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Wishful thinking and real problems: Small modular reactors, planning constraints, and nuclear power in Jordan

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HIGHLIGHTS

- Jordan is planning to purchase two large reactors from Russia.
- Large reactors would be inappropriate to Jordan's small electricity grid.
- Small modular reactors would be more appropriate to Jordan's grid, but have problems.
- The market for small modular reactors will be smaller than often projected.
- Jordan should consider the financial impact of building a large nuclear reactor.

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ABSTRACT

Jordan plans to import two conventional gigawatt scale nuclear reactors from Russia that are expensive and too large for Jordan's current electricity grid. Jordan efforts to establish nuclear power might become easier in some ways if the country were to construct Small Modular Reactors, which might be better suited to Jordan's financial capabilities and its smaller electrical grid capacity. But, the SMR option raises new problems, including locating sites for multiple reactors, finding water to cool these reactors, and the higher cost of electricity generation. Jordan's decision has important implications for its energy planning as well as for the market for SMRs.

1. Introduction

Influential sections of Jordan's policy-making elite have long desired acquiring nuclear power. Yet, they have been hampered by many constraints, the most important of which are Jordan's small installed electrical capacity and the country's relatively low financial resources.[1] If one goes by some of the claims of vendors of small modular reactors (SMRs), these designs will allow Jordan to overcome these constraints and install nuclear power at lower cost.

Small Modular Reactors have for long been considered a key element needed to expand nuclear power in developing countries (Heising-Goodman, 1981; Ingersoll, 2009; Vujić et al., 2012; Nian and Bauly, 2014; Abdulla and Morgan, 2015). Among the characteristics of SMRs that make it specially attractive to developing countries are the suitability of the lower power levels to electrical grids with smaller capacity and the expectation that these would be more affordable even in the face of financial limitations (Kessides and Kuznetsov, 2012; Hidayatullah et al., 2015).[2]

Jordan has been listed as a potential customer for SMRs and it appears that Jordanian policymakers certainly do know of SMRs and their advantages. Yet they are pursuing the purchase of two

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[1] Jordan is not unique and most developing countries face technical and financial hurdles in acquiring nuclear reactors (Jewell, 2011).

[2] Note that the term SMR is used to mean two different although related concepts: “small modular reactors” and “small and medium reactors”. Small refers to reactors with a design power output of less than 300 MW whereas medium refers to reactors with outputs between 300 and 700 MW. In this paper, we use them somewhat interchangeably reflecting such usage in the literature.

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large Russian reactors that would be expensive and destabilize Jordan's electricity grid. In other words, Jordan belies the expectation that small developing countries would prefer SMRs.

This case study also relates to a substantial literature concerning policy making in nuclear energy. Several scholars approach the question of whether or not countries can or should acquire nuclear power by examining various techno-economic considerations (Deutch et al., 2003; Jewell, 2011). As described later, a similar approach has also been adopted in evaluating the suitability of small modular reactors (ITA, 2011; IAEA, 2013a; Locatelli et al., 2013; Black et al., 2015). However, there is also much evidence that decisions about nuclear reactors are driven by a range of social and political factors (Jasper, 1990; Byrne and Hoffman, 1996; Amir, 2010; Ramana and Saikawa, 2011; Sovacool and Valentine, 2012; Mathai, 2013). As we discuss below, Jordan's decisions seem to support this latter approach to understanding policy making.

This paper explores reasons for Jordan's decision to purchase a large reactor and the likely consequences of these factors for the SMR market elsewhere as well as the implications of the introduction of large nuclear reactors for Jordan's future electricity supply. It begins with section outlining our methodology and a brief history of Jordan's interest in nuclear power. Then it explores Jordan's interest in SMRs as well as interest in Jordan as a potential market for SMRs by proponents of these designs. This is followed by a history of the process used by Jordan to select its first nuclear reactor vendor and the multiple considerations that seem to have played a part in the decision to go with the Russian reactor design. This is followed by two sections on the challenges associated with a large reactor design as well as small reactors. The paper concludes with exploring the implications for Jordan's energy policy and government policies in countries developing small modular reactors.

2. Method

The paper is based on a combination of historical and discourse analysis, analysis of data from the World Bank and the U.S. Department of Energy, physics based calculations of water requirements, and a technical examination of the characteristics of different kinds of reactors and Jordan's electricity grid. The historical and discourse analysis used reports from the nuclear trade press, official government statements, articles in the popular newspapers and magazines, and unstructured interviews. The interviews were conducted by one of the authors during a field trip to Amman in June 2014. Interviewees included the leadership of the Jordan Atomic Energy Commission, current and former members of parliament and former government officials who occupied senior positions in the nuclear project in Jordan. Though not included in this work, the analysis also relied on extensive calculations of the levelized costs of different electricity sources that were published elsewhere (Ahmad and Ramana, 2014, 2015; Ahmad, 2015).

3. History of Jordan's interest in nuclear power

Jordan has been interested in acquiring nuclear power plants for decades. In 1955, a Jordanian representative, K. Tukan, went to the first International Conference on the Peaceful Uses of Atomic Energy in Geneva, Switzerland to talk about the electrical power needs of Jordan (Tukan, 1955). A little over a decade later, Admiral Lewis Strauss, then a former Chairman of the U.S. Atomic Energy Commission, proposed a plan to construct a nuclear desalination plant (then called desalting plant) in Jordan, which received bipartisan support in the U.S. Senate (WP, 1967). But that did not materialize. In 1988, Jordan, along with Iraq, Kuwait, Lebanon, Libya, the Palestinian Authority, Saudi Arabia, Syria and Tunisia formed the Arab Atomic Energy Agency as an independent body within the Arab League system in order to coordinate nuclear-energy research among Arab states (International Institute for Strategic Studies, 2008, p. 10).

