international risk
governance council

OPINION PIECE

PRESERVING THE NUCLEAR OPTION

Overcoming the institutional challenges facing small modular reactors

AN OPINION PIECE FOR IRGC
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* Participants listed on page 42

Disclaimer

The views and policy prescriptions contained in this document are those of the author, and are not a consensus judgment by IRGC, its reviewers, its sponsors or the participants in the November 2013 workshop.

Abbreviations

BAU	Business as usual
B-O-O	Build, Own, Operate
CMU	Carnegie Mellon University
IAEA	International Atomic Energy Agency
INPO	Institute of Nuclear Power Operations
IRGC	International Risk Governance Council
LWR	Light Water Reactor
MW	Megawatt
MWe	Megawatt-electric
NPT	Nuclear Non-Proliferation Treaty
OECD	Organization for Economic Co-operation and Development
PWR	Pressurized Water Reactor
PSI	Paul Scherrer Institut
SMR	Small Modular Reactor
US	United States
U.S. NRC	United States Nuclear Regulatory Commission
WANO	World Association of Nuclear Operators

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PREFACE

About IRGC and Small Modular Reactors

The International Risk Governance Council (IRGC) is an independent non-profit foundation that aims to help improve the understanding and management of risks and opportunities by providing insight into systemic risks that have an impact on human health and safety, on the environment, on the economy and on society at large.

Established in 2003 at the initiative of the Swiss government, IRGC is based at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, with network partners in Europe, the US and Asia.

As a science-based think tank and neutral collaborative platform with multidisciplinary expertise, IRGC's mission includes developing concepts of risk governance, anticipating major risk issues, providing risk governance policy advice for key decision-makers and building bridges between science and policy in today's challenging governance environment.

IRGC opinion pieces are written by specific named authors, providing them with greater freedom to express their opinions on topics that might be of a controversial nature. The reasons that led IRGC to consider the topic of small modular reactors and the institutional challenges that would need to be overcome for their development are explained in the foreword by Granger Morgan.

The world needs energy and some of this energy can be provided by small modular nuclear reactors that are much less expensive than large ones. The wave of distrust toward nuclear power generation in the world does not do justice to all the benefits that many economies have derived so far from having access to a source of electricity that can be abundant, cheap and safe, with respect to certain criteria. Trade-offs have to be made and their resolutions may differ in various cultures and institutional settings, as does the legitimacy of using the nuclear fuel for producing electricity.

By publishing this paper, IRGC suggests that governments in the world continue to consider the development of safe, secure, sustainable and affordable nuclear power generation. This paper does not address technical issues (mostly the challenges of material science), economic issues (discussion of these challenges exists elsewhere), or the issue of public attitude. It focuses on the institutional challenges facing small modular reactors. Readers can find additional information in literature presented in the end notes[0].

FOREWORD

Nuclear power is capable of producing large amounts of reliable electricity without adding any carbon dioxide to the atmosphere. Nuclear power plays an important role in meeting electricity demand in a number of industrialized countries. For example, installed nuclear capacity in France is over 60 000 MW and nuclear power meets roughly 70% of French demand. In the United States installed capacity is roughly 99 000 MW and nuclear power meets about 19% of US demand.

While the share of electric generation from nuclear power might be reduced in parts of Europe and Japan, it is growing in other parts of the world. There are over 430 nuclear power plants now in operation worldwide. Approximately 70 new reactors are under construction – 30 in China alone. And, around the world, there are over 150 projects in various stages of planning – again as many as 50 in China alone.

While some of the plants now being planned may never get built, clearly nuclear power is not dead.

In this thoughtful report, Ahmed Abdulla provides an overview of the status and the various issues facing conventional light water power reactors – the kind of large plants that have been used for almost all electricity generation. He then turns to a much more detailed discussion of small modular reactors or SMRs.

In the past, reactors have been constructed on-site, often with significant variation from plant to plant. The promise of SMRs is that they could be manufactured in a factory as a single integrated unit and then shipped out as a single unit to be installed at a pre-prepared site. The hope is that such factory production could lower costs and increase quality control and reliability. Proponents argue that in this way safe, affordable, reliable carbon-free power could be made abundant across the world.

Abdulla provides a clear, readable assessment of how far present reality falls short of that vision. In addition to a technical assessment he provides a systematic review of issues ranging from cost to waste, liability and weapons proliferation.

The task of decarbonizing the world's energy system is going to take a portfolio of everything we've got (and regrettably even then we'll certainly fall short). Nuclear power in general and SMRs in particular may be an important part of that portfolio for some parts of the world. Abdulla's discussion in this report provides a basis for assessing how much and how soon they may play a role.

Prof. M. Granger Morgan
Chair, IRGC Scientific and Technical Council

SUMMARY

This paper suggests that overcoming nuclear power's challenges requires changes in the existing construction, deployment, and institutional paradigms that govern the technology. Such changes may be catalyzed by the development and deployment of small modular nuclear reactors (SMRs), which would complement large light water reactors (LWRs), or perhaps be used by emerging nuclear energy states to gain experience with nuclear power operation, before moving on to larger units. SMRs can produce electricity, and can also provide services such as desalination or district heating.

Small nuclear reactors have the potential to improve performance in nuclear power generation by enhancing their performance across several areas, including safety of reactor operations, waste management, proliferation, and high economic cost. Perhaps the most promising SMRs are those that could be fabricated and fuelled in an internationally supervised factory, shipped to a site where they operate without refuelling, and are then removed upon end-of-life to an internationally supervised waste processing facility. The main feature of SMRs is their smaller size, which guarantees greater **affordability** in terms of the total upfront capital that needs to be made available for each project. Economic competitiveness can be improved through **mass fabrication** on a factory assembly line, allowing **modularity**. Most designs rely on **passive safety** systems to manage the consequences of an accident. Finally, waste recycling concerns can be addressed with **long core-lives**: some novel SMRs are able to operate for up to thirty-two years without refuelling and, once the fuel is exhausted, the reactor module is extracted from its vault in one piece and shipped to a secure facility for processing.

However, it is important to note that many obstacles would have to be overcome for SMRs to achieve mass deployment. First, the commercial nuclear industry has very little experience with untested **technical paradigms** such as underground or sea-based reactors. Second, there are many **institutional challenges**, and strong political backing would be needed to overcome many of them. Current international treaties are not an impediment to the development and mass deployment of SMRs, but many national regulatory regimes do impose large barriers on SMR development and deployment. As far as the global liability regime is concerned, more than half of the world's nuclear facilities are not covered by any liability regime currently in effect.

SMRs face institutional challenges. In the case of emerging nuclear energy countries, there is little institutional support – on a trans-national or even international level – for states that do not have a framework in place to purchase, build, and run nuclear power plants on their own. They would benefit from help with issues that involve security, human capital development, accident response, or managing complex projects. More research on the following fronts would help SMR development:

- Comparative risk assessment of alternative SMR deployment options and technologies.
- Bilateral and multilateral agreements on enhanced nuclear safety and security.
- Definition of the minimum emergency infrastructure that is needed for safe and secure operation of SMR plants.
- A global liability regime that ensures all reactors are covered by currently existing programs, perhaps coupled with the development of viable alternatives or supplementary regimes on the regional level.

1.
INTRODUCTION

In order to avoid the huge negative consequences of climate change, the world needs to decarbonize its energy systems. Over the past few decades, there have been several fortuitous movements in this direction. Many countries are now less carbon-intense, thanks to their use of new energy sources such as natural gas and renewable energies, as well as a more efficient use of energy. The technical and economic performance of both wind and solar power continues to improve. The cost of electricity derived from wind is now at a point that even with a low carbon price it would be cost effective without subsidy. And, in recent years, the cost of solar power has decreased even faster, although it is still significantly more expensive than wind. Three of the world's largest economies – the United States, the European Union, and China – continue to either incentivize or sponsor the development and deployment of diverse low-carbon technologies ranging from renewables to nuclear fission and fusion.

And yet, when compared to the scale of the problem, progress to date has been dismal. Among other factors, the development of China and India will continue to be fuelled by coal at least over the next two decades[1], despite the considerable investments that China is making in other sources of energy. The US Energy Information Administration estimates that over the next two decades, global primary energy use is destined to grow in most regions. And, despite the rise of renewable energy technologies and the more efficient use of energy resources, we can still expect fossil fuels to dominate the global energy mix well into the middle of this century, especially in non-OECD countries[2]. Overall, energy consumption in OECD countries shows a slowing pace of increase (see Figure 1 below), and it is increasingly decoupled from economic growth. But even in some parts of the OECD, increasing energy demand will still be met, in part, by fossil fuel energy[3].

