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Multinational uranium enrichment in the Middle East

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ABSTRACT

The Joint Comprehensive Plan of Action (JCPOA) agreed to by Iran and the P5+1 in July 2015 placed restrictions on Iran’s nuclear program while other Middle Eastern countries– Egypt, Jordan, Saudi Arabia, Turkey, and the United Arab Emirates–are planning to build their own nuclear power plants to meet increasing electricity demands. Although the JCPOA restricts Iran's uranium enrichment program for 10–15 years, Iran's neighbors may choose to develop their own national enrichment programs giving them a potential nuclear weapons capability. This paper argues that converting Iran's national enrichment program to a more proliferation-resistant multinational arrangement could offer significant economic benefits–reduced capital and operational costs–due to economies of scale and the utilization of more efficient enrichment technologies. In addition, the paper examines policy aspects related to financing, governance, and how multinational enrichment could fit into the political and security context of the Middle East. A multinational enrichment facility managed by regional and international partners would provide more assurance that it remains peaceful and could help build confidence between Iran and its neighbors to cooperate in managing other regional security challenges.

1. Introduction

A lot of effort has gone into helping reach an agreement between Iran and the P5+1 – The United States, Russia, China, France, The United Kingdom and Germany – over Iran's nuclear program. However, so far little effort has gone into exploring the next steps. With Iran gaining the international community's conditional acceptance of its nuclear program and the UAE constructing four planned nuclear reactors, nuclear energy has become a reality in the Middle East. Turkey, Saudi Arabia, Jordan and Egypt also are at different stages of planning their first nuclear power plants.

Regardless of the economic suitability of nuclear power for countries in the region, national nuclear programs, particularly those that would include nuclear fuel cycle activities such as uranium enrichment and/or reprocessing, would offer states the implicit capability to develop nuclear weapons, posing a major security threat. Such a threat seems especially prevalent when we look at existing geopolitical tensions within the region, especially between Iran and Saudi Arabia whose rift has only deepened over the years. Additionally, the spread of non-state actors and terrorist groups in the region makes the management of nuclear security, against sabotage of nuclear facilities, a more urgent and complex task.

Considering Iran's plans to expand its uranium enrichment program to produce fuel for nuclear power reactors, which will also have the effect of shortening the time needed to produce a significant quantity of highly-enriched uranium (HEU) for a nuclear weapon, other regional powers such as Saudi Arabia would certainly value added assurances that Iran's enrichment program remains peaceful. Consequently, the concept of multinational enrichment could be seen by regional players as a major step in ensuring nuclear security, therefore, allowing them to forgo their own national programs.

In a recent study, Alexander Glaser, Zia Mian and Frank von Hippel proposed to use the next 10 years to convert Iran's enrichment program to a multinational one that could include other countries in the region that are planning to establish civil nuclear programs as well as one or more members of the P5+1 group (Glaser et al., 2015). In a subsequent study, Ali Ahmad and Ryan Snyder presented a preliminary assessment of the enriched uranium capacity required to fuel planned nuclear power programs in the Middle East, and found the range of enriched uranium capacity to be between 1.2 and 4.4 million SWUs per year (Ahmad and Snyder, 2016).

With the proper framework, a multinational uranium enrichment facility could add to the transparency of current and future enrichment operations taking place in Iran and in the region. This would further

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reassure the international community of Iran's non-proliferation promises and consequently lead to better relations between Iran and both its neighbors and world powers.

In April 2016, Behrouz Kamalvandi, the spokesman for Iran's Atomic Energy Organization (AEOI), said “There is an enormous ground for cooperation with neighbors, especially in the Persian Gulf region, in the peaceful nuclear energy field” (PressTV, 2016). More recently, Ali Akbar Salehi, AEOI's President, announced Iran's “readiness to share our accumulated experience in the nuclear industry with our Persian Gulf neighbors” and “to establish a regional nuclear scientific contact group, as was the model between Brazil and Argentina” during a World Nuclear Association conference in London (Nuclear Intelligence Weekly, 2016). More specifically on enrichment, Kamalvandi, mentioned the role that could be played by Iran's enrichment facilities “Our centrifuges can help with the regional development at very reasonable prices. What is called for is to work out a cooperation mechanism among ourselves.”