Interest in nuclear power picked up in the early 1990s, especially after Saudi Arabia halted its supply of oil to Jordan (Ibrahim, 1990). But it was not till 2007 that the pace accelerated and the government established a Committee for Nuclear Strategy tasked with developing a program to install nuclear power generation capacity sufficient to provide 30% of electricity by 2030, and to provide for exports (WNA, 2015). The nuclear law was modified and the Jordan Atomic Energy Commission (JAEC) and the Jordan Nuclear Regulatory Commission (JNRC) were created.

In 2007, JAEC started conducting a feasibility study on nuclear power, including a comparative cost/benefit analysis (Hibbs, 2007). Around the same time, the Jordan University of Science & Technology established a nuclear engineering program (Hibbs, 2007). Jordan subsequently signed an agreement with South Korea for a research reactor (MacLachlan, 2010). Korean Atomic Energy Research Institute and Daewoo Corporation were to build a 5 MW reactor at the Jordan University for Science & Technology; South Korea was to provide a $70 million loan to help finance the reactor (WNA, 2015).

In November 2009, JAEC awarded an $11.3 million contract to WorleyParsons for pre-construction consulting for Jordan's first nuclear power plant (MacLachlan, 2009a). WorleyParsons was “to evaluate the nuclear power plant technology most suitable for Jordan… conduct a feasibility study and financial assessment of the project, as well as assist in [issuing] the tender for the plant vendor” (WNN, 2009). Jordanian energy plans from that period reportedly foresaw an operating nuclear power plant as early as 2015 (Energytribune, 2010).

4. Jordan and SMRs

In 2007, Khaled Toukan, who was to become the JAEC chairman, announced that Jordan was trying to decide by 2010 between a limited-scale nuclear power infrastructure based on small and medium-sized reactors, and large reactors that would transform its entire electricity production infrastructure away from fossil fuel consumption (Hibbs, 2007). Speaking at the World Nuclear Association’s annual symposium, Mohamed ElBaradei, then Director General of IAEA, called upon major vendors to propose small- to medium-size reactors that are more appropriate for many countries interested in introducing nuclear reactors, citing Jordan specifically as looking for reactors with power outputs in the 100-to 400-MW range (NW, 2007).

There have been several assessments of the size of the SMR market in developing countries. These suggest that SMRs should allow several developing countries to acquire nuclear capacity, which may not have been possible if these countries are restricted to large reactors. Jordan has been often identified as a potential market for SMRs, in large part because of its small installed electricity generation capacity and its relatively low GDP (Fig. 1). The GDP values can be compared with the current estimates of the cost of the Vogtle nuclear power plant in the United States, which are currently estimated at somewhere between $17 and $21 billion (Henry, 2015; Barczak, 2016).

An elaborate assessment was performed by the IAEA starting in 1996, which concluded that the “overall market is estimated at about 60–100 SMR units to be implemented up to the year 2015. It is recognized that forecasts, just like national development plans, tend to err on the optimistic side. Therefore, an overall market

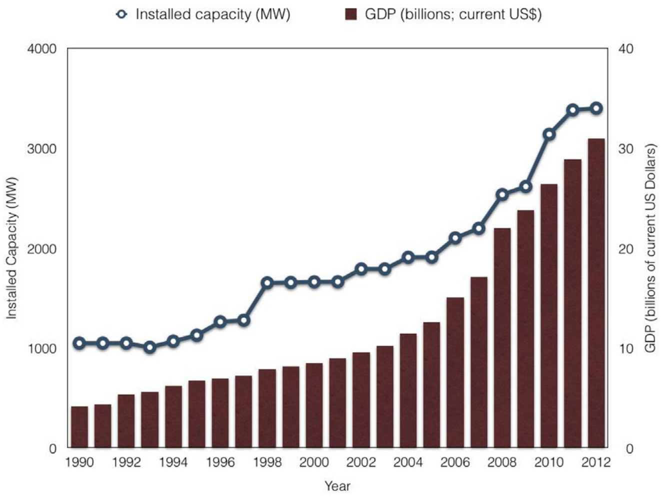

Fig. 1. Electrical capacity and gross domestic product of Jordan source: data from the World Bank Development indicators database and the U.S. Energy Information Administration.

estimate of 70–80 units seems reasonable" (IAEA, 1998, p. 12). The IAEA projected that a significant fraction of these units would be constructed in developing countries. The assessment assigned numbers of SMRs to geographical regions but not specific countries. The IAEA foresaw 15–25 SMRs in the "Middle East and South and Middle Asia" region, of which 9–16 units were expected to be medium sized (300–700 MW) reactors (IAEA, 1998, p. 213).

In 2011, the U.S. Department of Commerce's International Trade Administration identified 27 countries as "markets of interest for new nuclear expansion" and rated them "on the basis of how closely they matched seven characteristics of a potential SMR market.[3] Jordan was second on the ranking list, behind Latvia and tying with Turkey (ITA, 2011, p. 9).

In 2013, the IAEA published an overview of various models to evaluate the "economic competitiveness of small and medium sized reactor (SMR) technologies compared to other energy sources and large reactors" (IAEA, 2013a, p. 1). On this basis, the IAEA concluded that SMRs may indeed be "attractive" to "developing countries with certain conditions" provided there are economies of construction achieved through various means such as "design standardization, mass production, simplification, [and] construction in series" (IAEA, 2013a, p. 57).

There have also been several assessments by academic researchers. A group of researchers used eight strategic scenarios that characterized the conduciveness of a country to the introduction of SMRs and identified eleven countries, including several developing countries, that were "more suitable for the short-term deployment of SMR" (Locatelli et al., 2013). In 2015, one study used the Analytic Hierarchy Process (AHP), "a Multi-criteria Analysis (MCA) method used for decision-making involving several criteria" including "financial and economic criteria", "Electric grid, technology, and infrastructure criteria", and "Government policy, regulatory framework, and emission reduction criteria" to "rank" ninety seven "countries in terms of their likely suitability for domestic SMR deployment" (Black et al., 2015). Jordan was placed in the two quartiles in the study utilizing Analytic Hierarchy Process to evaluate multiple criteria, with a ranking that exceeded countries like China, Turkey, and Latvia (Black et al., 2015, p. 91–92).