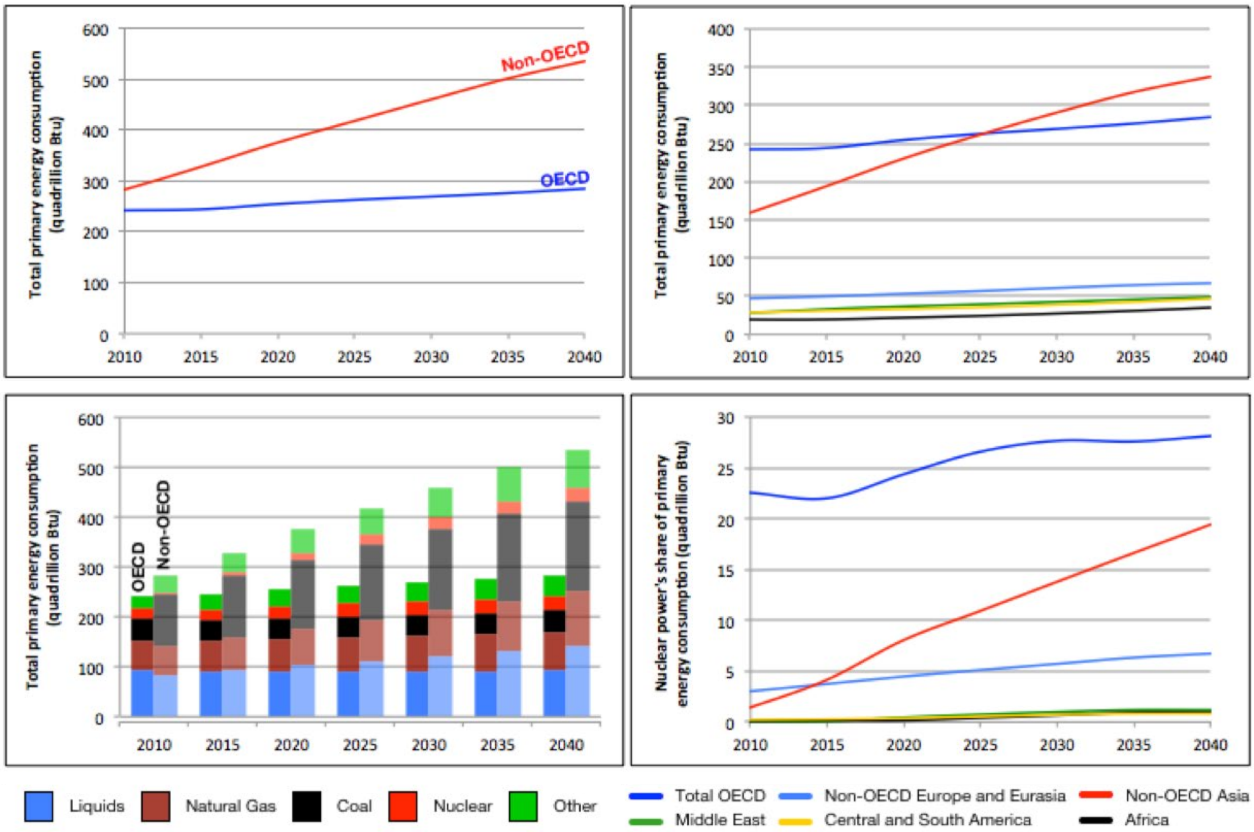

Figure 1: A more than 50% increase in world primary energy demand is anticipated in the thirty years from 2010 to 2040. **Top left**: The source of most of this increase is growth in non-OECD economies. **Top right**: Growth in primary energy demand is anticipated in all regions of the world, though the fastest rate of growth is in non-OECD Asia, due to the robust growth in the Chinese and Indian economies. **Bottom left**: There will be an increase in the consumption of all fossil fuels, along with a strong growth in nuclear power and renewable energies in non-OECD economies. Unfortunately, the rise in energy demand is greater than the growth of low-carbon technologies. **Bottom right**: Despite doubts regarding the future of nuclear power in the OECD, projections suggest that the level of energy production from this source will slightly increase. The major part of the growth comes from non-OECD Asia and non-OECD Europe and Eurasia, namely China, India, and Russia[4].

Eliminating or scaling back the use of nuclear power, a course of action being followed in industrialized economies such as Belgium, Germany, Japan, Switzerland, and possibly France to a certain extent, will require further efforts to reduce global greenhouse gas emissions. Despite its problems, nuclear power is a proven source of low-carbon base-load electricity. So far, the movement away from nuclear power in certain countries is more than offset by increased nuclear penetration in China, India, Korea and Russia, among others. That said, the projected growth in energy demand diminishes the significance of projected growth in nuclear energy in these countries. See Figure 2.

Given the scale of the challenge to decarbonize the power grid in mitigating climate change, what is needed is a portfolio of low-carbon energy options in conjunction with a major transition to low-carbon electricity generation. Instead of **shutting down nuclear power plants and abandoning the technology, a strong case can be made for promoting it wherever it is politically, economically, and institutionally viable. Developed appropriately, nuclear power has a role in providing electricity in a way that is safe, reliable, affordable and sustainable**.

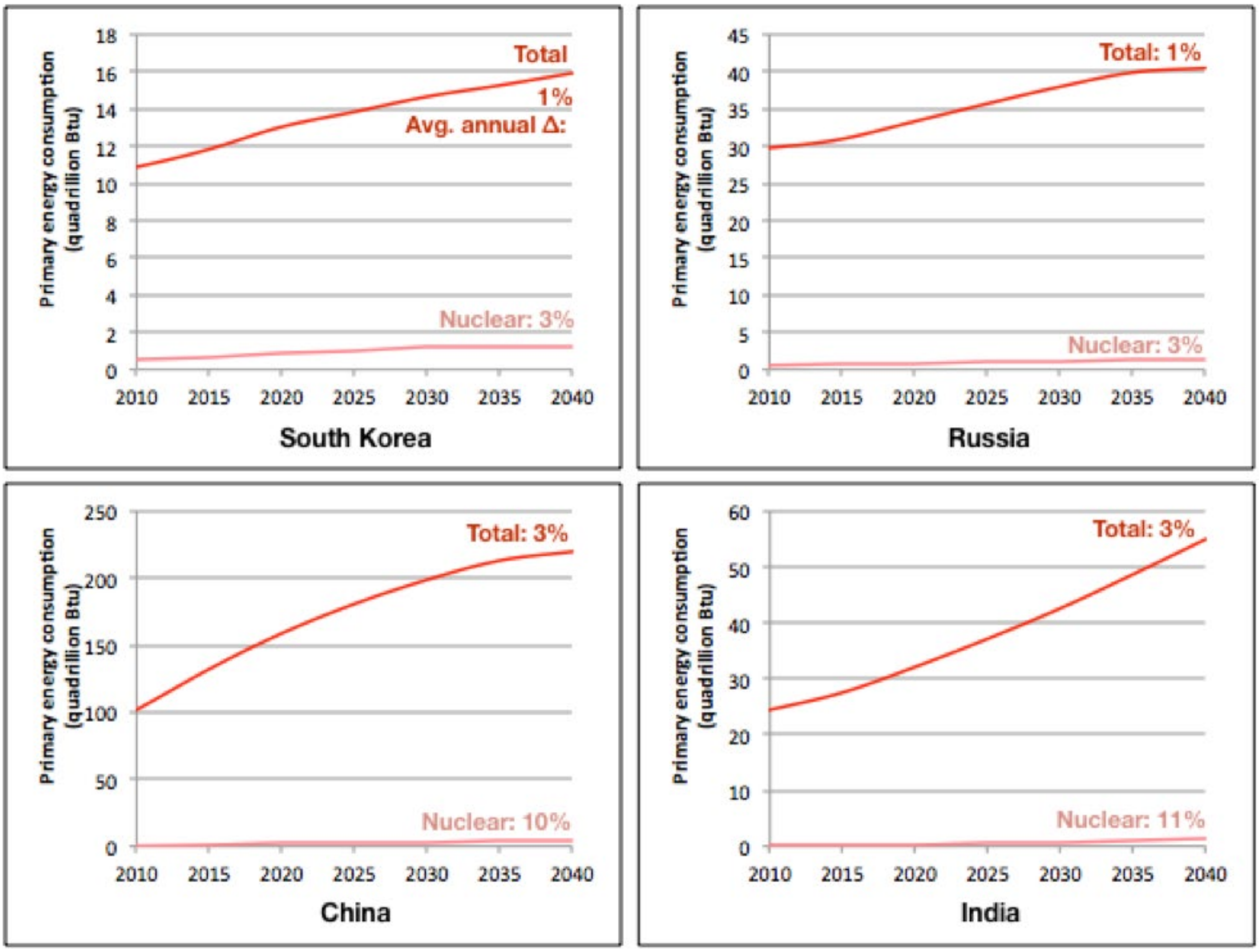

Figure 2: Reliance on nuclear power is projected to grow particularly in South Korea, Russia, China, and India. In the latter two countries, however, it is starting from a fairly low base compared to total energy demand. That, coupled with the growth in demand, implies that nuclear power will struggle to maintain its share of global energy provision despite increased penetration[5].