As part of assessing the concept of establishing a multinational uranium enrichment in the Middle East, this paper examines the economics of such a proposal. Such an economic analysis could provide further incentive for concerned countries to move forward with a joint initiative as opposed to establishing their own national enrichment programs. Our results showed that having a multinational uranium enrichment facility could indeed offer significant cost savings due to benefiting from economies of scale and higher utilization of efficient enrichment technologies. Politically, such an arrangement also could improve transparency and promote cooperation between Iran and its neighbors. It is worth noting that Israel is not included in this analysis because it does not have a civilian nuclear program.

Beyond economics, the paper highlights some relevant policy questions such as how a multinational uranium enrichment facility in the Middle East could be governed and financed* Additionally, the paper examines the political context for such an initiative in the region, and more importantly, how it could help reduce tension and security concerns while promoting technical cooperation and trust.

2. Method

The analysis presented in this paper is based on a combination of discourse and quantitative elements. The discourse analysis used information obtained from the existing academic literature on the deployment of nuclear power in Iran, Egypt, Jordan, Saudi Arabia, Turkey and the United Arab Emirates. Additionally, the discourse analysis used information sources such as official government statements and documents, policy reports released by international organizations such as the International Atomic Energy Agency (IAEA) and articles in the popular media.

The quantitative analysis used a discounted cashflow methodology to estimate the levelized cost of uranium enrichment for each country separately and for the Middle East region as a whole. Estimates of overnight capital costs and labor costs based on proposed enrichment capacities are obtained using a microeconomic-cost-engineering model proposed by Rothwell (2009). Fig. 1 shows the parameters used to estimate the levelized enrichment costs ($ per SWU).

Overnight capital costs are estimated using a function of plant's enrichment capacity proposed by Rothwell:

$$k_i = 0.914 \times (SWU_i)^{0.76}$$

where k_i is the overnight capital cost in 2008 dollars, measured in billions, and SWU_i is the plant's annual enrichment capacity, measured in millions. Annual capital costs are calculated using a capital recovery factor that depends on a certain discount rate and loan payback period.

Similar to Rothwell's approach, the model assumes contingency (cost of known uncertainties) and interest during construction (IDC) rates to be 10% and 7.5%, respectively. It should be noted that the cost of physical depreciation of the plant's centrifuges and other equipments, which essentially covers the cost of replacing old centrifuges with newer ones, are calculated based on the assumption that depreciation cost would be 1% of the overnight capital cost.

This model is based on different centrifuge technologies found at five different facilities in the U.S., France and Brazil. Specifically, the performances of these technologies vary with their maturities and thus have different separative capabilities from the centrifuges currently operating at Natanz, in Iran. For example, annual SWU capacity per centrifuge is estimated to be at 3 SWU/yr in Iran, while at URENCO plants it is between 50 to 100 SWU/yr (Rothwell, 2009). These ranges in separative performance make estimates of the capital costs rather difficult given the underlying confidentiality of certain cost parameters of enrichment technology. Further data regarding Iran's enrichment technology would need to be revealed for a more accurate assessment of capital costs. Nevertheless, the performance of enrichment technology could be further enhanced with the cooperation of shareholders and external suppliers.[1]

As for discount rates, they vary with the credit rating of each country. For Saudi Arabia and UAE, a discount rate of 5% is assumed. Egypt, Jordan and Turkey have weak credit ratings, thus, they are assigned a discount rate of 10%.[2] Lastly, Iran is assigned a discount rate of 7% mainly due to political risk. The loan payback period is assumed at 30 years. Further, it should be noted that when calculating overnight capital cost, an inflation adjustment rate of 10% was used. This is the accumulated inflation rate of the U.S. dollar since 2008.

With regards to energy costs, two main variables contribute to the energy cost of enrichment, electricity consumption in kilo-watt-hour (kW h) and price of purchased electricity. Electricity consumption is assumed at 62 kW h/SWU based on the figures provided by the American Centrifuge Plant (ACP) and Enrichment Technology Company (Rothwell, 2009). The model assigns a baseline value for electricity price a $100/MW h. As shown in the results section below, the energy cost element has in fact the smallest share of the total levelized cost (about 5%). Consequently, even if countries in the Middle East would be able to purchase electricity at lower prices, this would not change much the total levelized costs estimated in this paper.

As for labor cost, it depends on the plant's annual enrichment capacity which determines the staff size and the fully burdened salary per employee. Staff size is also estimated using Rothwell's model:

$$L_i = 1.915 \times (SWU_i)^{0.43}$$

where L_i is the number of staff in 100 s, while the “fully burdened” average annual salary per employee was estimated for each of the studied countries. This was done by calculating the ratio of average annual salaries in each country to the average annual salary found in the United States. This ratio was then multiplied with Rothwell's estimated burdened annual salary in the United States of $ 120,000 to get a rough estimate of fully burdened salaries in the countries studied in this paper.

