or the economy, is also contemplated.

Concerning the expansion of nuclear power in newcomer countries, this paper discusses the pros and cons associated with the use of SMRs as an alternative to full scale large NPPs. The advantages and disadvantages are discussed, and the attributes of the new SMR designs, including the advantages of proposed SMRs in terms of both economics and safety, are described and evaluated. The paper concludes by describing the attributes of a strong national safety culture with an emphasis on the need for a stronger international nuclear safety (and security) regime. The importance of better appreciation of and response to the perception of safety risks amongst the public and decision makers is highlighted and described.

2. Status of "Newcomer" countries

Newcomer countries, interested in adding nuclear energy to their mix of national electrical supply, are starting to consider their options. In most cases, firm orders have yet to be placed, although negotiations are under way with one of the vendors around the world, while other countries have yet to reach even that stage. Table 1 provides a summary of the status of the nuclear power ambitions of newcomer countries.

The status of the countries on this list is a moving target, reflecting changes in national nuclear policy. For example, Vietnam at one point had decided to adopt nuclear power and was deeply engaged in negotiations with vendors but decided in the fall of 2016 to cancel its nuclear ambitions (at least for now) for economic reasons, and not because of technological considerations or safety concerns. The estimated capital costs had doubled since 2009, projections of electricity demand growth had halved, and public debt was about to spiral out of control (Nguyen, 2016).

Another example is that of Kuwait, a major oil exporting country. Since the early 1970s, Kuwait has been actively planning the development of a national nuclear power program, especially during periods of high oil prices. Plans were suspended following the 1979 Three Mile Island accident and the collapse of oil prices in the mid-1980s. In 2009, there was a second serious attempt to resurrect the nuclear program (IAEA, 2016a). The Kuwait National Nuclear Energy Committee (KNNEC), established for this purpose, completed several feasibility, planning and site selection studies and entered into a number of bilateral agreements with several nuclear vendor countries. The Fukushima Daiichi nuclear accident in

April 2011 led, almost immediately, to the cancellation of the national nuclear power program, once again.

Table 1: Status of nuclear power programs of countries currently without operating nuclear power plants (Source: Authors' assessment based on statements made by Member States at IAEA General Conferences and at other public forums; IAEA, 2017b and WNA, 2017).

Country status	Number	Countries
First NPP under construction	4	Bangladesh, Belarus, Turkey, United Arab Emirates
First NPP ordered	0	
Decision made, preparing infrastructure	5	Egypt, Jordan, Kenya, Poland, Saudi Arabia
Active preparation with no final decision	9	Ghana, Indonesia, Kazakhstan, Malaysia, Morocco, Niger, Nigeria, Philippines, Sudan
Considering nuclear power program	12	Albania, Algeria, Chile, Croatia, DR Congo, Peru, Sri Lanka, Thailand, Tunisia, Uganda, Uruguay, Zambia

Note: Egypt is expected to join the category "First NPP ordered" in early 2018 and soon after the category "First NPP under construction". On 11 December 2017, Egypt and Russia signed notices to proceed with the implementation of the Intergovernmental Agreement (IGA) of 2015 between the two countries for the construction of four NPPs at El Dabaa (WNN, 2017b). Table as of 14 April 2018.

3. Reactors under construction

About 450 reactors are now operating worldwide, most of them large light-water reactors (LWRs[1]). In countries that are currently building new reactors, almost all are large LWRs with a design similar to the vast majority of NPPs now operating worldwide. However, although all these large new LWRs incorporate modern features such as advanced control systems and improved metallurgy and fuel, some of them also incorporate advanced passive safety features that make the designs much more resistant to certain important classes of accidents (IAEA, 2015).

[1] There are two varieties of LWRs operating today: Pressurized water reactors (PWR) and boiling water reactors (BWR)

Most of the seventeen countries now building altogether 56 new reactors, as shown in Figure 1, already have one or more operating NPPs, but three of them, Bangladesh, Belarus, and the United Arab Emirates, do not (marked light grey).

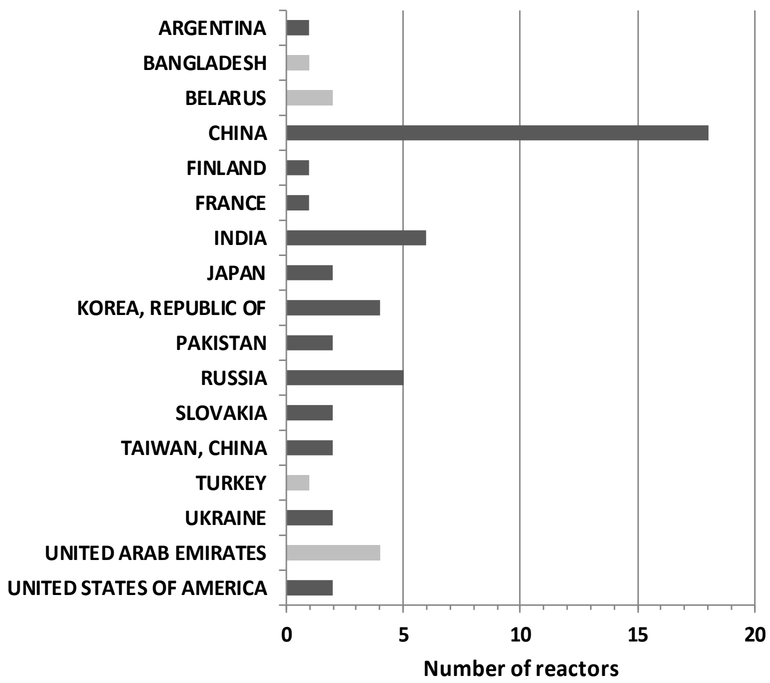

Figure 1: Reactors under construction as of 14 April 2018 (Source: IAEA, 2018)

Even though, as noted, the reactors now being marketed actively around the world are essentially all large LWRs, almost all the reactor designers/vendors worldwide are focused on developing so-called "advanced" reactors, which fall into three categories (GIF, 2016):

i. Advanced large LWRs: with the claim of much improved safety achieved by taking advantage of passive features and other safety advances

ii. Large reactors using a different (non-LWR) design

iii. SMRs: smaller than conventional reactors

There is a renewed interest in SMRs in developed and developing countries alike, although for different reasons; the section below focuses on SMRs, their technologies, and their advantages and disadvantages generally.