2.

OBSTACLES TO THE DEVELOPMENT AND DEPLOYMENT OF NUCLEAR POWER

Throughout its history, nuclear power has faced concerns that can be broadly divided into four categories: safety of reactor options; waste management; concerns about proliferation; and high economic cost. We briefly elaborate on each one of these below in the context of current nuclear power plant facilities, which is dominated by light water reactors (LWRs). Two decades into the atomic age, light water technology began to dominate other nuclear designs worldwide. LWRs were chosen to provide plutonium for the American nuclear weapons program during the Cold War. Despite their challenges, the nascent American nuclear industry chose to market LWRs for use by domestic energy utilities. By the late 1970s, LWRs had begun to dominate nuclear power plants globally due to American dominance in the nuclear export market.

Light water is ordinary water[6]. LWRs use it both for moderating the nuclear reaction by absorbing some of the neutrons generated in the core of the reactor, and for cooling the core by transporting the heat it generates to another loop of water which, when it boils, produces steam that is fed into a turbine-generator complex. Because nuclear reactors continue to generate heat even after they are shut down, the presence of water in the core is critical for plant safety.

Safety of reactor operations

Like all human activity, nuclear power is not without risk. For decades, surveys of public attitudes towards nuclear power have consistently depicted this technology as inherently riskier than others. The risks associated with nuclear power are viewed as involuntary and uncontrollable, and the consequences of accidents involving the technology are considered intangible, long-lived, and partly unknown[7]. Figures 3 and 4 below collate data from various public opinion surveys on nuclear power conducted in OECD countries over the past four decades. To discuss the nuances involved in such surveys is to digress. Generally, men support nuclear power more than women, and introducing climate change into the discussion engenders a “reluctant acceptance” of the technology[8]. Historically, after every nuclear accident, the technology has witnessed a drop in public support, usually in areas affected by, or close to the accident; as time passes, the opposition softens somewhat[9]. That said, there is evidence that a string of nuclear events erodes public trust, which can harden public opposition to nuclear power. This is most clearly illustrated in the case of Japan[10].

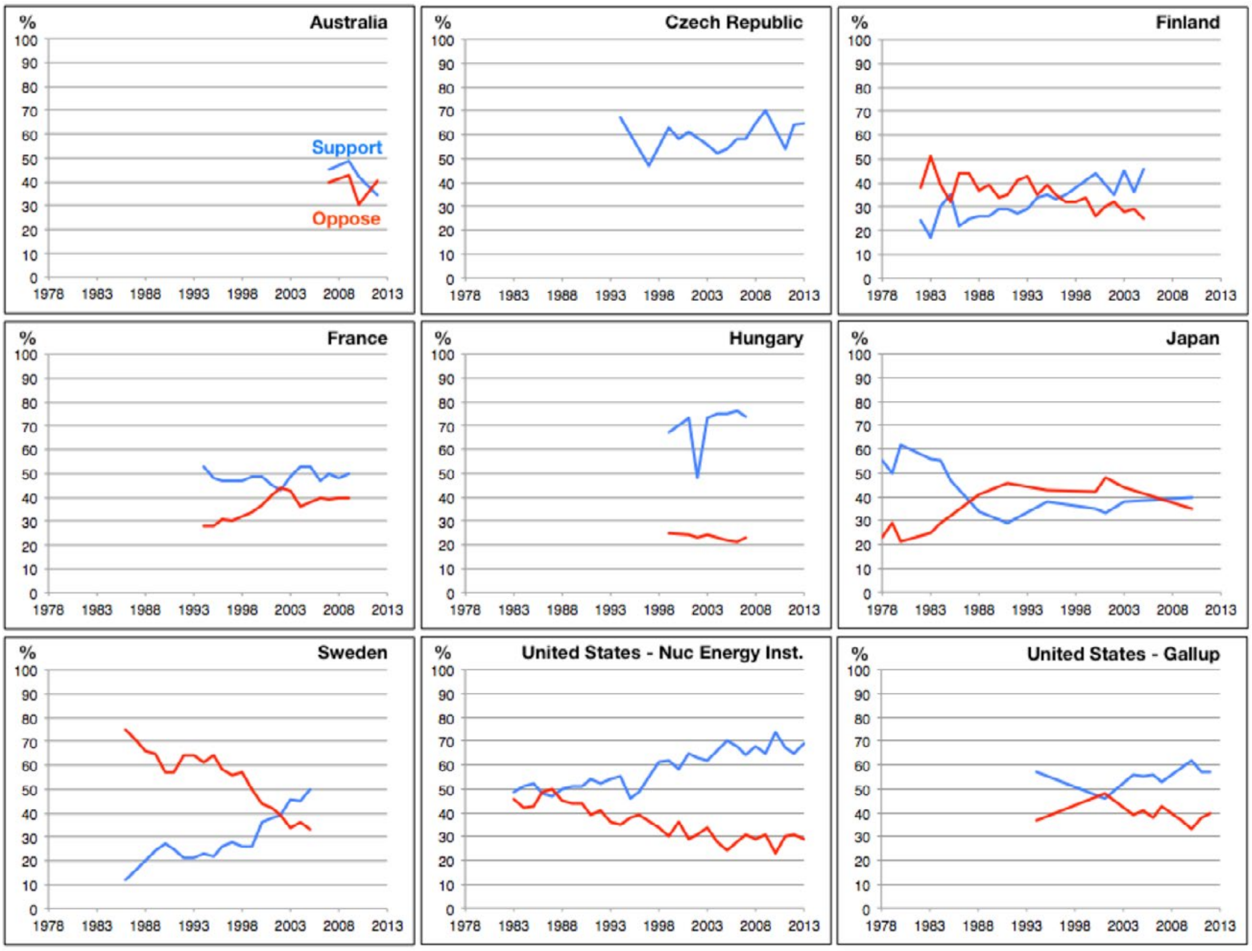

Figure 3: Results from public surveys on nuclear power in a range of OECD countries. Caution should be used when interpreting this data. “Support” implies strong or somewhat strong support; “oppose” implies strong or somewhat strong opposition. These studies asked a generic question of the type, “are you in favor of nuclear power?” as opposed to, “do you support increased nuclear construction?” Data used to create these figures was compiled from multiple sources[11].

Engineers go to extraordinary lengths to reduce these risks, as evidenced by the small number of power plant accidents since the inception of the technology. However, the technical methods and measures they necessarily adopt fail to resonate. People are not reassured. Many pose the same questions about these facilities as they do any large, complex, and potentially dangerous one. Some of the concerns are linked to the necessity to reprocess or store waste rather than the electricity generation process itself.

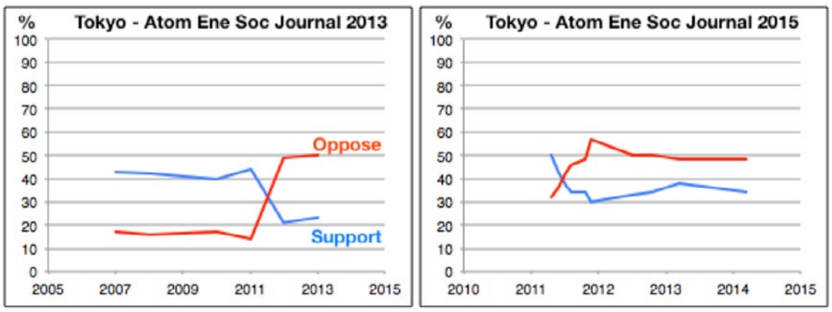

Figure 4: Results from public surveys on nuclear power in the Tokyo Metropolitan Area before, during, and after the Fukushima Nuclear Disaster (March 2011)[12].