Throughout this paper, enrichment capacities have been derived from nuclear power capacities. The conversion between the two uses the assumptions listed in Table 1.

3. Proposed nuclear capacity in the Middle East

To estimate the costs of potential national enrichment plants, we first need to assess the region's nuclear power programs. Fig. 2 outlines

[1] It is worth mentioning that there are some uncertainties that are hard to quantify. The comparative economic assessment presented in this paper is based on enrichment plants being located in different countries, built at different times, and possibly with different levels of cost support from governments.

[2] Egypt, Jordan and Turkey have an S & P credit ratings of B-, BB- and BB, respectively, as of March 2017. Countries with credit ratings below investment grade rating of BBB- of S & P would find it more dificult to borrow funds i.e. are likely to pay higher interest rates and consequently suffer a higher cost of finance

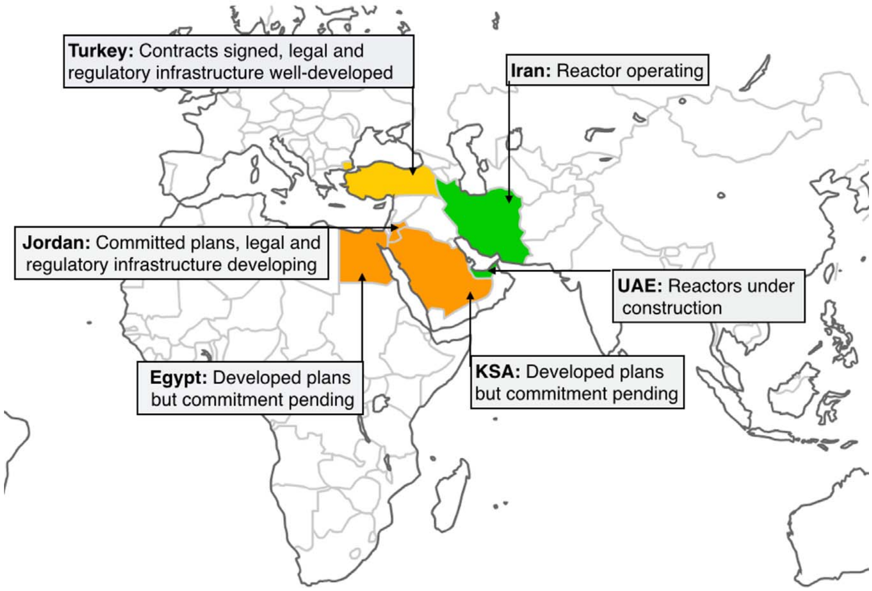

Fig. 1. Parameters used to estimate levelized SWU cost.

Table 1
Assumptions used to derive enrichment needs from nuclear power capacities.

Parameter	Value
Fuel burn-up	45 GW-days
Thermal efficiency	33%
Capacity factor	90%
Product assay	3.5%
Feed assay	0.71%
Tails assay	0.25%

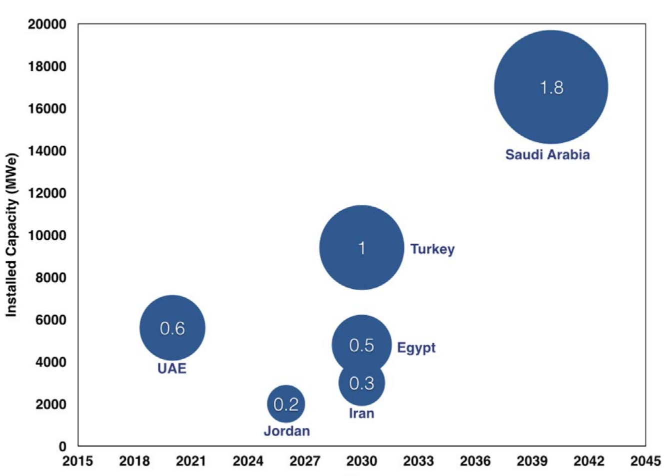

Fig. 2. Status of civilian nuclear programs in the Middle East.

current developments of nuclear power programs in the Middle East. Further information on these programs can be found below:

3.1. Iran

Iran currently possesses the most developed program in the region with one reactor in operation, Bushehr- 1, at a current capacity of 1000 MWe. The Russian reactor began commercial operations in 2013, and is currently supplied with fuel by TVEL, a subsidiary of Rosatom (McAuley, 2015). The country's future plans include the installment of Russian and Chinese reactors. (Islamic Republic News Agency, 2016) Combined, Iran's projected nuclear capacity is estimated to fall between 2000 and 3000 MWe by 2030 (Ahmad and Snyder, 2016).