4. Small modular reactors

The use of the word "small" usually denotes a reactor with an electric power level below a few hundred megawatts electric, although some proposed new SMR designs might be as small as 20 MWe. The term "modular" denotes a reactor design that could (or likely would) be deployed using numerous identical modules at a given site. The idea is to potentially deploy two or four SMR modules at a site, but in the more ambitious schemes, this could involve the deployment of eight to ten (or more) SMR modules at a site. The successive addition of multiple units at the same site would not only lower the capital cost per added unit relative to the previous unit, but also ease-over the finance requirements proportionally per unit.

The technologies being developed range from small LWRs (using technologies that are in most features very similar to those used in today's large LWRs) to advanced reactor technologies of many different types: fast-spectrum sodium or lead-cooled reactors, high-temperature gas reactors, homogeneous-fuel reactors, liquid-salt-coolant reactors with pellet fuels, pebble-bed designs, fast-spectrum gas reactors, and a few others (IAEA, 2016b). While most SMRs are designed to generate electricity, a few aim to produce process heat for industry, and some aim to produce both heat and electricity.

As of today, despite the nearly 40 different SMR design concepts being developed around the world, there are almost no SMRs being seriously offered for sale by the designers/vendors who are working on them. The first offers for an actual sale in the marketplace are still a few years off, although a few of the design companies might dispute the statement that they are not yet for sale. The current roadblock, universally, is either that these designs are yet to demonstrate their ability to compete in the marketplace for electricity generation (and/or for process heat in a few cases) (NNL, 2014), or need regulatory approval, or both.

However, around the world very few SMRs are now being built, and in each case as a prototype of what might be offered for sale more broadly sometime later (IAEA, 2016b). Among the SMRs now under construction are:

- Argentina: a 27 MWe (megawatt-electric) water reactor (PWR)
- China: a 105 MWe pebble-bed high-temperature gas reactor
- Russia: a 70 MWe integral PWR being built for a cargo ship
- Russia: a 50 MWe integral PWR being built for an icebreaker ship.

A few other designers/vendors are currently planning to start construction on a prototype soon, but these decisions are typically in a state of flux pending regulatory approval, financing arrangements, and/or design maturity.

5. Advantages to SMRs

. *5.1 Economics*

The economics of nuclear power are largely characterized by high upfront capital costs but low, stable and predictable operating costs. The projected median investment costs of commercially available new nuclear builds have been reported at $4900 per kW installed (range $1800 to $6200) depending on technology and country (IEA/NEA, 2015). An advanced 1000 to 1600 MWe light water reactor, therefore, can command overnight construction (OC) costs[2] between $5 to $8 billion (based on median specific costs) or more[3] –

[2] Overnight cost includes pre-construction (owner's), construction (engineering, procurement and construction) and contingency costs, but not interest during construction (IDC) and cost escalation, e.g., inflation.

an investment volume that exceeds the capitalization capability of most utilities around the world. Such volumes of capital and associated risks usually cannot be shouldered by private sector entities without some support from the government.

This capital-intensive nature of nuclear power is a major challenge for investors (Samadi, 2017). The economic viability of capital-intensive projects is inherently sensitive to interest rates underlying their finance arrangements. These projects are also often characterized by significant technical complexity which can be a major cause of schedule delays and cost overruns[4]. Furthermore, interest during construction (IDC) is the second largest component (after OC costs) of the final investment costs of today's new nuclear build. IDC accumulated over construction periods of more than five years can quickly lead to prohibitively steep financial burdens – not only due to the very nature of IDC but also because of the delay of initial revenue generation.

The construction time of the Olkiluoto 3 NPP in Finland, the 'first of a kind' Areva EPR (1600 MW) was originally scheduled for five years with completion in 2009. However, construction delays postponed the plant's start-up to May 2019 – a ten-year delay. The capital cost was initially put at €3.2 billion but now the overall cost is estimated at closer to €8.5 billion. The two VC Summer Westinghouse AP 1000 units in South Carolina initially priced at $9 billion reached $14 billion in 2015 and were cancelled after the vendor Westinghouse filed for Chapter 11 bankruptcy protection (reportedly due to a loss of $6.1 billion on its AP1000 projects). In the fall 2017, the plant owners decided to shoulder a $9 billion loss rather than risk further delays and associated cost increases to possibly $18 billion. Note that South Carolina is a regulated market and the lion's share of the loss will be recovered via rate

[3] Note: Some Asian countries report much lower costs for planned new nuclear builds, but it is not always clear what is included in these estimates.

[4] These delays and overruns are not uniquely a nuclear phenomenon but have been routinely observed in many non-nuclear but technically complex projects such as airports, railroads, harbors, opera houses, etc.

increases. Elsewhere (China, Korea, UAE), however, nuclear plants have been or will be completed on time and on schedule. Still, construction completion on time and on budget remains the single largest risk faced by NPP project sponsors, i.e., in terms of the uncertainty regarding the eventual investment costs followed by long payback periods of up to 20 years and more until they have recouped the initial investment.

Nonetheless, recent experience in many non-OECD countries, including newcomers, paints a difference picture of NPPs being built at a relatively lower specific cost, on time and on budget. For example, construction of the first of four APR-1400 reactors at UAE's Barakah site was recently completed (Cook, 2018). These are very large LWRs. According to publicly accessible information, a quasi-fixed-price arrangement with the vendor consortium for the four units amounts to $20.4 billion (i.e., less than $4000 per kWe). Although construction has proceeded on time and on budget, the issuance of an operating license for Unit I is taking a longer time than anticipated. This is attributed to the additional time needed for human resource development, team building, and training of a diverse staff recruited from over 20 countries, clearly signifying the extremely high importance of the safety culture in the UAE nuclear power program.

Historically, and still at present, the construction of all nuclear power plants operating today has had direct and/or indirect financial backing from the government. Direct financial backing has involved government ownership, as well as funding or other support mechanisms; indirect backing has been through NPPs being operated and financed in regulated electricity markets. These operations are characterized by rates regulated by government agencies on a 'cost plus' basis, which has essentially enabled operators to fully cover generating costs (including costs arising from construction delays and other operational inefficiencies)[5] at decreased risk. The risks of economic inefficiency such as cost overruns from plant completion delays in regulated markets have essentially been borne by the rate payer. In liberalized markets, competitive generating costs that turn a profit under often volatile market clearing prices rather than 'cost plus'-derived rates determine revenue and economic success. Owners and operators in these markets face both volume and price uncertainty and all market risks rest with the investors.