In June 2014, JAEC co-organized a workshop on SMRs along with the International Framework for Nuclear Energy Cooperation (IFNEC). The workshop was aimed at better understanding how to deploy SMRs in different markets, including countries with no nuclear power and was attended by a variety of stake holders such as reactor vendors, utility companies, regulators, and energy planning authorities (IFNEC, 2014).

Several senior Jordanian officials including the Minister of Energy and Natural Resources, as well as the Chairman and deputy Chairman of JAEC, attended the IFNEC workshop and spoke about Jordan's interest in SMRs, reiterating their suitability with Jordan's grid capacity, lower investment cost, and enhanced safety. They also raised other, more speculative, possibilities, such as constructing reactors closer to where people live by reducing the emergency planning zone and using SMRs in what is called a load following mode, i.e., wherein the output of the nuclear plant is varied according to the demand for electricity.

5. The large reactor option

At the same time as Jordan expressed interest in SMRs, JAEC was negotiating with Russia to purchase a large light water reactor (LWR). This followed several years of discussions with various vendors offering large LWRs. When the time came, though, instead of issuing an open tender, Jordan invited reactor vendors to offer proposals and carried out what was described as a "competitive dialog" by some vendors (MacLachlan and Freebairn, 2010). The "competitive dialog" resulted in multiple applicants, all hoping to supply the country's first power reactor. All of the reactors had large power outputs, relative to Jordan's installed electricity capacity.

5.1. Vendor competition

A leading contender was France, with Jordanian Prime Minister Nader Dahabi telling a French parliamentary delegation in August 2008 that "Jordan intends to sign a nuclear cooperation agreement with a French company to purchase a nuclear reactor to supply Jordan with electricity, enriched uranium for peaceful purposes, and train Jordanian and Arab cadres in this domain" (MacLachlan, 2008). The following year Areva announced that Jordan could be the first customer for Atmea reactor design it had developed along with Mitsubishi (MacLachlan, 2009b). In December 2010, Japanese officials visited Jordan and lobbied in favor of Mitsubishi with the Prime Minister, the Energy and Mineral Resources Minister, the Minister of Planning and International Cooperation, the Minister of State for Mega-Projects, and JAEC Chairman Toukan (JT, 2010).

Another country that sought to sell a reactor to Jordan was South Korea, which reportedly made a "preliminary proposal" to supply either the APR-1400 PWR or its predecessor, the OPR-1000. This proposal was pursued by high-level Korean officials, including by Korean Prime Minister Han Seung-soo during a 2009 visit to Jordan (Hibbs, 2009a).

By 2009, JAEC and WorleyParsons had reportedly narrowed down the choices to the Atmea design from Areva & Mitsubishi; the Enhanced Candu-6 (EC6) from Atomic Energy of Canada Limited; the APR-1400 from Korea Electric Power Corporation, and the AES-2006 and AES-92 variants of the VVER design from Rosatom (MacLachlan, 2009a). Other countries and designs were out of the running for one reason or the other: the China Guangdong Nuclear Power Group, for example, could not sell Jordan its CPR-1000 model, because it was based on French technology and Areva retained some intellectual property rights; Westinghouse did not bid because, as described in greater detail below, the United States and Jordan had not worked out export arrangements (MacLachlan, 2009a).

The next round of selection in 2010 removed South Korea's

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[3] The seven criteria used by the U.S DOC are: (a) low population density, (b) anticipated population growth, (c) anticipated carbon emissions growth, (d) anticipated economic growth, (e) anticipated energy consumption growth, (f) importation of electricity, and (g) existing nuclear capacity" (ITA, 2011, p. 9).

APR-1400,[4] leaving only the Atmea, EC6 and the VVER designs; one source close to the selection process was quoted as saying that the APR1400 was "impossible to fit the existing grid" while another source close to JAEC was quoted as saying that the EC6 was especially attractive because of its smaller size (MacLachlan and Freebairn, 2010).[5]

But this factor was evidently not good enough to secure a purchase by Jordan. Two years later, JAEC 's review of the bids "concluded that the Atmea and AES [i.e., VVER] are the best contenders to meet the requirements and needs of Jordan"; observers of the market suggested that the decision was driven by the fact that both Russia and France "have in the past expressed great willingness to finance reactor exports", in comparison with Canada (Chaffee and Harki, 2012, p. 7). In other words, financing trumped considerations of grid appropriateness in making a decision about what nuclear reactor to construct.

5.2. *Financing*

When in 2015 Jordan finally chose Rosatom, it was not surprising that the announcement mentioned that Russia was to finance 49.9% of the nuclear power plant (Bora, 2015).[6] At that time, JAEC Chairman Toukan stated, "We are in talks with several regional and international investors who are interested to invest in the project and be partners in Jordan's stake in the project…We will witness signing of some deals with those investors before end of this year" (Tayseer, 2015). Whether this prediction comes true remains to be seen.

There is uncertainty about what kind of contractual model will be used to construct the reactor. Some reports suggest that a Build-Own-Operate (BOO) model, where Rosatom will not only construct the reactor, but also operate it and sell the electricity to Jordan, is being considered (WNN, 2013; WNA, 2015).[7] It is also reported that Rosatom promised cooperation "on attracting further financing" and assistance in what was termed "a public awareness campaign" to garner domestic support for the project (NIW, 2015).

The deal with Rosatom had another advantage: it offered to take back spent fuel to Russia (Rosatom, 2015). Given the significant levels of political opposition and public controversy over Jordan's nuclear program, JAEC officials would like to minimize the potential for public outcry; in the many countries that have attempted to do so, finding communities willing to host geological repository has been extremely difficult (Feiveson et al., 2011). JAEC Chairman Toukan, in fact, told Jordan's Petra news agency that the Russian practice of taking back spent nuclear fuel was "what made the Russian offer attractive" (Ben Solomon, 2015).