Waste management

Nuclear power plants produce significant amounts of long-lived, highly radioactive waste. Each 1 000 megawatt electric (MWe) light water reactor produces twenty tons of waste annually, all of which is stored on-site in actively cooled spent fuel pools. After cooling down for several years, in the case the facility is facing a shortage of space, that waste may be transferred to dry storage casks. While nuclear fuel is reprocessed routinely in France, Japan, Russia, and the UK, no country today, with the exception of Finland and Sweden[13], has provided any real adequate solution to the problem of waste storage and, after years of debate, plans for deep geological repositories in some nations have been abandoned[14].

Because it is highly radioactive, concern over the safety and security of nuclear waste will continue to pose a problem for thousands of years. Not only does nuclear waste require a long-term solution that is technically adequate, it also entails having social institutions that are able to protect the public and the environment from potential exposure, including malicious acts, over a long period. Since it is such a liability, the waste from a nuclear power plant remains in the custody of an operator or country (unlike the waste from fossil fuel generation which is released into the air).

Concerns about proliferation

States might be drawn to using a civilian nuclear energy program as a façade to develop nuclear weapons, or to acquire the capability to produce them should they be deemed necessary for existential reasons. Although a number of today's nuclear weapons states have used their civilian nuclear infrastructure to advance their strategic military goals, many states have also acquired the capability to develop nuclear weapons, yet have stopped short of doing so. Prominent examples include Argentina, Brazil, Germany, Japan and Korea.

Non-state actors have also expressed interest in acquiring nuclear devices and nuclear material. Nuclear facilities need to remain on sufficiently high alert to pre-empt such attacks, and overcome them in the unlikely event they occur. But it is also possible to divert material from other areas of the nuclear fuel cycle whether it be from the preparation and transport of fresh fuel to operating reactors, or the extraction of spent fuel from reactor sites. Even the waste disposal site needs to remain vigilant. It is a matter of material control and accounting for which adequate technical solutions exist on both a national and international level. The problem resides in building up sufficient political willingness to develop these material control systems, and perhaps to establish international fuel banks and waste sites to ensure that materials transit through secure, internationally supervised facilities.

High economic cost

Nuclear power plants are not competitive in many deregulated energy markets, and the multi-billion dollar capital expenditure that is involved makes them unaffordable in many regulated markets. Utilities currently building nuclear power plants are either very large or sovereign-backed; indeed, most are both.

Nuclear power is costly for a number of reasons, some of which we describe below. Because it is needed and because the technology is highly regulated, most reactor designs need to incorporate multiple redundancies for every critical system component. Firstly, for public safety, designs have to prove they can withstand severe accidents. Safety systems and tight regulation increase costs. Secondly, because these projects are large and complex, the manufacturing, transportation, installation, and testing of critical components is costly. Thirdly, the construction of a new plant requires a highly skilled workforce: due to the worldwide slowdown in nuclear installation from the late 1970s to the early 2000s, only a small portion of this talent pool was retained. Countries undertaking large nuclear projects, such as China, have gone to great lengths to both develop an indigenous talent pool and attract good engineers from around the world to execute these projects. Fourthly, quality control and quality assurance activities, both on and off-site, add a significant premium to nuclear investments.

Given the costs of siting, design evaluation, regulation, and construction, engineers build large nuclear reactors with the aim of spreading the costs across as great a number of kilowatt-hours as possible. The fact that these projects have long lead-times – in other words, they take a long time to build – further incentivizes enlarging the reactor size, so that utilities can recoup their investments quickly. Historically, this increase in reactor size, instead of improving the viability of nuclear power plants, has damaged their economic prospects[15]. Nuclear-grade components have become so large that only a limited number of manufacturers are equipped to manufacture them. As millions of components and innovative building techniques become the norm, so the complexity of each project becomes more difficult to manage. In today's world, and with few exceptions, each proposed nuclear power plant can seem like a first-of-a-kind project with its own set of technical, economic, and regulatory hurdles. Other economies of scale, such as those associated with modular construction, equipment standardization, and the establishment of integrated project teams have not been fully exploited by the nuclear industry. Significant learning economies in nuclear power have yet to materialize due, among others, to these factors.

In the next section, we will describe small nuclear reactors (SMRs), which have the potential to address some of the concerns regarding safety, waste, proliferation, and cost.

3.

THE POTENTIAL ROLE OF SMALL MODULAR REACTORS IN FUTURE NUCLEAR POWER GENERATION

Overcoming the challenges of nuclear power requires changes in the existing construction, deployment, and institutional paradigms that govern the technology. One innovation that can potentially catalyze such changes is the development and deployment of small modular nuclear reactors (SMRs), which would complement large LWRs among global nuclear power plant facilities, or perhaps be used by emerging nuclear energy states to gain experience with nuclear power operations before moving on to larger units.

SMRs are nuclear reactors with a power output of 300 MWe or less. They come in a number of sizes, ranging from 5 MWe to 300 MWe. They also come in a number of technologies, ranging from smaller versions of conventional LWRs to advanced, non-light water designs. As already stated, LWRs use conventional water as both a coolant to transfer heat from the core to the steam generator thus facilitating electricity generation, and a moderator, absorbing some of the neutron released by the chain reaction in the core to control the fission process. Non-light water designs, on the other hand, use gas, salts, or liquid metals to perform the cooling functions; some need no moderation. Each of these technologies has both advantages and disadvantages, and a discussion of each goes well beyond the scope of this paper, though some of their characteristics will emerge during the discussion.

No.	Name	Developer	Country	Type	Capacity (MWe)	Status
1	CAREM-25	CNEA	Argentina	iPWR	25-150	1 UC
2	FBNR	FURGS	Brazil	PWR	72	-
3	ACP100	CNNC	China	iPWR	100	-
4	CEFR	CNEIC	China	LMR	20	1 OP
5	CNP-300	CNNC	China	PWR	300	1 OP
6	HTR-PM	Tsinghua Univ.	China	HTR	105	1 UC
7	Flexblue	DCNS	France	PWR	50-250	-
8	AHWR300-LEU	BARC	India	HWR	304	-
9	PHWR-220	NPCIL	India	HWR	220	16 OP
10	4S	Toshiba	Japan	LMR	10	-
11	SMART	KAERI	Korea	iPWR	100	-
12	ABV-6M	OKBM	Russia	PWR	8.6	-
13	BREST-OD-300	RDIPE	Russia	LMR	300	-
14	KLT-40S	OKBM	Russia	PWR	35	2 UC
15	RITM	OKBM	Russia	iPWR	50	-
16	SHELF	NIKIET	Russia	PWR	6.0	-
17	SVBR-100	JSC AKME	Russia	LMR	100	-
18	UNITHERM	RDIPE	Russia	PWR	2.5	-
19	VK-300	RDIPE	Russia	BWR	250	-
20	WWER-300	OKBM	Russia	PWR	300	-
21	EM2	General Atomics	US	HTR	240	-
22	G4M	Gen 4 Energy	US	LMR	25	-
23	SMR-160 (HI-SMUR)	Holtec Intl.	US	PWR	160	-
24	mPower	Babcock & Wilcox	US	iPWR	180	-
25	NuScale	NuScale Power	US	iPWR	45	-
26	PRISM	GEH	US	LMR	155	-

Table 1: Compiled by the author, highlights the size, type, and countries of origin of the twenty-six SMRs currently under development.

BWRs: Boiling light water reactors
HTRs: High temperature, gas-cooled reactors
HWRs: Heavy water reactors
LMRs: Liquid metal reactors
PWRs: Pressurized light water reactors
iPWRs: Integral pressurized light water reactors
UC: Under construction
OP: Operational

Affordability

The main innovation of SMRs is their smaller size. It guarantees greater affordability in terms of the total upfront capital that needs to be made available for each project. Even if SMRs cost more per kilowatt of output energy, the total capital expenditure required to deploy each unit will be significantly lower than the many billions of dollars required for large LWRs today. Companies can therefore plan incremental capacity additions as demand increases. The pool of potential owners is thus inherently larger. Affordability does not imply economic competitiveness, however. Even if SMRs are affordable, a utility will only decide to acquire one if it is competitive with other forms of energy generation on purely economic terms, or if it serves auxiliary or strategic needs that justify the premium a utility would pay for its deployment. This analysis is highly dependent on context.

Mass fabrication and modularity

Economic competitiveness can be improved through mass fabrication on a factory assembly line. Advanced manufacturing makes possible the fabrication of extremely complicated components and modules in a cost-efficient manner, and with high levels of quality control. Airframe manufacturers, for example, employ these techniques to enhance economic performance and assurance quality.