SMRs are expected to mitigate some of the key economic challenges associated with LRs. With an electricity generating capacity of typically below 300 MWe per unit, SMRs present a lower investment risk exposure to project sponsors compared to LRs. Despite the lower upfront capital cost per unit, for SMRs the specific investment costs per kWe installed are expected to be higher than for LRs, at least initially. This can result in substantially higher generating cost of electricity per kilowatt-hour compared with LRs (IAEA, 2016b). Expert judgments about projected early SMR generating costs display a wide range, from slightly below a new build LR to 50% higher or more (Abdulla et.al, 2013; NNL, 2014; SMR-Start, 2017). Other SMR disadvantages in the short run have the potential to turn into comparative advantages in the longer-run (Rogner, 2009). These are set forth in the "box" (Figure 2) below.

[5] Regulators would typically allow 'plausible expenses' plus a 'fair return' on the capital invested.

- High up-front capital costs
- High level of complexity
- Ex-ante cost uncertainty
- Completion risks: construction and supply chain risks
- Long lead times (engineering & construction, etc.)
- Long payback periods
- Sensitive to interest rates
- Reliability/availability/load factor
- Market risks (i.e. competitiveness of output, service; demand)
- Wavering political support
- Public acceptance
- Regulatory risks
- Energy/environmental policy risks
- Decommissioning and waste cost/liabilities

Expected comparative advantage of SMRs versus large reactors

Figure 2: Key challenges (risks) of nuclear power affecting overall nuclear economics. Source: Adapted from Rogner, 2009.

Historically, the manufacturing or construction of many reactor components does not scale proportionally to size, which is the main reason why current commercial reactors have steadily become larger and larger. Although the economics of SMRs (capital costs, operation and maintenance costs and fuel costs) are not yet known, there are several factors that eventually may counter the economies of scale of LRs, mainly faster technology learning, standardization, shop fabrication and reduced levels of complexity of SMR designs.

Figure 3 shows the historically observed tendency of increasing specific OC costs as plant unit sizes decrease (lack of economy of scale) when everything else remains equal. It then lists factors expected to offset the lack of economy of scale (in essence the MWh generated by LRs). Simpler plant designs allowing reduced number of structures, systems and components lower overall OC. Many integrated SMR designs can be shop fabricated and then transported as quasi complete modules to the sites for installation rather than constructed in the field.

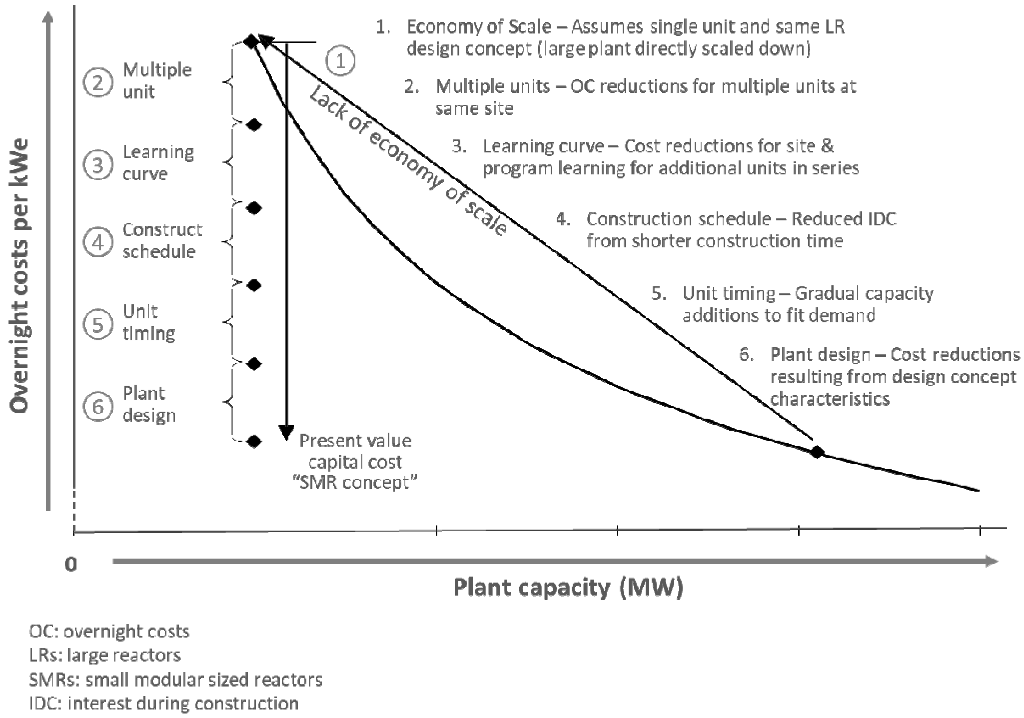

Figure 3: Generic view of factors affecting comparative costs of small modular reactors (SMRs) and large reactors (LRs). Source: IAEA, 2013

Modular and in-shop manufacturing not only enables standardization and manufacturing in series (spreading fixed costs over multiple units), and improves quality control, but most importantly shortens the time to market substantially and results in substantial cost savings. Shorter construction schedules lower financial charges that accrue without countervailing revenue and condense the exposure to cost escalation risks. The term 'modular' in SMR implies the erection of multiple units at the same site which through infrastructure sharing reduces costs.

However, the most promising OC mitigation factor is a different form of economies of scale known as technology learning or learning by doing. Technology learning encapsulates the performance improvement of a technology as experience with it accumulates and is the result of both production and deployment. In nuclear terms, it represents the successive OC reduction unit by unit from the construction of a first-of-a-kind design to the construction of the n-th unit of that design. Constructing LRs of 1000 MW capacity one at a time allows for less learning than the sequential manufacturing of five 200 MW SMRs.