In summary, Jordanian nuclear officials started by talking about multiple criteria, including a good match between the reactor power output and electricity grid capacity, but in the end seems to have prioritized financing arrangements and spent fuel management over other considerations.

6. Challenges associated with a large reactor

Although Russia is in the process of developing SMRs, its main offerings on the reactor market today are of the VVER design. The multiple arguments for and against this purchase are listed in Table 1.

The main challenge associated with this proposed import of a Russian reactor in the case of Jordan is that there is a severe mismatch between the power output of the VVER, roughly 1000 MW or more, and the size of Jordan's electricity grid (Thomas, 2013, p. 51–52). A plant with a large power output relative to the size of the combined power generation capacity in a country could destabilize the electric grid for two main reasons.

First, and most obvious, if the plant is shut down for either regular maintenance or unexpected contingencies, a large fraction of the power supply to the grid would be unavailable and it would not be possible to meet the demand unless there is correspondingly large backup capacity. Second, there would also be technical problems for the grid: when a large unit is suddenly shut down (scrammed, in the parlance of reactor operators), say, for safety reasons, then there would be "large and rapid changes in frequency, voltage and power flow" (IAEA, 2012, p. 9); the same could also occur if the transmission system that connects the nuclear reactor to the grid develops a problem and the flow of electricity to the grid ceases.

These are the two main reasons why electrical planners typically recommend that the capacity of no single power plant should be larger than 10% of the grid's total capacity. Jordan's installed electricity capacity as of 2014 is only about 3400 MW. The construction of two 1000 MW reactor units could destabilize the grid. If Jordan were to go ahead with the construction of the two 1000 MW VVERs and would like to maintain stability of the grid, it would have to build up other power plants that would operate as back up to the nuclear reactors should they be shut down for dealing with routine maintenance or adding new fuel and removing spent fuel.

Further, these back up plants would have to have the ability to ramp up their power outputs quickly in case one or both reactors have to be shutdown suddenly. Plants that have this ability to quickly ramp up their outputs are sometimes used for meeting peak loads and the electricity that they produce is typically quite expensive. Such peaking plants could be run on diesel or natural gas.

6.1. *Demand projections*

Jordanian officials have an answer for the problem of inadequate grid capacity: they claim that they will need much greater quantities of electricity in the future. Thus, for example, in June 2014, Jordanian Energy Minister Mohammad Hamed said electricity demand will triple by the year 2030 in the Kingdom (Ghazal, 2014a). JAEC has also made similar claims.

In September 2011, JAEC released a "White Paper on Nuclear Energy in Jordan" that was prepared by WorleyParsons that estimated that electricity demand would grow from 3000 MW in 2012 to 15,000 MW by 2040 (WorleyParsons, 2011, p. 13). Regardless of the confidence one may have in such long-term projections, one immediate implication is that it is only around 2030 that the capacity of the grid might exceed 10,000 MW. A second implication is that regardless of when the nuclear plant starts operating, if the demand is continually growing till 2030 or 2040 without being met by other power plants that have smaller outputs and shorter construction times, then there will be a period of several years during which the gap between the demand and the available

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[4] Jordanian decision makers had argued that the APR-1400 would be too large for the country's grid whereas the OPR-1000 was not designed to be constructed in areas that are seismically active (Hibbs, 2009b).

[5] One reason for not considering the EC6 might have been its cost. There are no recent orders for the EC6 and so it is not possible to come up with reliable cost projections. However, a cost estimate for a similar design was reported in the press; according to this report, the bid for construction of two 1200 MW Candu reactors in the Canadian province of Ontario in 2009 was Cdn$ 26 billion (Hamilton, 2009). Canada was reportedly unable to offer financing, and that is likely to have been the reason the EC6 was not pursued.

[6] This is not the only project where Rosatom has undertaken financing, in part or full, the construction of reactors, and some have questioned the organization's ability to finance all the proposed projects (Carbonnel, 2012).

[7] Other reports suggest that Rosatom would own only its share (49.9%) of the project (JT, 2014). It is also not clear if the BOO agreement would hold only for a fixed period of time.

Table 1
Arguments about importing large nuclear power plants from Russia.

Claims in support of importing large nuclear power plants	Rebuttals or challenges
Jordan's electricity demand will triple by 2030	• Even if demand projections are realistic, it is only by 2030 or later that grid capacity might exceed the 10 GW, the threshold grid capacity required for grid stability if a 1 GW nuclear reactor unit is to be added. • Jordan needs to fill the gap between supply and demand prior to 2030; it is and will be constructing other sources of power
Electricity excess would be traded via regional interconnections	• Current grid interconnections between Jordan and its neighbors have limited capacity. • There exist technical and political barriers to expand these interconnections and the financial feasibility is poor.
Rosatom offers attractive financing arrangements	• As things stand, Rosatom would hold 49% equity share in the project. Although this would make financing easier, Jordan still needs to raise substantial funds to cover its part, which could be challenging given the kingdom's strained economy. • Prioritizing ease of financing leaves the country exposed to several risks and Jordanian citizens will have to purchase expensive electricity from any nuclear reactors that are constructed. • Rosatom's financing is dependent on the Russian government's budget, which in turn is dependent on the country's economy.

generation capacity will widen, till the reactor starts feeding electricity into the grid. This could be followed by a period of excess capacity.

This idea of an unmet demand is also at odds with the expansion plans envisioned by Jordan's electricity planners. There are, for example, aggressive targets for renewable energy with 1800 MW to come online by 2018 (Ghazal, 2014b). Jordan's Ministry of Energy and Mineral Resources views the country as having "great potential" and ample "sources" of solar and wind energy (JMEMR, 2014, p. 18). The potential for wind power in Jordan has been studied for over a decade (Ammari and Al-Maaitah, 2003). Several solar and wind power projects have been proposed and are moving forward.