The smaller size of SMRs in turn facilitates secondary innovations that large nuclear power plants have yet to exploit. For instance, they can be configured to provide non-electric services almost exclusively, such as desalination or district heating. Combined heat and power is another possible option. Some technologies produce high temperature process heat that could be attractive for hydrogen production, and in applications in the chemical and mining industries. Moreover, the relative security of supply they afford allows for deployment in off-grid or geographically constrained locations, ranging from Arctic communities to Antarctic research stations and remote islands.

SMRs can change the deployment paradigm in other ways. Small reactors can be installed on barges or ships to create floating power plants. A majority of the world's population lives close to water, so most of the demand is near to coasts. In fact, smaller reactors can be installed on submersible platforms, as indeed they have been for decades. The ocean provides a permanent heat sink and is therefore the ultimate line of defense. On land, SMRs will utilize less water than large reactors, most of which are located close to shores, thus making in-land deployment next to smaller cooling sources possible. Underground deployment is also feasible as a method of reducing the profile of a plant as a target for attack, and several developers have proposed this.

Safety

Finally, some SMR technologies are quite novel, and can help break the dominance of LWRs and their accompanying problems. Most designs rely on strengthened inherent safety features or passively safe[16] systems to manage the consequences of an accident. Some light water SMRs even achieve what has been called the "triple crown" of nuclear safety in the event of an accident: they would need no operator intervention, no additional water inventory, and no on-site power, a radical departure from the current LWR safety paradigm. Non-light water technologies eliminate the risks of a meltdown through a variety of inherent characteristics, and each of these designs has its own advantages and disadvantages.

Several SMR designs employ approaches to mitigating risks that would be considered infeasible in large reactors. For instance, one vendor, NuScale Power, envisions encasing the module in a stainless steel vessel that serves as its containment. This vendor, together with others, believes that siting the module underground in a pool of water will lead to increased safety[17]. Some vendors propose that modules be sealed in the factory to prevent tampering with the fuel[18]; several plan to construct reactors capable of operating for a decade or more without refuelling[19].

Finally, one advantage of SMRs is their smaller core inventory, which reduces the consequences of radioactive release. But, since most SMR designs have yet to be finalized, it is difficult to validate claims that their core damage frequencies would be substantially lower than that of large reactors.

Waste recycling

Some SMR designs promise to recycle the waste that has been accumulating as a legacy of the LWR industry into fresh fuel. Others promise to have such long lives that refuelling becomes less of an issue. Large LWRs require a third of their core to be refuelled every eighteen months, necessitating shutdown and maintenance. Some novel SMRs claim to operate for up to thirty-two years without refuelling; once the fuel is exhausted, the reactor module is extracted from its vault in one piece and shipped to a secure facility for processing. Eliminating the risks associated with fresh and spent fuel transport, as well as on-site spent fuel storage, radically alters the proliferation risk profile of a facility. The fewer times nuclear materials are accessed on-site, the smaller the risk of proliferation. Of course, designs that promise longer core-lives also require fuel enriched to a higher level, which is also problematic from a proliferation standpoint. There are few easy trade-offs. On the other hand, light water SMRs do generate more waste per unit of electricity generated than large reactors. Although this is hardly the largest problem facing nuclear power, since studies suggest that uranium reserves are ample to power a modest build-out of nuclear power plants[20], it is important to consider the full fuel cycle implications of mass SMR deployment.

In view of their potential contribution to overcoming some of the challenges related to power generation in general and nuclear power in particular, it is important to note the technical and institutional obstacles that would have to be overcome for SMRs to achieve mass deployment. Some of these are listed and described in the next section.

4.

OBSTACLES TO THE DEVELOPMENT AND DEPLOYMENT OF SMALL MODULAR REACTORS

It is also possible to argue against the development and deployment of SMRs. In fact, each of the above SMR advantages can be turned into a disadvantage or compromised by poor planning. Mass factory fabrication, for example, requires a factory. All existing models of SMR commercialization either ignore or underestimate the difficult task of building such a facility. It would be a multi-billion dollar undertaking. The economic viability of non-electric end-use scenarios also requires in-depth assessment.

In general, making the strategic case for SMR development and deployment, if it involves considering factors that cannot be monetized – such as emissions profiles, security of supply, and national prestige – is harder for developing countries, or companies beholden to shareholders with short-term investment horizons. A more strategic decision-making outlook is required for SMRs to be appealing as an energy choice.

Technical considerations

The commercial nuclear industry has very little experience with untested deployment paradigms such as underground or sea-based reactors. Although they might appear attractive at the outset, one must not discount the potential risks associated with these options: a risk-informed design framework is necessary, and few concepts have reached a sufficiently advanced state for their developers to invest the considerable resources necessary to carry out such a review. To give but two examples: floating sea-based reactors are more difficult to capture but, should one be hijacked, defusing the emergency by counterattacking the platform and recapturing it could be even more difficult. Similarly, underground reactors would likely reduce the consequences of aircraft impact. However, maintenance and access would be more difficult and, in the case of a safety or security incident, emergency responders would be more constrained than they would in an aboveground design.

Finally, passive safety systems need to prove that they can withstand design-basis threats, as well as very low probability, beyond design-basis disruptions. Developers of reactors with novel fuels need to demonstrate that these fuels are technically and economically viable, robust under emergency conditions, and scalable for commercialization. Then they need to qualify and license them, a process that requires the construction and operation of a prototype, which might well cost billions of dollars in the US[21], depending on the design. If the fuel is associated with an existing reactor design, the costs are much lower, but still on the order of tens or hundreds of millions of dollars. Reactors with innovative core geometries need to pass a similarly daunting gauntlet. In the US, vendors developing advanced reactor designs are obviously aware of these issues, but none have the resources to complete development. In Russia and Japan, government sponsors this work more directly, but it still only occurs on a small scale. China and India are aggressively pursuing high temperature SMRs and sodium-cooled fast reactors, respectively. Solving the outstanding technical challenges facing these designs thus occurs in government-supported (or government-owned) labs in these countries.

Institutional considerations

The obstacles to SMR development and deployment are not only economic and technical. There are many institutional challenges, and only political will can help overcome many of them. A general wariness of novel reactor designs has forced the international community, and the international nuclear control regime, to maintain the LWR paradigm and actively promote it in emerging nuclear energy states. Innovations such as higher-enrichment fuels, which would allow for longer-lived cores, are probably out of the question unless a major nuclear supplier state engages in a sovereign-backed campaign to develop and promote them.

International treaties are not an impediment to the development and mass deployment of SMRs, although new treaties creating better arrangements could definitely be crafted. However the political will to see such treaties through to ratification does not exist. National regulatory regimes, however, do impose large barriers on SMR development and deployment. Their experience with the current generation of large LWRs makes these institutions wary of innovations in light water technology, let alone advanced SMRs. Some regulatory regimes might be more accommodating, but any effort to certify an advanced SMR and license a first plant, even if the design were ready today, would require a time horizon of ten years at minimum.

Risk of incidents and accidents

If fundamental design flaws appeared in a mass-produced reactor in one country, that might mandate shutting down all reactors of the same design, wherever they might be. Unlike the aircraft industry, where substitutes can be put readily into service at short notice, the nuclear industry provides energy, which is not in itself an end product. The economic and political consequences of such disruptions would be severe in countries that are underprepared. This highlights the need for extensive quality control and rigorous pilot testing of any mass-produced design.

Successful mass deployment of SMRs internationally would result in a much larger number of facilities at which problems could develop. Unless designs are dramatically improved, so that SMR incident rates are much lower than for conventional reactors, this will lead to an increase in the number of safety and security incidents. Discussions of the risk profiles of different reactors often fail to mention this point: if SMRs become a vehicle for the mass deployment of nuclear power, the overall risk of nuclear incidents might increase, even if the risk of an incident at a single reactor site is reduced through innovations in safety and security. Compounding this concern is the fact that the tools available to assess proliferation risk and resistance are inadequate, as a recent report by the National Research Council made clear[22].

Public opinion

The last major category of obstacles to the development and deployment of SMRs is public attitude to nuclear power in general, which was mentioned earlier. Whether through proven safety or better risk communication, nuclear power plants will only be built where local communities do not reject them. Addressing this challenge, long acknowledged inside and outside the industry, is of fundamental importance to the future of the technology. Existing tools, such as surveys, paint an incomplete picture of public attitude and provide little information as to how the problem could be addressed.

5.

MAJOR CHANGES IN THE INSTITUTIONS GOVERNING NUCLEAR POWER ARE REQUIRED BEFORE SMALL REACTORS CAN BE DEPLOYED

If we cannot at present imagine a cost-effective carbon-free portfolio that foregoes nuclear power, and if SMRs were to potentially be a vehicle for effecting the changes needed for nuclear power to become a viable energy option, the institutional challenges facing this technology would have to be identified and addressed.