Assembly-line manufacturing of SMRs and fast learning-by-doing, the prerequisites for specific OC reductions to levels comparable with LRs, require the realization of a substantial market deployment. SMR vendors need assurances that there will be a sufficiently large market for their reactors in order to invest in manufacturing capacity, set up supply chains, fuel supply, human resource development and maintenance services (Lyman, 2013). The first wave of buyers, aware of the lack of competitiveness of their new plants versus LRs[6], expect some kind of compensation for the extra risk they are assuming[7]. This constellation amounts to solving a nuclear chicken and egg problem which usually means the need for government funding or other government support.

5.2 Finance

SMRs will always have lower upfront capital requirements per unit than LRs. This means that the financial commitment necessary to begin building SMRs at a site is commensurately smaller and easier to finance (lower investors' financial risk exposure compared with large unit sizes). Modular in-shop manufacturing and delivery of quasi complete units to sites reduce construction schedules and improve probability of on-time plant completion, hence minimize escalation charges and IDC. This approach also helps avoid the demand for 'risk premiums', e.g., higher returns on investments for equity finance and higher interest rates on debt finance often found in the finance of LRs. Thus, the successive addition of multiple units at the same site would not only lower the capital cost per added unit relative to the previous unit but also ease over proportionally unit finance requirements. Revenue generation from

[6] Another potential risk faced by early movers is that they may have to compete against later buyers who reaped the benefits of the cost-buy down.

[7] The LR risk may not exist for SMRs in niche markets where large reactors would not be viable.

already completed units may also help finance the construction of subsequent units. Furthermore, realized revenue from existing modules can also help build investor confidence.

5.3 Grid compatibility

In industrialized countries, demand uncertainty, such as the prospects of slow rising or even declining electricity demand coupled with potentially significant changes in daily and seasonal demand load profiles, makes the expansion or simple replacement of LRs an economically risky proposition, especially in liberalized electricity markets. SMRs would substantially mitigate this risk (GIF, 2016). In many developing countries, the ability to absorb LRs onto the existing electrical grid is difficult, whereas SMRs can be more easily accommodated. Also, for many grids the occasional loss of a single LR unit from the grid would represent an unacceptably large perturbation on the grid itself, whereas the loss of a smaller unit would not be such a large problem. SMRs could also provide other services (besides electricity) including seawater desalination, hydrogen production, district heating, unconventional oil recovery, or high-temperature industrial applications.

5.4 Safety

There is a claim that SMRs are safer than the large LWRs, and for many of the designs this is transparently true. Although the reasons for improved safety vary and are not all shared by all the SMRs (GIF, 2016; IAEA, 2016b), a number of these features have been identified. For one, most of the smaller SMRs will have less thermal energy production per reactor (module), during operation and also after shutdown, from radioactivity remaining in the spent nuclear fuel. Therefore, they are easier to cool, especially following an accident and shutdown, reducing the risk of core meltdown and the potential release of radioactive material from the damaged NPP. Some of the SMRs rely entirely on passive approaches to decay-heat removal and have a very extended time before overheating is an issue, providing an inherent stability and safety feature for these reactors.

The design of most of these reactors is also simpler to understand, providing an enhanced operational efficiency. Some do not require electrical power to operate and are proposed to have better fuel consumption (including much longer intervals between refueling; in some cases, 20 or more years without refueling). A few of the SMR designs would never have spent fuel on-site, because an entire SMR core module after 20 (or more) years of operation would be removed from the site and replaced by a new SMR core module. Some of the SMRs are proposing to use liquid metals as coolants; thus, due to the high boiling point of these metals, some of the SMR pressure vessels operate at or near atmospheric pressure. Some SMR designs have much improved separation of systems and functions to reduce the likelihood of compromising multiple safety functions. Certain SMRs are designed for easier underground siting, increasing both cost effectiveness and providing superior levels of safety and physical security. Nevertheless, many SMRs would require a much smaller emergency-planning zone (or none), because the radioactivity in the core is so much less, or the timing for any release would always be much longer than for a large LWR.

Given this long list of potential advantages, the question that remains is what is delaying their deployment? In a nutshell, it is a classical chicken-and-egg situation. Due to lack of proven economics, as mentioned, there has not yet been enough market pull for SMRs. This has been compounded with an insufficient technology push, because of the absence of the necessary sales prospects needed to buy down costs (Pedraza, 2017). As noted, to be successful in the marketplace, any SMR needs to generate electricity at a cost that competes in the marketplace, considering all costs. Demonstrating economic competitiveness convincingly is still for the future and will not be discussed further in his paper. Can shop fabrication and other proposed economies succeed? Nobody yet knows.

6. Challenges facing SMRs

Despite their many potential advantages, SMRs are still nuclear reactors and as such carry with them several common risks of nuclear-power technology. As with LRs, investments in SMRs are subject to regulatory risk, public sentiments and acceptance and changing energy policy. As well, SMRs share the same nuclear fuel cycle challenges. These exist at the back-end with spent fuel management (including final disposal) and decommissioning, and include proliferation concerns throughout the fuel cycle, including at the front end, during operation, and at the back end. However, as mentioned earlier, some revolutionary-design SMRs would never have spent fuel on site (IAEA, 2016b), a clear advantage for some newcomer countries. On the other hand, the more revolutionary SMRs will need to pass lengthy pilot and demonstration-plant stages, requiring dedicated government support, without which these challenges would be even more difficult. Another challenge is how to adequately address the cross-border license, liability and regulatory issues: who regulates and who is liable.

7. Importance of Safety Culture

The nuclear-power industry and the national regulatory agencies with successful programs have studied the question of safety culture extensively over the years (IAEA, 2016c; INSAG, 1991; NEA, 2016), because of its pertinent role in the operations and sustainability of nuclear programs. Several studies have identified the attributes of a weak safety culture for an individual NPP or a national nuclear-power program (INSAG, 1991; Morrow et al., 2014) in relation to operations, management and political environments.

Traits of a weak safety culture include (INPO, 2013; USNRC 2014), but are not limited to:

- a lack of rigorous operator training, and/or the inability of the operating crew members to improve their training (or indifference to this issue),
- a broad absence of a "questioning attitude" concerning errors and problems when they arise,
- a cultural environment that impedes the ability of any individual to raise safety (and security) concerns without fear of being ridiculed, ostracized, or retaliated against,
- a weak or unstable political and social atmosphere in the country that prevents NPP management from taking steps as needed to improve safety,
- a predominantly "top-down" NPP management approach that does not recognize the invaluable information coming "up from the bottom",
- a weak national nuclear regulatory agency and/or that lacks independence from the political echelon, and/or lacks sufficient resources to carry out its responsibilities, and
- a broad culture characterized by widespread corruption in which financial payoffs, bribes, and similar activities impede the honest transactions of all kinds that allow safe activities to flourish.