Jordan has also been investing in natural gas based power plants that would help meet peak loads and with "future deployment of large quantities of intermittent renewable energy" (EBRD, 2014). For example, it has installed two internal combustion engine plants near Amman that are said to offer "fast-reacting back-up capacity…needed to balance renewable power" (Press release, 2015). These investments suggest that Jordan's renewable energy plans will likely meet a substantiate share of growing electricity demand.

6.2. *Regional grid interconnections*

An alternative solution that Jordanian officials sometimes offer to the problem of excess capacity is that because there are grid connections with neighboring countries, excess electricity from the nuclear plant can be exported to these neighboring countries. In March 2011, for example, JAEC Vice Chairman Kamal Araj offered both these reasons to *Nucleonics Week*, a standard trade journal: "By 2020, the target date for commissioning the nuclear power plant, electricity demand is projected reach 5000 MW. If Jordan has an isolated grid, any single unit should not exceed 15% of the load, about 750 MW, but Jordan's grid is not isolated… Jordan is currently part of an interconnection project that includes Libya, Egypt, Jordan, Palestine, Syria, Lebanon, Turkey, and Iraq. Negotiations are taking place to increase the interconnection capacity within these countries. Also the government of Jordan is currently exploring the possibilities to directly connect the Jordanian grid with the northern part of Saudi Arabia's grid" (Isted, 2011).[8]

The interconnection project that was mentioned was launched nearly twenty five years ago (MEE, 2007). What is not mentioned here is that these grid interconnections are of very limited capacity in comparison with the power output the reactors that are being planned, roughly 2000 MW. Put together, these interconnections can export only 570 MW out of Jordan (into Egypt, Syria and Palestine), and import 650 MW into Jordan (from Syria and Egypt); further, the Association of Mediterranean Energy Regulators recently concluded that there are significant technical barriers to expanding such interconnections and the financial feasibility is poor (MEDREG, 2015, p. 21). In addition to technical problems, media commentators have also attributed failure to factors such as political chaos and government bureaucracy (Mills, 2015).

Many assessments have pointed to various potential benefits from the development of more integrated electricity planning, including greater transmission capacity (AlKhal et al., 2006). Nevertheless, the elucidation of these benefits has not led to actual integration in either electricity planning or rapid construction of inter-country transmission capacity. Thus, there is reason to be skeptical of the JAEC's claims that electrical connections with neighboring countries would solve the problem of mismatch between the output of VVER reactors and Jordan's small electrical grid.

6.3. *Other challenges*

There are also some non-technical challenges associated with establishing a partnership with Russia's Rosatom to build Jordan's first nuclear power plant. The terms of the agreement with Russia appear to limit Jordan's choices to Russian technology, not only for reactor construction but also for other requirements for the project, such as uranium fuel. There is interest in Jordan to mine its own uranium ore, refine it and fabricate it into fuel[9]; but, at least according to Rosatom, the agreement calls upon Rosatom to provide the nuclear fuel supplies for the reactors and take-back the resulting spent fuel to Russia (Rosatom, 2015). Separately, a government-to-government arrangement for a nuclear project with costs running into several billions of dollars, such as being envisioned between Jordan and Russia, would also have significant implications for bilateral relations between the two countries, as well as Jordan's trade and foreign policy. However, some of these challenges would have applied even to an agreement to purchase SMRs depending on the terms and value of the contract.

A separate source of concern is the ownership of Rosatom,

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[8] Note that the 15% figure used by Kamal Araj exceeds the more commonly used rule of thumb of 10% and represents an effort to make a large reactor seem more compatible with Jordan's grid.

[9] The interest does not mean that uranium mining and processing will actually be taken up; there is evidence that Jordan's uranium resources are of poor quality and mining it will not be economically viable (Bossone et al., 2013; Seeley, 2014).

which is owned by the Russian government. As a result, Rosatom's investment commitments would be greatly affected by the state of the Russian economy. In January 2016, for example, the Russian government reportedly is considering suspending loans to foreign countries (TMT, 2016). This puts the *Al*-Amra project at risk.

7. Challenges associated with SMRs

While there is a better match between Jordan's electricity grid and demand characteristics and the smaller power output of SMRs, there are several other challenges that would have to be faced. These are summarized in Table 2.

7.1. Cost of electricity from SMRs

At the INPRO Forum, Araj also highlighted another important challenge for SMRs: “Electricity cost generated by SMRs should be competitive compared to large NPPs” (IAEA, 2013b, p. 11). This is a widely expressed consideration among potential customer countries for SMRs (IAEA, 2009; Ramana, 2016). How do SMRs fare on this question?

Although there is still much uncertainty about costs, SMRs, when they are commercially available, are expected to be significantly cheaper than the large reactors being constructed currently. Proponents of SMRs suggest construction costs could be “several hundred million” or “hundreds of millions” (Carelli et al., 2010, p. 406; Kessides and Kuznetsov, 2012, p. 1822), in comparison with the 10–20 billion dollar cost typically associated with large reactors. Whether these expectations are going to be borne out remains to be seen.

At the same time, SMRs also produce much less electricity, roughly an order of magnitude smaller, than large reactors. The cost of electricity will be determined by how these two reductions compare to each other. The economic principle that guides much planning for industrial or electrical production is the idea that scaling up the size, wherever possible, will lead to reductions in the cost per unit of production. The idea is intuitively obvious: a reactor that produces twice as much electricity will not need twice as much concrete or twice as many operators to manage the power plant. For this reason, SMRs are expected to have higher capital and operating costs per megawatt of capacity, when compared to the large reactors currently under construction or contemplated for construction.

There is, however, another economic principle that might help make SMRs more competitive: this is the idea that manufacturing will benefit from “learning”. As more units of a certain kind are constructed, manufacturers would make improvements to the processes used and thereby lower costs. There are good reasons to expect this mechanism to be more effective if the manufacturing process is largely confined to a factory as opposed to different sites.