Much of the analysis presented in this paper is informed by presentations and discussions resulting from an international workshop that was convened in November 2013 to identify these challenges and explore ways of overcoming them. This section highlights the results of sessions dedicated to identifying the institutional challenges confronting SMRs. As mentioned earlier, there is a large variety of SMR designs, and much debate about whether some reactors might prove more appropriate for mass and global deployment than others. Therefore, the organizers chose, during this workshop, a subset of six very different designs in an effort to conduct a comparative assessment of novel innovations and deployment paradigms. Workshop organizers iterated on the choice of the six candidate designs. The selection criteria were: (1) choose a limited number of designs (six) so as not to overwhelm participants; (2) each of these had to be novel in at least one respect; (3) as many technologies as possible were to be represented; (4) at least one of the designs had to be a light water SMR, so as to contrast this technology with non-light water ones. A description of the six chosen designs, along with their technology readiness levels (TRL) in the authors' judgment, can be found in Tables 2 and 3 below. The technology readiness standards adopted are those of the US Department of Energy[23].

Reactor	TRL	Description
Babcock & Wilcox Generation mPower	5	180 MWe light water reactor that integrates the nuclear steam supply system into one module, the mPower received one of the US Department of Energy's two cost-share awards. Work on the design has slowed down due to a lack of enthusiasm from customers.
OKBM KLT-40S	7	35 MWe light water reactor previously deployed on Russian ships. Prototype floating nuclear power plant using 2×35 MWe KLT-40S reactors is nearing completion.
Toshiba 4S	4	10 MWe underground liquid metal reactor with a sodium coolant and a long (30 year) refuelling interval.
Tsinghua / CNEC High Temperature Reactor, Pebble-bed Module	8	2×105 MWe high temperature reactors that utilize pebble fuels as opposed to fuel rods. A 10MWe prototype was built by Tsinghua University and operated for a number of years. A full-sized prototype is being built in Shidaowan.
JSC AKME SVBR-100	2	101 MWe liquid metal reactor with a lead-bismuth eutectic coolant, SVBR-100 technology was deployed previously on the Soviet Union's Alfa-class submarines, where maintenance proved challenging.
General Atomics Energy Multiplier Module (EM^2)	3	265 MWe high temperature fast reactor that uses a full helium cycle, with a design that calls for a 32-year deployment without refuelling. Complicated core geometry and the full helium cycle pose challenges.

Table 2: Technology readiness levels of the six SMR designs under investigation.

Participants at the workshop also discussed whether they could identify a subset of SMR-specific design features that stand out as being helpful for the mass deployment of SMRs globally. Most of the participants came from industry, though there were participants from intergovernmental organizations and academia as well.

	B&W mPower	KLT 40S	Toshiba 4S	HTR-PM	SVBR 100	GA EM^2
Power output (MWe)	180	2 × 35	10	2 × 105	101	265
Reactor vessel height (m)	25.3	3.9	24	25.4	7.9	10.6
Underground?	Y	Floating	Y	N	N	Y
Coolant	H_2O	H_2O	Na	He	Pb-Bi eutectic	He
Breeder?	N	N	N	N	N	N
Fuel reprocessed?	N	Y	Optional	N	Optional	Optional
Refuelling period (yrs)	4	3	30	Cont.	7–8	32
Fuel enrichment (%)	<5	<20	<20	8.5	<20	12 / 6
On-site refuelling?	Y	Y	Once	Y	Y	N
Spent fuel on-site?	Y	On-ship	Y	Y	N	Y

Table 3: A comparison, across various attributes, of the six SMRs chosen for investigation.

Participants were asked to select and rank five characteristics out of a list of fifteen that – in their judgment – would most help promote the adoption of SMRs in OECD countries. These are countries with well-developed nuclear institutions (even if they have no operating nuclear power plants).

Characteristics that would most help promote the adoption of SMRs in OECD countries include, in decreasing order of importance:

- Inherent safety of designs and improved operational safety;
- The on-time, on-budget delivery of the first few plants;
- SMRs that cost less per kWe than conventional designs;
- Reducing the consequences of a release by decreasing reactor inventory (or size);
- And the development of an international regulatory framework.

When it comes to emerging nuclear energy states (defined as states with no or underdeveloped nuclear institutions, and little experience in the field), the most important characteristics are:

- Inherent safety of designs and improved operational safety;
- The adoption of international certification and regulatory regimes;
- The adoption of a build-own-operate (B-O-O) paradigm, a novel option that sees a nuclear reactor built, owned, operated, and potentially retrieved (if possible) by a supplier state or vendor;
- Ensuring scalability (i.e. catering to smaller grids and offering the opportunity to deploy multiple modules on a single site).

In the case of emerging nuclear energy states, it is clear that there should be better institutional support – on a trans-national or even international level – for newcomer states that do not have a framework in place to purchase, build, and run nuclear power plants on their own. Some of these nations might need help on issues related to security, developing human capital, responding to crises, or managing highly technical projects. The support that currently exists in this area mainly consists of IAEA technical documents and bilateral meetings. While this is valuable, the process remains a complicated, multi-decadal effort that is also very expensive.

Even if the technical, public perception, and economic challenges to SMR deployment are overcome, institutional challenges will remain. Overcoming the institutional challenges might be catalyzed if SMRs prove to be an economically competitive technology, but the challenges will remain even if we assume that mass factory production of SMRs has become a reality, that costs have diminished to the point that they are at or below those of other base-load sources of electricity and process heat, and that a technically adequate arrangement has been devised to deal with waste in a secure way.

We identify ten major institutional barriers to SMR deployment. We list these according to the scale of the challenge each poses, with the most challenging barrier first.

1. **Lack of a greenhouse gas control regime**: Without a regulatory regime that places an explicit or implicit price on the emission of carbon dioxide, constructing and operating existing designs, let alone developing innovative SMRs, will remain an economically unattractive proposition in almost all cases.

2. **Political instability; political lack of support; financial instability**: Given the length of the development, construction, and operation cycles for nuclear power plants, financial instability generally challenges nuclear power. Moreover, given the sensitive nature of the technology, political instability is similarly challenging. Even if there is an SMR that could be sold to smaller countries, those that attempt to finance construction through loans might suddenly see conditions worsen and have default become a possibility. Alternatively, governments of less stable countries that commit to SMRs might be deposed by agents that then seek either to divert material, or to compromise the integrity of the SMR in general. Moreover, some less stable nations, when faced with an accident at another plant, might decide to abandon their ambitions in dramatic fashion to secure short-term political gain, compromising long-term strategic goals or eroding public confidence in the decision-making system. Several newcomer states, defined by the IAEA as states that have expressed interest in developing a nuclear energy program, are facing serious security issues at the moment. These are bound to impede entire development agendas, including efforts to acquire nuclear power plants[24].

3. **Public concerns about reactor safety and/or waste**: As mentioned earlier, nuclear power has always been perceived as problematic in the court of public opinion. Evidence is emerging that, even in nations with limited civic participation in public affairs, populations are starting to speak out against this technology[25]. It follows that public perception issues will surely manifest themselves with SMRs.

4. **Inadequate institutional infrastructures**: Few of the SMRs in Table 1 have been certified and licensed for deployment in their nations of origin, and no designs have been exported to other nations. The only integral PWR design that has been certified so far is the Korean Atomic Energy Research Institute's SMART reactor[26] and, in the US, industry groups have criticized the limited progress made by the country's Nuclear Regulatory Commission (US NRC) in resolving many policy issues, from initial licensing to operator staffing to post-operation remediation. Although NRC staff has issued Commission Papers on a number of these issues as they pertain to light water and advanced SMRs, no final resolution has been reached on any[27]. This not only increases the risk for foreign and domestic customers interested in acquiring SMRs, but also increases the probability that vendors will eliminate SMR-specific innovations in an effort to reduce regulatory/licensing risks stemming from uncertain requirements. Other challenges include low collaboration among national regulators during design certification, which, depending on the location, could lead to different deployment rules for the same SMR unit. Similarly, the presence of inexperienced regulators in newcomer states would challenge efforts to deploy SMRs in large numbers. Insufficient emergency response capacity is another example of inadequate institutional capacity.

5. **Political and regulatory restrictions on trans-boundary flows in nuclear technology**: Most countries impose restrictions on the transfer of sensitive equipment, technology, material, and expertise. Despite efforts to harmonize these export control practices among the world's leading nuclear suppliers, decisions regarding such transfers are still

made in national capitals by panels consisting of representatives from ministries with substantial security responsibilities, including foreign affairs, commerce, and defense. The process requires these panels to sit down, deliberate, and decide on each technology or information-sharing request.