8. Achieving high levels of NPP safety

Achieving and ensuring high levels of NPP safety involves meeting several different figures-of-merit for NPP[8] safety, but the most commonly used one today is the annual probability of a reactor core-damage accident, known as the core-damage frequency (CDF) (USNRC, 2011). This is determined today using the well-tested analytical method known as PSA (probabilistic safety assessment) (ASME-ANS, 2009). The details of PSA and its results are beyond the scope of this short review, but the general conclusion is that, if one of today's

[8] In the following sections, the terms NPP and reactors are used interchangeably.

nuclear power plants is well designed and well operated, the CDF is in the range of a few x 10^{-5} per year, and the probability of a large radioactive release is generally in the range of a few percent of CDF or around 10^{-6} per year (USNRC, 2015). Although there are wide variations from plant to plant, PSA studies of numerous NPPs around the world confirm this broad finding (IAEA, 2015). Furthermore, as a broad statement the national regulatory agencies around the world generally agree that a NPP reactor with a CDF in the above range is "acceptably safe" in that country.

Of course, the advanced reactors now being designed, including the SMRs, generally promise a smaller CDF than the above, sometimes substantially smaller, as well as much smaller radioactive releases in the event of an accident, thus achieving higher safety levels. Some of the developers claim CDF reductions compared to large LWRs of an order of magnitude or more, and reductions in releases by even larger factors (IAEA, 2016b). These claims are backed up only by analysis, because of course none of these has yet been built, and also there has generally not been enough review by independent experts to validate these analyses, even though as a general matter many of them make good engineering sense. In the end, whether these will be achieved in practice awaits further developments.

In order to achieve this high level of safety, the NPP must be *well designed and well operated*. In practice, there are a number of different ways to describe the appropriate attributes, but in brief, this would include that the NPP is well-designed and well-built and meets all applicable codes and standards (IAEA, 2006b). Furthermore, the NPP would have to be well-operated, ensuring that the operating crew, maintenance and engineering staff are well-trained. Information about problems and issues that are faced are shared widely (internationally). Most importantly, there must be a strong safety culture present on a national level from all levels of society, top to bottom, including the presence of a national, strong, independent regulatory agency to oversee the activities of the NPP.

Weaknesses in the skills and knowledge of the operating crew or of the plant's maintenance and engineering staff, if they exist, or if a plant does not systematically take advantage of lessons-learned from problems occurring elsewhere, could obviously be a major reason why a plant may fail to achieve adequate safety levels and could lead to weaker safety performance. However, a broad consensus exists that, given a fully developed, qualified and robust national nuclear regulator, empowered to undertake its responsibility independently, a weak safety culture is typically the most important reason for poor overall safety performance (INSAG, 1991; INSAG, 2006; NEA, 2016).

9. Critical importance of safety culture for "newcomer" countries

As in countries with established nuclear power programs, safety culture is the major concern for a newcomer country, if the country is to achieve adequate safety and security for the proposed new NPPs. Designing and building the NPPs correctly is an important aspect of establishing a sustainable nuclear program; however, all else being equal, achieving acceptable safety culture can be the vital make-or-break attribute of nuclear programs in newcomer countries. If a strong safety culture is absent, these plants cannot and will not be operated safely and securely.

When establishing a safety culture, two different types of safety are considered. The first is the socio-cultural aspect of safety culture, which involves the organizational, communication and operational procedures that account for the cultural environment and collective preferences for certain values over others (e.g., reluctance to engage with supervisors on an emerging safety issue), including tribalistic versus pluralistic value systems. In short, this ensures that the cultural factors interact with the specific operational needs of an organization. Furthermore, the culture must not be characterized by rampant bribery/corruption and must not be too “top down”. The culture must also be concerned with the safety of workers, encouraging a “questioning attitude”, to ensure that effectiveness and transparency exist across the operations.

The second type is the political-cultural aspect of safety culture, which includes the support of political structures, such as the government and policy makers. It is of critical importance that the national safety regulatory agency be independent of politics. There must also be a long-term political commitment to the NPP program and national legislation committing to the main international conventions (IAEA, 2017c). An acceptably strong legal (contracts) system and court system should be present and there must be enduring continuity of the social and political institutions. If these attributes are present, there is a good chance that the NPP program can achieve acceptable safety. Without all these attributes, achieving an acceptable safety culture, on a national level, is unlikely.

10. Strengthening the current International Nuclear Safety Regime

The strength of a national safety culture must be complemented with the presence of an international safety regime, that addresses the global concern of nuclear safety (Rogner and Shihab-Eldin, 2017a; 2017b). It is abundantly evident that the primary responsibility for the safety (and security) of any nuclear facility lies with the owner/operator of the facility, overseen by the governmental authorities within the country where the facility is established, licensed and operated. However, radiation releases from severe nuclear accidents do not respect jurisdictions or national borders; hence, there is the clear need for a robust and effective international nuclear safety regime. The regime should be composed of an interrelated 3-level hierarchy. At the core is a set of safety standards and guides, supported by expert international support services and, if feasible, a higher level empowered international regulator, complementary to any national safety regime (e.g., national nuclear regulator).

The establishment of the international Convention on Nuclear Safety (CNS) in the mid-1990s was a major step forward (IAEA, 2006a). For now, it represents the vehicle for achieving the worldwide implementation of the Fundamental Safety Principles (FSP), which consist of three layers: Fundamentals, Standards, and Guides (IAEA, 2006b), and which represent an integral part of an effective Global Nuclear Safety regime.

The CNS strives, amongst other things, to “achieve and maintain a high level of nuclear safety worldwide through enhancement of national measures and international cooperation.” Each country party to the CNS is required to take the appropriate steps to ensure the safety and security of the nuclear installations within its respective jurisdiction, and within the framework of its national law, including legislative, regulatory and administrative measures, as well as other steps necessary for the implementation of its obligations under this convention. Towards this end, the CNS requires Parties to submit, every three years, national reports on the implementation of their obligations, based on FSP, and status of compliance with the Article of the Convention for "peer review” by other Contracting Parties. The reports present evidence as to how Parties meet their obligations. Any actions identified during the peer review need to be addressed and are subject to review at the next convention meeting. The CNS also postulates that national implementation should be aided and thus strengthened by the inclusion of a variety of international institutions that engage in nuclear safety (INSAG, 2006).