Since SMRs are smaller, more reactors would have to be constructed to supply the same amount of electricity. The combination of the larger numbers and modular construction has led advocates of SMRs to predict that the benefits of serial production can compensate for diseconomies of scale (Carelli et al., 2010; Kessides and Kuznetsov, 2012). However, the number of reactors that have to be constructed in order to benefit from these effects range from large to astronomical, depending on assumptions about the rate of learning (Glaser et al., 2015).

Similar principles were to have operated in the case of large nuclear reactors and their construction costs were expected to come down due to learning. In the two countries with the most reactors, the United States and France, costs have instead risen over the years (Hultman et al., 2007; Koomey and Hultman, 2007; Grubler, 2010; Rangel and Lévêque, 2013). This history offers a good reason to expect that learning effects may not adequately compensate for diseconomies of scale, and therefore SMRs will cost more per unit of power generating capacity.

There is another basis for this expectation: expert elicitations, wherein people with significant experience in nuclear reactor manufacture were presented a set of questions concerning their expectations for construction costs of SMRs and other advanced reactors (Anadón et al., 2012; Abdulla et al., 2013). These elicitations also come to a similar conclusion: SMRs will likely produce electricity at costs higher than conventional large nuclear reactors.

There is no public evidence that JAEC has examined the likely costs of electricity from SMRs but JAEC Chairman Khaled Toukan cited “low levelized cost of electricity” as one of the reasons Jordan opted for the VVER design when speaking to one of the authors in June 2014. Toukan's assertion about the economics of electricity from VVERs should be taken with a pinch of salt: our analyses of the cost of nuclear power in the region suggest that it is unlikely to be economically competitive with natural gas and solar photovoltaics (Ahmad and Ramana, 2014, 2015; Ahmad, 2015). SMRs are only going to heighten the economic challenge. This problem of SMRs not being economically competitive with large nuclear reactors is, of course, not specific to Jordan.

7.2. Not Guinea pigs

Jordanian policy makers do not want to try out new reactors that have not been constructed elsewhere. Samer Kahook, commissioner for the nuclear fuel cycle at Jordan Atomic Energy Commission, said it would be difficult for any of the MENA states to use a first-of-a-kind reactor “that has not been built in the home market” (Isted, 2013). Speaking at the 6th INPRO Dialogue Forum organized by the IAEA, Kamal Araj, currently Vice-Chairman of the Jordan Atomic Energy Commission, is reported to have said, “The promising future for SMRs are too good to be true but all promises have to be validated since technology user countries seek internationally certified SMR designs” (IAEA, 2013b, p. 11). This concern about SMRs not being validated in

Table 2
Arguments about small modular reactors.

Claims about suitability of SMRs for Jordan	Rebuttals or challenges
• Better compatibility with Jordan's small electricity generation capacity.	• Diseconomies of scale will lead to higher unit and electricity costs.
• Lower capital and investment costs, and therefore, lower financial burden.	• Most of SMR designs are still in the development phase and Jordanian policy makers do not want to venture into “first-of-a-kind” projects.
• Could be deployed incrementally to meet demand, which could help avoid having excess of supply.	• Prominent SMR vendors are US-based technologies. Acquiring these technologies would require Jordan to sign the so-called “123 agreement” with the US. Jordan has so far resisted signing such an agreement. • SMRs suffer shared challenges with large reactors in Jordan such as growing public disapproval, lack of suitable sites, and availability of cooling water.

the countries of their origin is expressed by other potential SMR customers as well (IAEA, 2009; Ansari, 2011).

This is a problem because there are no operating small modular reactors in any of the countries that are marketing SMR designs. In part, the challenge is one of licensing them without undermining accepted safety regulations (Ramana et al., 2013). The second challenge is that of economic competitiveness, due to the factors outlined earlier. The importance of having operating SMRs was highlighted by JAEC Chairman Khaled Toukan who told one of the authors in June 2014, "had one of the SMRs been built and operated already, we would have gone for an SMR as a start but Jordan cannot afford to venture into something that has not been proven".

7.3. *United States and the 123 Agreement*

Jordan could not purchase small modular reactors from the United States for a different reason. Because of its Atomic Energy Act, the United States has to enter into an intergovernmental accord called the 123 Agreement with any country seeking U.S. reactors. This provides the legal framework, alongside other agreements such as the nuclear non-proliferation treaty, required by U. S. law to establish nuclear cooperation programs. Jordan had to sign such an agreement with the United States. In 2008, a senior U. S. official announced that Jordan and the United States had negotiated the text of a nuclear cooperation agreement and were working on final signatures before submitting it to Congress (Horner, 2008). But this was not to be.

Negotiations with Jordan over the 123 agreement have to be seen in the backdrop of a similar agreement signed by the United Arab Emirates (UAE), which forfeited the right to carry out uranium enrichment or reprocessing of spent fuel (ENR) domestically.[10] Despite problems with the UAE's program, that agreement came to be regarded as a "gold standard" (Fisher, 2015). However, the UAE 123 agreement had a condition: the acquisition of ENR capabilities would be up for renegotiation should anyone else in the region conclude a more favorable deal. For all these reasons, U.S. officials wanted Jordan to agree to foreswear enrichment and reprocessing (Freebairn and MacLachlan, 2010; Schenker, 2015).

Jordan refused. For JAEC officials, keeping open the option of enriching uranium was too important to sign away. As JAEC Chairman Khaled Toukan told the *Financial Times*, "We will not agree to sign any agreement that infringes on our sovereign rights or our international rights under any treaties" (Peel, 2013). The reason had to do with a model of financing its nuclear program that the JAEC had advanced: exploiting the uranium resources found in the country and use profits from that enterprise to offset some of the cost of constructing nuclear reactors (Seeley, 2014). If Jordan were to agree not to enrich uranium, then it would affect the JAEC's vision of the future as a nuclear fuel supplier.

The impasse over enrichment has persisted and the failure to negotiate a 123 agreement has resulted in U.S. reactors, including SMRs, being precluded from the Jordan market.