3.2. United Arab Emirates

The United Arab Emirates started the construction of its first nuclear power plant in 2012. The country's national nuclear body, Emirates Nuclear Energy Cooperation (ENEC), had struck a deal with a South Korean consortium to acquire four reactors by 2020, each with a capacity of 1400 MWe. The first reactor, Barakah-1, is expected to enter commercial operations by 2017. Nuclear fuel supply will be provided by the same consortium yet the country had issued contracts for enrichment services with three different companies. Projected capacity is estimated to be 5600 MWe by 2030.

3.3. Turkey

In 2010, Turkey signed an intergovernmental agreement with Russia to build four nuclear reactors at Akkuyu, each with a capacity of 1200 MWe. (WNA, 2016d) Construction of the reactors have been put on hold as recent political tensions between the countries have raised uncertainties. Rosatom has suspended work after a Turkish fighter jet had shot down a Russian aircraft near the Syrian border last November (Kramer, 2015). According to another source, the deputy director general of the Akkuyu Nuclear Company said that “the work at the site is underway as scheduled. The talks continue on implementing the project.” (Russia Today, 2015). Depending on future political relations, which seem to have improved now, Turkey may continue with Rosatom or decide to acquire a nuclear agreement from other suppliers (Ulgen, 2016). Other agreements involve cooperation with France, Japan and China. Projected nuclear capacity is estimated to be between 3350 MWe and 9400 MWe by 2030. (Ahmad and Snyder, 2016).

3.4. Jordan

In 2015, Jordan signed an intergovernmental agreement with Russia for a potential nuclear power project, however, construction contracts for the two Qasr Amra reactors are yet to be finalized. (WNA, 2016a) According to IAEA reviews, the country still needs to improve its regulatory and development infrastructure (International Atomic

Energy Agency, 2014). Some of these improvements should be directed towards the country's current grid capacity which could require an upgrade in order to accommodate the upcoming two reactors, each with a capacity of 1000 MWe (Ramana and Ahmad, 2016). Moreover, nuclear fuel is also expected to be supplied by Rosatom (WNA, 2016a). By 2030, Jordan's projected nuclear capacity stands at 2000 MWe (Ahmad and Snyder, 2016).

3.5. Egypt

Egypt, despite having an established nuclear research program, is in the early phase of acquiring a nuclear power program. Although the country had dedicated efforts towards nuclear power technology since the 1960s, its political and economic circumstances have hindered its progress (James and Bowen, 2008). However, Rosatom had recently signed an intergovernmental agreement with Egypt for the construction and operation of four reactor units, each with a potential capacity of 1200 MWe (Rosatom, 2015). Future fuel supply and resource training were also a part of the collaboration. The first unit is said to be installed by 2020 at a northern site known as El Dabba (Fahmy et al., 2016). Estimated projected capacity by 2030 is around 4800 MWe (Ahmad and Snyder, 2016).

3.6. Saudi Arabia

As for Saudi Arabia, recently collapsed oil prices might have put the country's nuclear power program on further temporary hold. The oil exporting country, like Iran and UAE, has long been assessing the need to diversify its energy sources and meet increasing energy demand. It has dedicated efforts towards a nuclear power program since the late 1970's but only till 2011 did it announce ambitious plans to construct 16 nuclear reactors in the coming 20 years (WNA, 2016c). The King Abdullah City for Atomic and Renewable Energy (KA-CARE), has since extended their timeline till 2040, at which projected capacity is estimated to reach 17,000 MWe. Although we have used KA-CARE's estimates as our "high" capacity scenario for Saudi Arabia, we feel that these projections are likely to be very optimistic, if not unrealistic, given that the kingdom is yet to build the infrastructure required for a large nuclear program. Moreover, Saudi Arabia is yet to announce the names of the nuclear technology suppliers.[3]

4. Results

As discussed above, countries in the Middle East are proposing nuclear programs of different sizes. Fig. 3 shows the "high" projected SWU capacities estimated by Ahmad and Snyder. These values were used to estimate the total levelized SWU cost based on a discounted cash flow methodology and the cost model developed by Rothwell described in the methodology section. The size of the circle is proportional to the SWU capacity required by the corresponding country per year. According to projections, Saudi Arabia will require the highest enrichment capacity of 1.8 million SWUs per year should it demand to make its own enriched uranium fuel for its proposed nuclear capacity. On the other hand, Jordan will require the smallest capacity of 0.2 million SWUs per year to fuel two 1000-MWe reactors.