6. **Concerns about proliferation of nuclear materials**: This category includes threats of sabotage against nuclear facilities, regardless of the threat origin or part of the fuel cycle that is targeted.

7. **The nuclear premium (nuclear liability, insurance, and financing)**: Globally, there are several conventions governing liability in the case of an accident. Given the lack of a global regime, there exist substantial gaps in the current international framework: more than half of the world's nuclear installations are not covered by any regime currently in effect, meaning that liability ultimately rests with the sovereign nations hosting these reactors. If there is not a global effort to change this, it might hamper efforts to deploy SMRs in certain parts of the world.

8. **Lack of mature, diverse supply chain**: The nuclear supply chain must grow enough to handle the new paradigm. The lack of experience with nuclear construction in most of the world, including in most developed countries, is potentially a major risk (and, therefore, cost) driver.

9. **Absence of a very different waste environment (low volume; no proliferation value)**: The goal of such an environment should be to render waste unusable by proliferators, first through a significant reduction in volume, then by ensuring that what remains is of no proliferation value.

10. **Lack of progress on nuclear arms control and disarmament**: The suspension of movement towards this goal, or weakening of the international community's commitment to non-proliferation, might embolden state and non-state actors to exploit SMRs.

Scenarios of possible development of SMRs

To address the institutional challenges highlighted above would require major changes to the international nuclear governance regime. A wide range of possible SMR deployment scenarios exists. Here, we identify and describe three very different possible futures: a business as usual (BAU) scenario, a mixed export limitations scenario, and a strict export limitations scenario.

1. "Business as usual"

In a BAU scenario, all existing elements of the international nuclear governance regime remain in place: (1) exports of nuclear technologies are limited to countries that are in compliance with their obligations under the Nuclear Non-Proliferation Treaty and have instituted full-scope IAEA safeguards, or, if outside the Treaty, are in compliance with non-proliferation and nuclear security and safety guidelines suggested by the Nuclear Suppliers Group; (2) no new international agreements with legally binding obligations are made about the export, use, or operation of nuclear technologies; (3) management and operation of SMRs remain the responsibility of operators in host nations, including spent fuel management; and (4) aside from legal obligations stemming from the Treaty and other existing nuclear conventions, and commitments stemming from Nuclear Suppliers Group guidelines, manufacturers of SMRs located in different nations face different levels of nationally imposed controls on export of nuclear technology and know-how.

2. "Mixed export limitations"

In a mixed export limitations scenario, there is a new multi-national agreement among supplier states that: (1) places no restrictions on SMR export to nations that comply with the international nuclear governance regime outlined in the BAU future, under the assumption that international entities such as the IAEA have resources to exercise their full responsibilities; and (2) allows export of SMR systems of any design to any nation so long as the exporting entity, nation, or region retains full management and operating responsibility across the entire fuel cycle, and retrieves and returns all spent fuel to its country of origin, or to an internationally supervised facility.

3. "Strict export limitations"

An alternative vision for a future world of SMRs could require a new international agreement to be negotiated among supplier states, a primary stipulation of which is the formation of a globally representative consortium of manufacturers and fuel suppliers. This consortium's role would be to: (1) harmonize policy and practices for legacy contracts, stipulating that large LWRs can be sold only in countries that comply with the nuclear governance regime; (2) manage the manufacture at protected locations of sealed, pre-fuelled SMR reactors for all export markets under a full build-own-operate (B-O-O) regime and require that all spent sealed SMR reactor modules be returned at the end of their service life to an internationally approved and supervised originating facility; and (3) establish and operate a global liability regime and an international accounting system for all fissionable isotopes.

6.

SOME INSTITUTIONAL CHALLENGES CAN BE OVERCOME WITH ADDITIONAL RESEARCH

Challenge 1

A comparative risk analysis must be performed for different SMR deployment strategies and technologies; even if not all branches of such analysis can be populated with numbers; comparing the risk profiles of radically different options might elicit interesting conclusions.

First, the benefits of innovative ownership schemes that seek to change the operational paradigm of nuclear power, such as the B-O-O model, are very much open for debate. In light of concern about proliferation, it might initially seem appealing to give emerging nations an opportunity to "lease" power from a low-carbon energy source without owning and operating it, and without managing its waste. However, developing countries have additional motivation for acquiring civilian nuclear power plants, including developing human capital, accruing national prestige, cementing institutionalization, and engendering a sense of responsibility. There might also be strategic reasons for not adopting the B-O-O model. Aspiring nuclear energy states might not be willing to compromise their energy security by shifting responsibility for their nuclear program to a third party that is likely to be backed by a sovereign nation.

Challenge 2

Nuclear safety and security can be enhanced not just through sweeping international treaties, but also through bilateral and multilateral agreements. Prospective customers in emerging nuclear energy states must move towards developing and signing such agreements.

There is an alternative to the development of a centralized international system to regulate SMR deployment. One possible model involves a two-pronged approach of strengthening the IAEA's oversight of global nuclear power plant facilities, while developing the World Association of Nuclear Operators (WANO) into a stronger agency with the same level of collaboration between operators as seen in the Institute of Nuclear Power Operations (INPO) in the US. Concerns about the erosion of national sovereignty present a hurdle to progress on this front, and collaborative efforts to reform WANO would be an attempt to sidestep any sweeping international reforms.

In the absence of sweeping international arrangements, a second possible model envisions a growing number of bilateral and multilateral arrangements. A developing country wishing to purchase an American reactor that had already been certified by the US NRC could, for instance, arrange for its national nuclear regulator to collaborate with the US NRC to acquire sufficient information and technical expertise to review the documentation and achieve expedient design certification at home. Certification of a reactor design in a major market would make its certification in others easier, and bilateral agreements, such as the ones the United Arab Emirates (UAE) engaged in with multiple nations at the outset of its civilian nuclear power program, can facilitate collaboration among nations. Indeed, efforts need simultaneously to be redoubled to grant the IAEA sufficient manpower and resources, and perhaps greater authority, to fulfil its mission in a world where nuclear reactors are adopted more widely. Similarly, efforts to standardize codes in the nuclear industry have to be accelerated to truly internationalize the industry, engender cooperation among industry, and improve quality. Efforts towards this end have already commenced using the aerospace industry as a model [28]. We believe that SMRs, given their potential for mass deployment, offer the industry one of the better opportunities to standardize deployment procedures and the requisite governance schemes.

Challenge 3

The minimum emergency infrastructure needed for the safe and secure operation of SMR plants needs to be determined, and how this infrastructure can be made adaptive to the scale of SMR deployment.

Notwithstanding quality construction and competent regulation, the myth of absolute safety needs to be abandoned. Irrespective of the level of responsibility a vendor takes for plant construction and operation, the effects of a nuclear accident will manifest themselves most seriously in the area around the plant. Every nation wishing to purchase an SMR must therefore accept the burden of responsibility that comes with the acquisition of a nuclear power plant. That includes developing a safety culture and level of emergency response and crisis management infrastructure robust enough to cope with the effects of potential accidents. Withholding such capabilities in the name of "non-proliferation" can be quite dangerous for them and for their neighbors.

While vendors can design ways to increase coping with time in the event of an accident, no vendor can guarantee accident-free operation. Again, the idea that nuclear power's social institutions must remain active in perpetuity is not new[29]. Bilateral and multilateral initiatives help accelerate the development of such infrastructure, as existing nuclear energy states share their expertise, equipment, and technology with emerging nuclear energy states. On the level of plant operators, it is imperative that WANO strive to achieve the level of information-sharing exhibited by INPO in the US. Strengthening WANO will not be an easy task, but information-sharing works in the interest of all plant operators, and thus of their customers and of the nuclear industry at large.

Questions about institutional robustness will undoubtedly be raised if mass deployment of SMRs appears likely. Perhaps the most effective rebuttal to those advocating a particular arrangement is to remind them that the three most well-known nuclear accidents – Three Mile Island, Chernobyl, and Fukushima – occurred in three countries with considerably different institutions and safety cultures.

Challenge 4

Efforts to develop a global liability regime to ensure that all reactors are covered by the regimes that currently exist, or to develop regional alternative to a global liability regime must be accelerated.

No global third party nuclear liability regime exists. There are multiple conventions to which states subscribe and, given that some subscribe to none, there are substantial gaps in the current international framework: more than half of the world's nuclear installations are not covered by any liability regime currently in effect, and these reactors are found in states that take ultimate liability in the event of an emergency.

Table 4: Characteristics and status of the various global liability conventions.

