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Small modular reactors: A comprehensive overview of their economics and strategic aspects

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ABSTRACT

A key challenge for engineers and scientists over the coming decades is to develop and deploy power plants with sufficient capacity and flexibility to meet the growing demand for energy (mainly electrical) whilst simultaneously reducing emissions (primarily greenhouse gases). With fusion-based power plants not currently being considered viable for large-scale deployment for at least 40 years, other technologies must to be considered. Renewable and high efficiency combined gas-fired plants, along with nuclear solutions, are regarded as the most suitable candidates, with Small Modular Reactors (SMRs) developing as a favoured choice. However, two main impediments to the current deployment of SMRs exist: (1) safety concerns, particularly following the Fukushima accident, and (2) their economic models, with high capital costs only being available through a limited number of investors. The goal of this paper is to provide a review and a holistic assessment of this class of nuclear reactor, with specific focus on the most common technology: the Light Water Reactor (LWR). In particular, the paper provides a state-of-the-art assessment of their life cycle, along with a comparison of their relative merits with other base-load technologies. It is shown that SMRs are a suitable choice when the power to be installed is in the range 1–3 GWe and the social aspects of the investment, such as the creation of new employment positions, is a goal of policy makers. The paper thereby provides governments and stakeholders with key economic and social boundaries for the viable deployment of SMRs.

1. Introduction

According to the DOE/EIA (DOE/EIA, 2011) the world energy consumption in 2035 will be more than double that of 1995, mainly due to increasing requirements in non-OECD countries.[1] Moreover, global electricity generation and energy consumption will increase by a factor of 3 over the same timeframe with non-OECD countries increasing their consumption by 5–6 times; mainly due to an expected exponential growth in China. Specifically for nuclear power plants, it is forecasted that electricity generation will increase from 2.6 trillion kWh in 2008, to 4.9 trillion kWh in 2035, and with many nuclear reactors approaching the end of their productive life (Schneider et al., 2011) the market is expected to expand significantly. Although the Fukushima accident has directly prevented an immediate deployment of nuclear power in some countries (e.g. Germany, Switzerland and Italy), other nations (China, Emirates, Russia, India and to some extent the USA and UK) are still pursuing their programs vigorously.

Since nuclear power provides zero greenhouse gas emission electricity (if correctly managed at affordable prices), the construction of new reactors is now also being considered in many “new-comer countries”. According to World Nuclear Association (WNA) (WNA, 2013), 53 countries including Poland, Turkey, Vietnam, Kazakhstan are at various stages in the development of their nuclear infrastructure. In particular:

- Contracts signed, with a well-developed legal and regulatory infrastructure: UAE, Turkey.
- Committed plans, with a legal and regulatory infrastructure being developed: Vietnam, Jordan, Belarus, Bangladesh.
- Well-developed plans but full commitment still pending: Thailand, Indonesia, Egypt, Kazakhstan, Poland, Lithuania, Chile.

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[1] The OECD (Organisation for Economic Co-operation and Development) is an international economic organisation of 34 countries founded in 1961 to stimulate economic progress and world trade (www.oecd.org). The 34 countries are mainly form Europe, North America and Australia. Non-OECD countries are from Africa and Asia (with the exception of South Korea and Japan), including Russia, India and China.

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- Developing plans: Saudi Arabia, Israel, Nigeria, Malaysia, Morocco, Ghana.
- Under discussion as a serious policy option: Namibia, Kenya, Mongolia, Philippines, Singapore, Albania, Serbia, Croatia, Estonia, Latvia, Libya, Algeria, Azerbaijan, Sri Lanka, Tunisia, Syria, Kuwait, Qatar, Sudan, Venezuela.

In all such countries, governments are required to create (i) a suitable environment for investment, including professional and independent regulatory regimes, (ii) policies on nuclear waste management and decommissioning, (iii) involvement with international non-proliferation measures and (iv) insurance arrangements for third party damage (IAEA, 2007a). This article aims to show to what extent a particular type of nuclear reactor, termed the "Small Modular Reactor" (SMR) might provide a candidate solution to fulfil the energy needs in these emerging nuclear markets. Specifically, the paper focuses on the Light Water Reactor (LWR), predominantly the Pressurised Water Reactor (PWR), since more advanced Generation IV (GEN IV) reactors will not be available for commercial deployment for at least two decades (IAEA, 2006; Locatelli et al., 2013). GEN IV designs still need a great deal of research and development to be sufficiently reliable and economic to justify their commercial large-scale deployment, as demonstrated by the recent experience with the PBMR reactor (Thomas, 2011). Therefore, because of the dramatic difference between GEN IV reactors and commercial GEN III/GEN III+ reactors, GEN III + LWR will be the only SMRs considered in this paper.