While the CNS offers a set of attractive incentives based on a common interest to achieve a high level of safety, it assigns the ultimate responsibility for nuclear safety to individual countries (IAEA, 2017c). This represents a serious shortfall and renders the CNS as a “quasi voluntary" instrument without effective enforcement measures to ensure compliance such as imposing sanctions in the case of non-compliance. Unlike the comprehensive safeguards agreements with the IAEA that verify that non-nuclear weapon States party to the Non-Proliferation Treaty fulfil the non-proliferation commitment they have made, and non-compliance can evoke international enforcement action via the UN Security Council, there is no [direct] mechanism of international enforcement of FSP or the CNS obligations. National political priorities and military or security interests prevent effective universal implementation.

The way forward, in an ideal world, would be the establishment of an international regulator overseeing nuclear safety matters globally and empowered to take or call for enforcement action from a competent body. In the real world, because of escalating political fragmentation, both nationally and internationally, major international movement toward such an ideal situation is unlikely in the foreseeable future. A step-by-step approach is feasible, leading gradually to a stronger and legally more binding nuclear safety regime. Examples of such measures include the following:

1. Make currently voluntary use of IAEA and OECD/Nuclear Energy Agency safety services[9] quasi mandatory.

2. Compile and maintain an up-to-date publicly accessible database with knowledge and information on nuclear safety, including CNS reviews and findings of safety review services, including country and OSART mission reports

[9] Examples include but are not limited to the IAEA's Operational Safety Review Team (OSART) missions, Integrated Regulatory Review Service (IRRS), Peer Review of Operational Safety Performance Experience (PROSPER), and Independent Safety Culture Self-Assessment (ISCA).

3. Create awareness and call attention to aspects of the nuclear safety regime that need urgent attention or improvement and determine what can be done to rectify the situation.

4. Work towards building momentum among non-governmental organizations and the civil society to call for, and ultimately realize, a stronger nuclear safety regime.

5. Encourage a closer involvement of the nuclear industry, such as the World Nuclear Association and the Nuclear Suppliers Group, with nuclear facilities. This also includes involving other international players, such as all the major nuclear power plant vendors worldwide.

Experience has shown that in the short-to-medium term, it is unlikely that step-by-step enhancements presented above can be deliberated or negotiated at the boards and committees of the intergovernmental organizations engaged in matters of nuclear safety. While the context is not the same, examples do exist of successful processes of education, raising awareness, mobilization of public opinion and public pressure that has led to the realization of international agreements to regulate and mitigate other global risks from human activities that transcend national boundaries. Two such examples are the Convention on International Civil Aviation administered by the International Civil Aviation Organization, and the 2015 Paris Agreement on Climate Change (with 195 signatories) which aims to reduce global greenhouse gas emissions and limit the increase in the global average temperature to well below 2°C above pre-industrial levels. The success of these initiatives provides us the support and encouragement that the time for the consideration of similar grass-root efforts to enhance global nuclear safety is now[10].

[10] Nevertheless, the summer 2017 decision by the US President to withdraw from the Paris Agreement cautions against overoptimistic expectations of the effectiveness of Conventions.

11. The dynamics of risk perception

Nuclear safety is a multifaceted composition of several factors (Rogner and Shihab-Eldin, 2017b). As discussed earlier in the paper, these include functional aspects (such as plant design, manufacturing, construction and operation), regulatory aspects; socio-political aspects (such as political civil society acceptance, public tolerance, etc.), and economic aspects. Thus, a strong and sound nuclear safety culture embraces all the above aspects in an inclusive and inseparable holistic fabric with the ultimate objective of the full avoidance of catastrophic accidents (Budnitz, 2017).

Another key aspect of a safety culture is the set of factors responsible for the perception of risk (from nuclear accidents) amongst the public and decision makers. These include voluntary vs. involuntary (i.e., degree of control over an activity involving risk), direct (positive and negative) experience vs. abstract events and metrics, immediate vs. delayed impacts (health, environment), chronic vs. catastrophic, degree of impact, knowledge within general public and experts (or lack thereof), technology change and specific risk performance (i.e., risk from flying), and perceived benefits or losses. We argue that a better understanding and appreciation of these factors would inform how to respond to the disparity that often exists between the public perception of risk and the engineering determination of risk and economics of risk mitigation in business practices. Furthermore, the public and experts assess these factors quite differently. Public perceptions of the risk factors can vary across countries and locations, and oftentimes might be influenced by their proximity to a nuclear source. With time, as new experience, knowledge or public information spreads (but also as memories fade), a shift in perception could occur, with a better understanding of the need and available alternatives.

An example in the shift in public perception of risk as a result of a nuclear accident can be seen in a nuclear energy survey-based study in China, which assessed the influence of the Fukushima nuclear accident in Japan in 2011 on the Chinese public's attitude and acceptance of nuclear power plants in China. Two surveys, in terms of answers to four questions, before and after the accident, were administered to separate subsamples of residents near the Tianwan nuclear power plant in Lianyungang, China (Huang et.al., 2013). The findings of the study showed that the percent of opponents to nuclear power increased modestly between 6 to 11 percentage points, whereas the support for the technology decreased more sharply between 23 to 36 percentage points (see answers to questions 1–3 in Figure 4). Huang et.al (2013) concluded "that previous supporters tended to sway toward more neutral opinions after the Fukushima accident, this shift was more common than the shift from neutral opinions to opposition. However, when asked whether they support construction of a nuclear power plant in their city, the percent of opponents increased markedly (41%), as seen in question 4".

Although China is not a newcomer country, the observed changes in risk perception and degree of acceptance of nuclear power amongst the Chinese public are attributed to the Fukushima accident. The study confirmed that the public's perception of specific risk can vary over time and locations, and further confirmed that the accident "had significant impact on risk perception of the Chinese public immediately following the accident, especially on the factor of perceived risk, which increased from limited risk to great risk" and decreased public acceptance of nuclear power (Huang et.al., 2013).