*SDR: Special Drawing Right; an international currency that translates to 0.69 US as of early December 2014.

Name	Year proposed	Entry into force	Liability cap	Ratified by
Paris Convention	1960	1968	15M SDRs*	Belgium, Denmark, Finland, France, Germany, Greece, Italy, Netherlands, Norway, Portugal, Slovenia, Spain, Sweden, Turkey, UK
Vienna Convention	1963	1977	No less than 5M $; upper limit can be fixed by national legislation	Argentina, Armenia, Belarus, Bolivia, Bosnia and Herzegovina, Brazil, Bulgaria, Cameroon, Chile, Croatia, Cuba, Czech Republic, Egypt, Estonia, Hungary, Jordan, Kazakhstan, Latvia, Lebanon, Lithuania, Macedonia, Mauritius, Mexico, Moldova, Montenegro, Niger, Nigeria, Peru, Philippines, Poland, Romania, Russia, Saudi Arabia, Senegal, Serbia, Slovakia, Trinidad and Tobago, Ukraine, Uruguay
Revised Paris Convention	2004	Not yet	No less than 700M €	Norway, Switzerland
Revised Vienna Convention	1997	1997	No less than 300M SDRs	Same as Vienna Convention above
Convention on Supplementary Compensation	1997	2015	No less than 600M SDRs	Argentina, Japan, Morocco, Romania, United Arab Emirates, US

Efforts to modernize the nuclear liability regime involve steering countries towards ratification of the revised conventions – since they increase minimum liability amounts – covering a wider range of damages, and explicitly declare that “grave natural disasters” are no grounds for exoneration. Efforts are on-going to harmonize nuclear liability law within the EU, which gives a sense of the scale of the effort required to harmonize global nuclear liability regimes. Movement towards this goal will be very slow.

Some existing nuclear energy states have not ratified any of the conventions. These include India, China, South Africa and Canada. Most of the developing world has yet to ratify any. In fact, some developing nations considering a nuclear program probably could not afford the minimum liability amounts for which they would be responsible – in the event of an accident, these nations would possibly default. The international community might not be willing to develop a form of shared international liability cap. However, if SMRs were to show promise and seemed destined for mass deployment, national nuclear industries might force such efforts into being as each lobbies its government to share liability for their products with customer nations.

Bilateral approaches with powerful neighbors or supplier nations, or shared regional liability caps, might be worth investigating as countries explore the notion of acquiring an SMR. The consequences of an accident involving an SMR would in all likelihood be smaller than those involving a large reactor. This, in theory, means that more countries would be able to cope with these consequences and that SMR-specific liability arrangements could be devised that would require small enough sums of money, helping them gain access to insurance and liability markets of which large reactors would be excluded. Potential customers would need at least to explore the potential for such alternative arrangements.

Challenge 5

Visions of a future world of SMRs need to become either more realistic, by acknowledging existing technical and institutional constraints, or more sophisticated, by proposing a roadmap to overcome these constraints in pursuit of their goals.

Our work suggests that the vision of reactors that can be fabricated and fuelled in an internationally supervised factory, shipped to a site where they operate without refuelling, and then removed upon end-of-life to an internationally supervised waste processing facility presents formidable technical challenges, virtually insurmountable institutional ones, and is perhaps undesirable. For one thing, it might perpetuate the two-tiered system of nuclear trade and investment that, currently, we are locked in, thus producing resentment among players in the lower tier. Efforts can be made to avoid the creation of such a system by, for example, building multinational consortia and exploiting existing elements of the governance regime to the full instead of pushing for new agreements.

Also of concern is the fact that the technical barriers are great if we wish to achieve this vision in the two or three-decade timeframe we are envisaging. Each of the three elements the vision puts forth: the shipment of the fabricated reactor loaded with fuel, the long core-lives envisioned, and the post-operation transport to and processing in a dedicated facility, presents a technical problem that remains unsolved on a commercial scale. For instance, given concerns about criticality, shipping fuelled light water reactors to a site would be out of the question: long core-lives require intricate core geometry, large core inventories, high fuel enrichment, advanced forms of controls such as moveable reflectors, or a combination of the above characteristics. Some of these are themselves security concerns, such as high fuel enrichment; those that are not remain unproven in anything but small-scale laboratory settings. Finally, post-operation transport would be possible only after a cool-down period for most designs, since reactors would continue to generate decay heat even after shutdown. We are not suggesting that designing such a reactor is impossible; only that existing designs are not consistent with this vision, and some characteristics required by this vision might pose challenges of their own.

Besides the technical challenges, the institutional barriers to achieving this vision are legion. The nuances of such a treaty would likely dwarf those of the NPT, and that itself was a controversial treaty, mainly because it enshrined the two-tiered system in international law. The main challenges associated with this vision is that it overturns 50 years of international norms by severely curtailing access to nuclear materials, technology, equipment, and expertise for exclusively peaceful purposes. Not only does it eliminate the right to pursue any part of the fuel cycle other than operating a reactor, it curtails freedom of choice by offering a limited subset of designs from which customers would choose.

7.

CONCLUSION

The opinions presented in this paper are those of the author, but are based on individual and group exercises conducted with 40 industry experts at a conference in Switzerland in November 2013. It is important to acknowledge experts' strong links to industry, and their possible bias: after all, industry is generally skeptical of radical departures from current practice, especially if new regulatory approaches are key to these policy innovations. Participants did not come exclusively from industry, however; some came from intergovernmental organizations and academia.

When participants at the November workshop were asked what factors most help promote SMR adoption in countries with developed nuclear infrastructure, safety and economic performance were judged to be the characteristics that most promote the adoption of SMRs. When it comes to potential newcomer countries, however, institutional factors were regarded as being of highest importance. In those settings where SMRs could prove themselves a technically and economically viable alternative to base-load fossil fuel generation, the deliberations at our workshop identified ten institutional challenges that would still need to be overcome for the safe and secure deployment of this technology. The four factors that pose the greatest challenge to the mass deployment of SMRs are: the lack of a greenhouse gas control regime; political and financial instability; public concern about nuclear safety and waste; and inadequate national and international institutions.

Despite the obstacles, much work can be done at this stage to analyze the comparative risk of deploying SMRs as opposed to large nuclear reactors. Different technologies and deployment options might cut certain branches off the proliferation tree, concentrating risk in one area, if not reducing it overall. The visions of mass deployment, whether realistic or not, must be developed by their proponents to illustrate the nature of the control regimes (and the technologies) that their implementation would require. For a newcomer nation wishing to acquire a small modular reactor, it is important to concentrate on bottom-up approaches to enhancing compliance with the nuclear control regime, through bilateral agreements regarding material control, training, and maintenance, as well as multilateral agreements that deeply involve the IAEA. Proposals for regional or international "liability pooling" to cope with the consequences of a potential accident must be explored by those nations that are financially vulnerable. This would ensure that the resources required for emergency management and clean-up were available in the event of an accident.

The decision to build a nuclear power plant depends on a multitude of social, political, institutional, economic, environmental and infrastructural factors. It should not be taken lightly, whether by an existing nuclear energy state or an emerging one. Every country will need to develop some level of technical and institutional support for any nuclear plant it chooses to build. Ultimately, given the scale of the climate problem, and the growing appreciation of the limitations of relying predominantly on renewable energy technologies [30], it is important to allow vendors to either establish or disprove the viability of these designs, some of which show great innovation and promise, because it is hard to see how the world can decarbonize the energy system without adopting a portfolio of "everything we've got."

Endnotes

[0] Abdulla, A. and Granger Morgan (2015): "Nuclear Power for the Developing World", Issues in Science and Technology Winter 2015: 55-61. Available from http://issues.org/31-2/abdulla.

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[1] International Energy Agency (2014) World Energy Outlook 2014.

[2] Ibid. See also: US Energy Information Administration. International Energy Outlook 2013 With Projections to 2040. US Energy Information Administration.

[3] Ibid.

[4] Data used to construct these figures was extracted from: US Energy Information Administration. International Energy Outlook 2013 With Projections to 2040. US Energy Information Administration.

[5] Data used to construct these figures was extracted from: US Energy Information Administration. International Energy Outlook 2013 With Projections to 2040. US Energy Information Administration.

[6] Light water is H2O. Another class of reactor technologies uses heavy water, which is deuterium dioxide or D2O. The most dominant design using the latter technology is the Canadian CANDU reactor.

[7] The literature on the public perception of nuclear power's risks stretches back decades. A seminal work in this literature is: Slovic P, Fischhoff B, Lichtenstein S (1982) Why Study Risk Perception? Risk Analysis 2(2): 83-93.

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