8. Common but different challenges: siting and cooling

Two other challenges confronting SMRs are important: public attitudes near potential construction sites and obtaining water to cool reactors. Both of these challenges are generic to nuclear power but are a particular problem for SMRs. To generate the same amount of electricity, many more SMRs have to be constructed as compared to large reactors, thereby implying the potential need for multiple sites where reactors would be constructed (or many reactors at a single site, which is a challenge for other reasons, including licensing (Ramana et al., 2013)). Likewise SMRs have greater water requirements to generate the same amount of electricity. Further, the two problems drive decisions in opposite directions: siting multiple SMRs at a single site would reduce the number of local areas where public opposition would have to be managed, but increase the stress on nearby water sources.

8.1. *Public attitudes*

There is significant public opposition to nuclear power in Jordan (Kane, 2013; Seeley, 2014; Schenker, 2015). One recent survey found that out of a list of 25 hazards, Jordan's public rated nuclear power second among personal risks and fourth among societal risks; only refugee influx, war, and terrorism rated higher (Al-Rawad and Al Khattab, 2015). An earlier poll conducted for the International Atomic Energy Agency found that more Jordanians opposed nuclear plant construction (41%) than supported such construction (35%) and only 33% of people supported an expansion of nuclear power as an answer to climate change (GlobeScan, 2005, p. 19, 21).

Following the Fukushima disaster, this opposition has resulted in parliamentary resolutions against nuclear power; in May 2012, the Jordanian parliament recommended shelving the nuclear program, which, in its words, "will drive the country into a dark tunnel and will bring about an adverse and irreversible environmental impact" (JT, 2012). The underlying reasons for this vote were laid out at the IAEA in June 2012 by a JAEC official who admitted that nuclear policy had been challenged after Fukushima and there was increased visibility of opponents in the media resulting in an impact at all levels of government including the Parliament; among the specific concerns mentioned were safety in general, water scarcity in the country, siting of reactors, and waste management (Haddad, 2012).

In addition to the national level opposition, there is also local opposition building up. The specific site chosen for the VVERs from Russia is called Al Amra. The choice of the site has led to major protests, in particular from members of the Beni Sakher tribe that lives around that area (Su, 2013; Abuqudairi, 2014). One member of the tribe, Hind Fayez, is a prominent parliamentarian and is quoted as saying "I will not allow the construction of the nuclear reactor, not even over my dead body… The Bani Sakher tribe also rejects the construction of the nuclear reactor in Qusayr Amra," (JT, 2013).

Regardless of whether JAEC manages to overcome this opposition and construct the proposed Russian reactors, any policy maker faced with such resistance would naturally prefer to focus reactor construction to as few sites as possible. With their smaller power outputs, SMRs would naturally be a less preferable choice when potential public opposition is considered.

8.2. *Water and cooling*

One of the main sources of concern that is driving citizen opposition in Jordan–the arid nature of the country and shortages of freshwater–is also a major technical problem. Nuclear reactors need large quantities of water to cool their radioactive cores and transfer the heat that is not converted into electricity to the surrounding environment.[11] Because of the laws of thermodynamics,

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[10] The UAE may be revising its position in the wake of the deal with Iran (Agencies, 2015).

[11] Water use is typically classified into withdrawals, which refers to the total amount of water removed from some source, and *consumption*, which refers to the amount of water that is withdrawn and not returned to the source. A part of the withdrawn water is returned to the source, but because it is carrying away the heat

a typical reactor can utilize only about a third of the heat generated by the fission reactions into electrical energy. The remainder is expelled into water bodies near the reactor (lakes, rivers, or the ocean), or, less frequently, into the atmosphere. The latter option lowers the efficiency of electricity production (because some of the energy goes into increasing the heat transfer to the atmosphere, for example, to power fans) and renders the power plant more expensive to construct and operate. Additionally, when the ambient temperature is hot, as is the case in Jordan during the summer season, these systems are less effective.

SMR advocates regularly make claims about reduced water requirements of small reactors (Kelley, 2011; IAEA, 2014, p. 87). However, the technical basis for these claims is dubious. Although a 200 MW SMR will require less water for cooling as compared to a 1000 MW reactor, it also generates only a fifth of the electricity generated by the latter. For each unit of electrical energy generated, SMRs that use water for moderation and cooling require slightly higher water withdrawal levels than a typical LWR as they operate at a slightly lower thermal efficiency.[12]

Consider the NuScale SMR design with an output of 45 MW and the EPR design with an output of 1600 MW. According to company officials, the NuScale reactor design's thermal efficiency is 30% (Landrey, 2009), whereas the French corporation Areva claims an efficiency of 37% for the EPR reactor being built in Finland (Areva, 2005, p. 16). Given the warmer climate of Jordan, the efficiency for an EPR will be about 35%.

The production of 1000 MW of electrical power would require about 22 SMRs as opposed to one large reactor; the latter, operating at 35% thermal efficiency, would reject roughly 1857 MW of heat into the environment; SMRs operating at 30% thermal efficiency would release roughly 2333 MW of heat.[13] Assuming that the difference between inlet and outlet temperatures is to be kept at the same level, then a switch from a large reactor to multiple SMRs would imply a roughly 25% increase in water requirements.

Lack of adequate cooling water could cause a severe accident. This was illustrated in the case of the accidents at Fukushima, where the complete loss of electrical power meant that it was not possible to circulate the water through the reactor to remove the heat being generated there. The Fukushima disaster also demonstrated that in the event of a severe accident, copious amounts of radioactive materials might be dumped into nearby water bodies. For coastal nuclear plants, the ocean serves to cool reactor cores and dilute any potential radioactive effluents. In the case of inland sites like Amra, however, the only sources of water are freshwater bodies such as rivers and lakes; these typically serve many other needs, including water for irrigation and household consumption. Inland nuclear power plants therefore pose far higher risks to nearby water sources and people dependent on these resources than comparable coastal plants and thus there are sound grounds for concern about the Amra plant.[14]

The JAEC is already cognizant of the contestation over water that is brewing. This is why they have proposed to “take the majority of the water [needed for the reactor] from the *Al*-Samra Waste Water Treatment Plant in nearby Irbid” (Oddone, 2015). If and when the reactor is commissioned, over 20% of the total capacity of the Treatment Plant will be used to supply power to the reactors. The output of the Treatment Plant is currently being used for irrigation (WT, 2015); diversion of 20% of the water to the reactor would mean a corresponding loss to the agricultural sector, again setting the stage for public concern. The treatment of wastewater will also add to the already high costs of generating nuclear power (Thomas, 2013, p. 29).