No doubt, given experience following earlier major accidents, e.g. Chernobyl in the USSR in 1986, it is expected that the observed changes will weaken significantly over time (Bisconti, 2017; NEA, 2010; NEA/OECD 2017). Experience to date suggests that short-to-medium term effects are strong and tend to fade with time, but some cumulative residual effect from major nuclear accidents appears to persist. To ensure a more conducive environment for stable business and government decisions concerning the future role of nuclear power, at country level and globally, requires better appreciation and understanding of the forces and factors behind the perception of risks among the public and decision makers, in order to develop effective government and private-sector strategies and action plans.

Newcomer countries have recognized the critical importance of keeping the public well informed, engaged, listened to, and involved. In the UAE, this is evident through their public engagement program, an integral part of its nuclear power program (ENEC,2015). The program is comprehensive and includes public forums and periodic public opinion surveys since 2011. This emphasizes that the public's perception of risk and the overall public opinion does play an integral part in ensuring a strong safety culture and the sustainability of national nuclear initiatives.

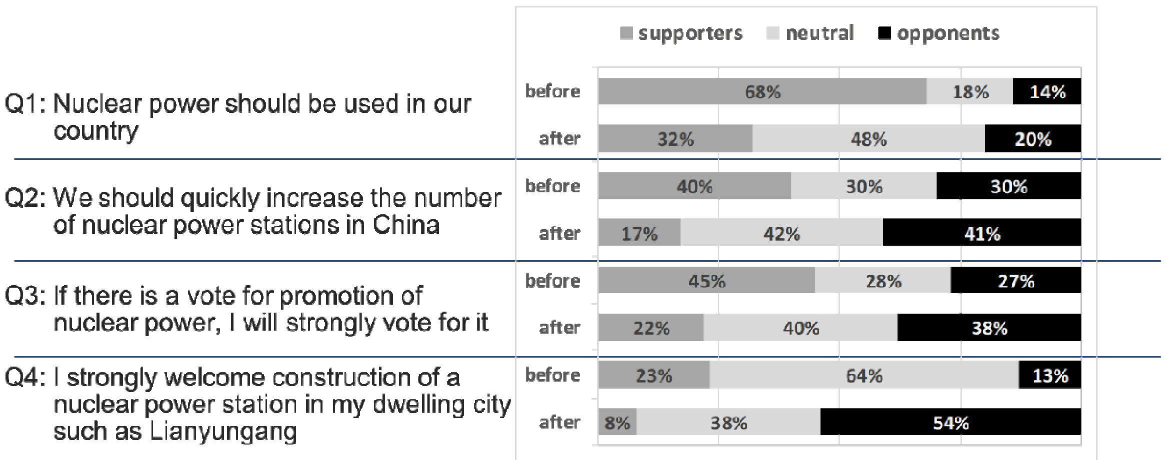

Figure 4: Effect of the Fukushima Daiichi accident on the risk perception of residents near a nuclear power plant in China. Results of surveys before (August 2008) and after (April 2011) the accident. Source: Adapted from Huang et.al., 2013.

12. Conclusions and policy implications

From the above discussion, seven conclusions and their associated policy implications seem to emerge naturally. Some of the policy implications relate to technical issues, but many of them concentrate on institutions and policies or on the interface between institutional or policy issues and technical issues.

i. Many countries around the world that have never deployed a nuclear-power plant (so-called "newcomer" countries) are considering the deployment of large NPPs similar to those now in widespread use around the world, but others are considering small modular reactors (SMRs), where the term "modular" is intended to capture the idea that a typical deployment scheme might place several (5 or 10 or even more) of these smaller units on a given site instead of the one, two, or four large NPPs that would typically be deployed using today's large-NPP technologies.

ii. There are no SMRs currently in use, but nearly forty different designs are in active research-and-development around the world by companies and government agencies, and today four of these new SMR designs are actually being built as pilot plants: two in Russia, one in China, and one in Argentina. Other SMR pilot plants will probably follow soon. Whether these succeed in the marketplace, either worldwide or in some niche markets, will typically be determined by whether the economics will turn out favorably, something that remains to be determined.

iii. The SMRs show great promise to enable the expansion of nuclear power in many electricity markets that are otherwise inaccessible to the larger LWRs. These smaller reactors are likely to be especially attractive in many developing countries, although not exclusively in them. Their potential advantages, which are not present for every design nor in every potential country, include lower per-unit capital costs, shorter construction times, enhanced safety and reliability, and better integration into the electrical grid (especially if the grid is “weak”).

iv. A key potential roadblock to the deployment of these new SMR designs, besides the financial issues already mentioned, is the ability of individual national regulatory authorities to review the SMR designs and approve them. The process to obtain regulatory approval has only recently begun in a few of the advanced countries and will require a few years to mature. There will be a need to address a new set of issues related to cross border license, liability and regulatory challenges. Another key potential roadblock is the need, in the case of revolutionary-design SMRs, for lengthy and costly pilot and demonstration stages, requiring strong government involvement, commitment and financial support.

v. Also, some of the “newcomer” countries have advanced technological capabilities and infrastructure, others do not. Even where these capabilities and infrastructure exist (but even more so where they do not), a major barrier to widespread deployment of nuclear power in some of these “newcomer” countries is the absence of a strong safety culture, comprised of a set of social and political issues that includes corruption culture, the culture of institutional continuity and integrity, and other good-governance matters. Policies that emphasize the positive attributes of these cultural issues, or discourage their opposite, are an urgent matter.

vi. The need for an independent regulatory agency with authority and independence from politics cannot be overemphasized. No country without this should deploy nuclear-power technology. Policies to provide assistance and mentoring are a vital component of a successful worldwide nuclear power endeavor.

vii. A serious nuclear accident anywhere is of a concern everywhere worldwide. There is therefore a need to strengthen the international safety regime. Ideally the aim is to set up an empowered international regulator, which may be the IAEA. A gradual approach would involve, where feasible, making some current advisory services of the IAEA mandatory. Many reasons stand in the way of reaching quick agreement amongst governments towards this needed outcome. A gradual approach, comprised of sustained and structured programs and campaigns, is thus needed. It would include well supported research and education activities aiming to raise awareness amongst the public, the political decision makers, the entities that operate the nuclear power plants, and the regulatory agencies.