2. Why SMRs

From annex IV of IAEA (2007b), which is considered a seminal text on SMR technology, small sized reactors are defined as those with an equivalent electric power less than 300 MWe, while medium-sized reactors are those with an equivalent electric power between 300 and 700 MWe. More often, the two are combined into the commonly termed "Small and Medium-sized Reactors" or "Small Modular Reactors" (SMR) representing those with an electrical output less than 700 MWe. For the purposes here, it will be assumed that a "Large Reactor" (LR) counterpart has a power output >700 MWe. The term SMR includes the nuclear options along with the remainder of the plant support infrastructure and equipment, namely the steam generator, turbine and fuel storage facilities, if necessary, and can be deployed as multiple units on the same site to increase total power output. Several SMR designs (detailed in Khan et al., 2010) are currently at different stages of development around the globe. Ingersoll (2009) provides a good summary of the innovative feature of these; "*reactor designs that are deliberately small, i.e. designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics.*".

SMRs usually have attractive characteristics of simplicity, enhanced safety and require limited financial resources. However, they are usually not considered as economically competitive with LR because of the accepted axiom of "bigger is better" i.e. a misguided application of the economy of scale principle. According to the economy of scale, the specific capital cost (currency/KWe) of a nuclear reactor decreases with increasing size, due to the rate reduction of unique set-up costs in investment activities (e.g. licensing, siting activities, or civil works to access the transmission network), the more efficient use of raw materials and the exploitation of higher performances characterizing larger equipment (e.g. steam generators, heat exchangers, pumps, etc.). Thus, when the size and the power increases, in the specific capital cost expression the numerator (currency) increases less than the denominator (KWe). Consequently, in large developed countries, during the last four decades, the reactor size has steadily increased from a few hundred MWe to 1500 MWe and more today. However, the economies of scale apply if and only if the comparison is 1 Large vs. 1 Small and the reactors are of a similar design, as has largely been the case in the past. This is no longer true today, however, where smaller, modular reactors have very different designs and characteristics from large-scale counterparts (Carelli et al., 2004). Thus, assuming by definition, that because of the economy of scale principle, the capital cost of a smaller size reactor is higher than for a large size reactor is simplistic and not wholly applicable. Despite this, a reasonable retort is "why has nobody built SMR in the last two decades?" There are a number of reasons, the most important being:

1. In the nuclear industry there is a strong belief in the economy of scale. However, this is not supported by data. An example is analysed by Grubler for the French case (Grubler, 2010). In this instance the author showed that with increasing the size came increased construction time without the economy of scale.
2. In general, in the last two decades relatively few reactors have been built globally, with most investors (mainly in South Korea, Japan and China) using "proven designs" i.e. the large GEN II reactors further developed in large GEN III reactors.
3. To be fully competitive the SMR needs to balance size reduction with technical solutions that can only be enabled by a reduction in size; a typical example of which is an integral vessel, incorporating the heat exchangers, able to rely on natural circulation. Solutions like these are impossible to be fully implemented on large reactors. It was not possible to implement these solutions in the 1970s because (quoting a senior engineer from an important nuclear vendor) "to properly exploit passive solutions like natural circulation you need a great deal of computer simulations and codes. Twenty to 30 years ago those tools were not available, so the only option was to use a pump (plus the backup pumps). From an engineering perspective it is much easier to control fluids using several pipes and pumps than to rely and make sophisticated simulations with computer codes".
4. One of the enabling factors to build cost competitive SMRs is the modularisation (again expensive to implement in terms of software resources) and the availability of heavy lift cranes which have emerged only in recent years.

In particular, SMRs by their nature, are designed to be factory manufactured, transportable and/or re-locatable, and be suitable for the production of heat, desalinated water and other by-products that industrial sectors require (I. M. A. Dominion Energy Inc., Bechtel Power Corporation TLG, 2004). The term "modular" in this context refers to (1) a single reactor that can be grouped with others to form a large nuclear plant, and (2) whose design incorporates mainly pre-fabricated modules assembled on site. Whilst current LRs also incorporate factory-fabricated components or modules, a substantial amount of fieldwork is required to assemble components into an operational plant. SMRs are envisaged to require limited on-site preparation as they are expected to be "plug and play" when arriving from the factory. Kuznetsov (2008) stresses these aspects by underlining how small reactor size allows transportation by truck, rail or barge and installation in close proximity to the user, such as residential housing areas, hospitals, military bases, or large governmental complexes. Fig. 1 presents a typical PWR with a loop configuration, i.e., large primary circuit piping and components external to the reactor vessel, whereas SMR as IRIS features an integral configuration, i.e., all major primary system components are placed inside the reactor vessel ("integral vessel"), and external piping is eliminated. While the vessel size is increased in integral configuration, the