9. Conclusion and policy implications

On paper, Jordan is a textbook case for SMRs. It has a small electricity grid and limited financial resources. It is also facing a growing mismatch between electricity supply and demand. Several nuclear vendor countries, including the United States, view Jordan as a potential market for SMRs. And, yet, when it came time to finalize the acquisition of a specific nuclear reactor design, Jordan appears to have decided on purchasing two large LWRs from Russia. Receiving help with financing the costly project seems to be at the heart of Jordan's decision. Moreover, Rosatom's offer to take the spent fuel back to Russia is attractive to the leadership of JAEC as it would lower political pressure on Jordan on non-proliferation grounds and offset questions ability to deal with nuclear waste, which might ameliorate public opposition.

The decision making process in Jordan offers some larger lessons for how other developing countries may think about SMRs.[15] There are three categories of reasons that seem to be at play in Jordan's choice of a large reactor. The first category consists of reasons that justify the choice on the basis of what is, in essence, wishful thinking. In the case of Jordan, this category includes the idea that the demand will grow rapidly and that the existing grid interconnections with neighboring countries will allow for electricity transfers, which would suffice to deal with the large capacity of conventional reactors.

The second set of reasons for choosing a large LWR as opposed to multiple SMRs have much greater validity and are publicly articulated. These include the fact that SMRs have not yet been constructed in those countries where they are being developed, the availability of financing from vendors that reduce the proximate investment cost, the higher economic costs associated with SMR electricity generation, and problems in negotiating the appropriate legal arrangements that allow for the export of nuclear technology from some suppliers such as the United States.

Finally, there is a third set of reasons that reflect valid concerns with SMRs, but which are seldom publicly articulated by policy makers, perhaps because articulating these concerns would undermine the case for acquiring any kind of nuclear reactors. These include the difficulty in obtaining public consent at multiple sites and the requirement for greater quantities of water per unit capacity to cool SMRs.

These lessons and this study of Jordan's decision making has significant implications for two sets of policies: Jordan's energy policy and government policies in countries that are seeking to manufacture and export SMRs.

First, key decision-makers in Jordan need to reassess their

(*footnote continued*)
not used to produce electricity, the returned water is at a higher temperature. The median value for water withdrawal for a generic nuclear reactor in the United States is 44,350 gallons per megawatthour (MWh) of electricity generated and the median consumption value is 269 gallons per MWh; the corresponding figures for a combined cycle natural gas plant are 11,380 and 100 gallons per MWh (Meldrum et al., 2013).

[12] The comparison here is between light-water SMRs and light-water large reactors. SMRs that use liquid metal or gaseous coolants are more efficient and would require less water; however, it is expected that it will take considerably longer to commercialize these reactors.

[13] Of course, the water consumption level also depends on other, non-operation related, activities and design features such as spent fuel cooling that we ignore here.

[14] These problems with inland plants may also be contributing to China's focus on coastal plants (King and Ramana, 2015).

[15] Some countries for which SMRs make little sense on techno-economic grounds–Saudi Arabia, for example–might acquire an SMR, for reasons that may be considered wholly extraneous to energy policy. In Saudi Arabia's case, there are good reasons to link interest among some policy makers to match Iran's nuclear activities with the recent agreement with South Korea (African Bulletin, 2014; WNN, 2015).

commitment to establishing a nuclear program in Jordan. As discussed above, regardless of size, nuclear power is a problematic option for the kingdom, pursuit of which poses technical and economic risks. Prioritizing ease of financing eases the "front end" of building electricity generation capacity in Jordan, but leaves the country exposed to several risks further along the way (Ahmad, 2015). This paper has detailed the potential impact of constructing a large nuclear reactor on the stability of the electricity grid. The mismatch between the proposed reactors and Jordan's electricity grid size should be obvious to any energy planner, which suggests that the decision to import the large reactors was likely made without adequate input (or despite the opposition) of those involved in managing Jordan's electricity grid. A second policy implication, therefore, is that before Jordan goes ahead with this purchase, there should be a careful and comprehensive study of the technical impact of introducing such large reactors into a relatively small electricity grid. Such a study will likely find that ensuring that the grid operates smoothly even during regular operations of the large reactor, let alone scrams, will require significant upgrades in the grid–equipment such as switchgears will have to be replaced to cope with such a concentrated input of electricity into the grid. Related to this is a third policy implication: purchasing these large nuclear reactors should not proceed absent a careful financial evaluation of the total cost to Jordan's energy system of adding two large reactors.

This analysis of Jordan's decision also has implications for government policies in countries that are developing SMRs. Many of these governments are investing extensively in vendor companies and organizations to help commercialize SMR designs, partly on the basis of claims that there will be a large demand for such reactors in developing countries. Taken together the reasons outlined above suggest that one cannot rely on purely technical and economic characteristics, such as electricity grid size and gross domestic product, when trying to evaluate the market for SMRs. Such characteristics might lead several countries to be deemed potential customers for SMRs. But, because of the various other factors that play into decisions about nuclear reactor acquisition, these countries may well choose a large reactor, or even a non-nuclear alternative. In other words, the number of countries that might actually purchase SMRs might be far more limited than many have previously assumed. Therefore, in deciding R&D priorities, governments should not presume that there will be a large export market for SMRs.

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