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Table 1

Status of nuclear power programs of countries currently without operating nuclear power plants (Source: Authors' assessment based on statements made by Member States at IAEA General Conferences and at other public forums; IAEA 2017b and WNA 2017)

Country status	**Number**	**Countries**
First NPP under construction	4	Bangladesh, Belarus, Turkey, United Arab Emirates
First NPP ordered	0	
Decision made, preparing infrastructure	5	Egypt, Jordan, Kenya, Poland, Saudi Arabia
Active preparation with no final decision	9	Ghana, Indonesia, Kazakhstan, Malaysia, Morocco, Niger, Nigeria, Philippines, Sudan
Considering nuclear power program	12	Albania, Algeria, Chile, Croatia, DR Congo, Peru, Sri Lanka, Thailand, Tunisia, Uganda, Uruguay, Zambia

Note: Egypt is expected to join the category "First NPP ordered" in early 2018 and soon after the category "First NPP under construction". On 11 December 2017, Egypt and Russia signed notices to proceed with the implementation of the Intergovernmental Agreement (IGA) of 2015 between the two countries for the construction of four NPPs at El Dabaa (WNN, 2017b). Table as of 14 April 2018.

Figure 1

Reactors under construction as of 14 April 2018 (Source: IAEA, 2018)

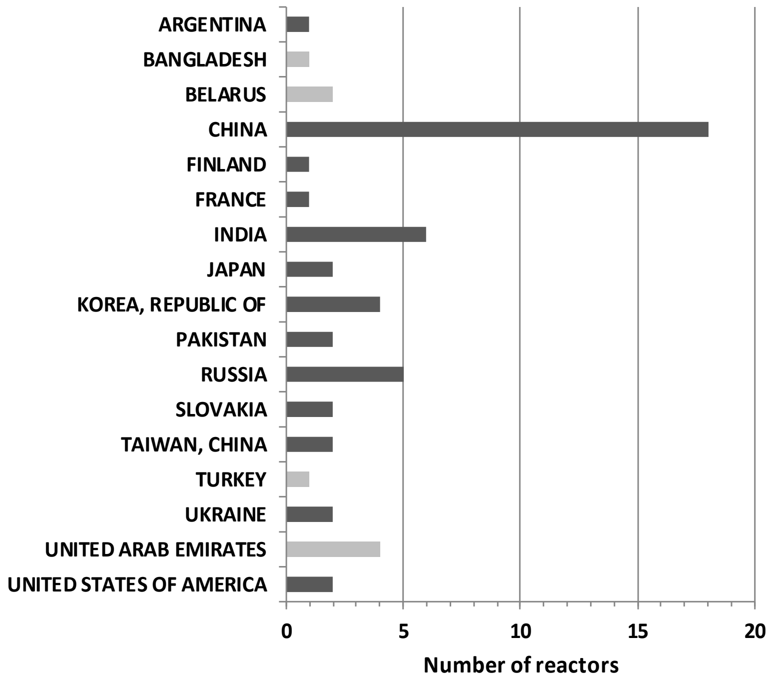

Figure 2

Key challenges (risks) of nuclear power affecting overall nuclear economics. Source: Adapted from Rogner, 2009.

- High up-front capital costs
- High level of complexity
- Ex-ante cost uncertainty
- Completion risks: construction and supply chain risks
- Long lead times (engineering & construction, etc.)
- Long payback periods
- Sensitive to interest rates
- Reliability/availability/load factor
- Market risks (i.e. competitiveness of output, service; demand)
- Wavering political support
- Public acceptance
- Regulatory risks
- Energy/environmental policy risks
- Decommissioning and waste cost/liabilities

Expected comparative advantage of SMRs versus large reactors

Figure 3

Generic view of factors affecting comparative costs of small modular reactors (SMRs) and large reactors (LRs). Source: IAEA 2013

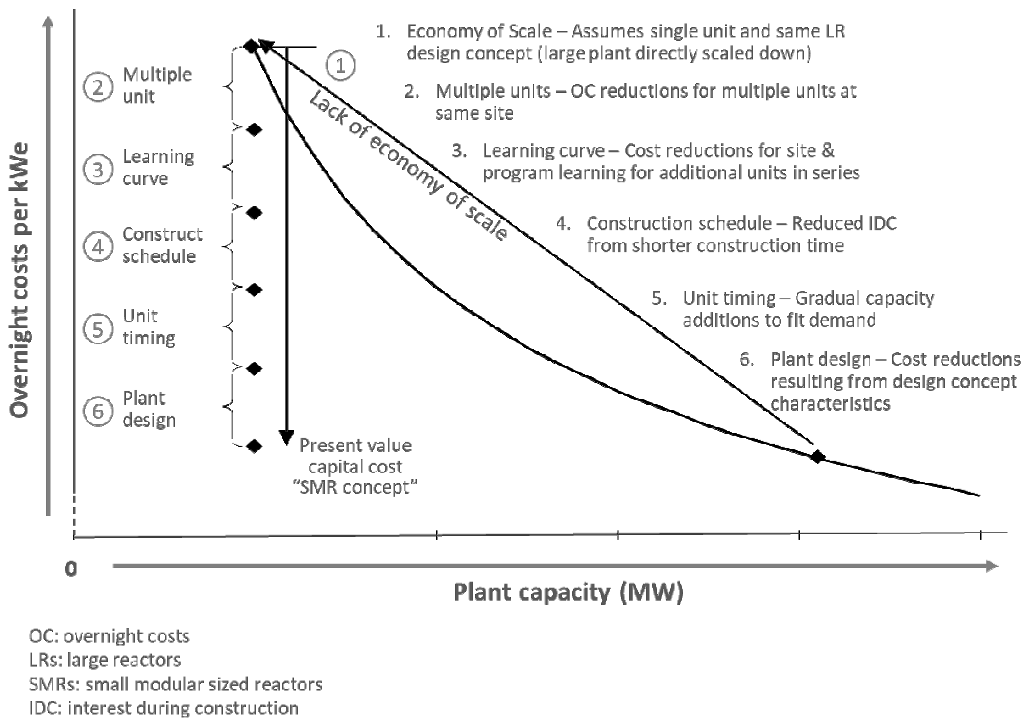

Figure 4

Effect of the Fukushima Daiichi accident on the risk perception of residents near a nuclear power plant in China. Results of surveys before (August 2008) and after (April 2011) the accident. Source: Adapted from Huang et.al, 2013.