Although Egypt, Jordan, Turkey and the UAE are likely to obtain their enriched uranium fuel needs from external sources, they may find it appealing to be part of a joint enrichment facility due to perceived political, economic and security benefits.[4]

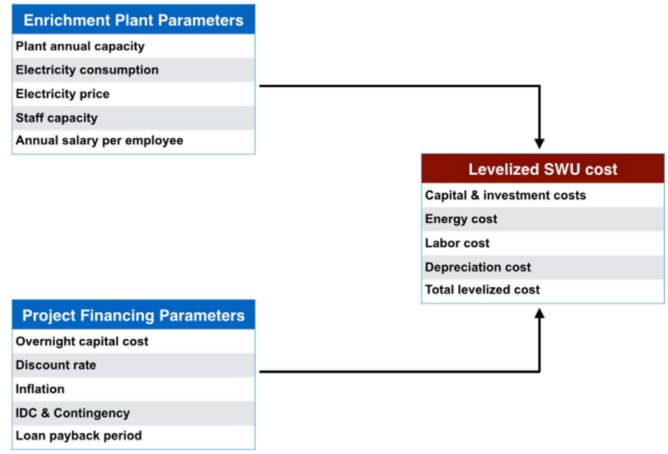

Fig. 3. High projected enrichment capacity of countries in the Middle East. Note: the numbers inside the blue circles reflect the size of the enrichment capacity needed (in million SWU per year), whereas the vertical scale is in MWe.

The various assumptions used to estimate the total levelized cost of uranium enrichment capacities in the Middle East are listed in Table 2. The assumptions are divided into plant and financing parameters. The most important parameter is plant capacity, which is used to derive all other costs. In terms of cost elements, the highest share of the total levelized SWU cost is that of capital costs. As shown in Fig. 4, capital costs of a one million SWU enrichment plant at 5% and 10% discount rates are 66% and 79% of the total annualized cost of enrichment services, respectively. Energy costs, on the other hand, are less than 5%, thanks to the huge energy savings achieved by shifting to centrifuge-based technologies.

The levelized SWU costs associated with each of the Middle Eastern countries are shown in Fig. 5. Since uranium enrichment is capital-intensive, country costs are mainly driven by the enrichment capacity required to fuel existing and proposed nuclear power plants and the discount rate given to each country. Fig. 5 also shows the average, inflation-adjusted, SWU price between 1995 and 2015 (red dotted line).

Clearly, and as predicted by the economies of scale, the higher the enrichment capacity the lower the levelized SWU cost. If proposed nuclear capacities in the Middle East materialize and countries seek developing their own enrichment programs, only Saudi Arabia would achieve costs below 110 $ per SWU, the average spot SWU cost between 1995 and 2015.[5] The cost range of uranium enrichment in the Middle East is between 222 and 86 USD per SWU, in Jordan and Saudi Arabia respectively. It should be noted, however, that the cost estimates shown in Fig. 5 exclude the cost of research and development. Substantial funds would be needed should any of the listed countries decides to establish a uranium enrichment program from scratch, relying solely on domestic resources. Consequently, costs could be higher if R & D costs are included. The problem with estimating R & D costs is the absence of reliable sources, especially that costs of some of the established programs, such as that of Pakistan, are distorted by using black market to purchase certain components. Additionally, costs of future enrichment technologies could be different from that of past projects due to benefiting from learning and efficiency advancements. For these reasons, the true cost of uranium enrichment in Iran may be lower than the estimate proposed in this paper since Iran has already invested in enrichment R & D, and such costs can be considered as sunk

[3] Last year, a deal to build two small reactors was secured between the Saudis and South Korea (Shamseddine et al., 2015). Also, a joint agreement for initiating feasibility studies within Saudi Arabia has been signed with AREVA, a French nuclear corporation (Irish et al., 2015).

[4] The UAE has already signed six contracts with different natural uranium and enrichment services suppliers for the next 15 years. However, the Emirati Nuclear

(footnote continued)
Energy Corporation stated that it "expects to return to the market at various times to take advantage of favorable market conditions and to strengthen its security of supply position" (WNA, 2016b).

[5] SWU spot prices decreased further in 2016 and 2017 to about 50 $ per SWU. Source: www.uxc.com

Table 2
Enrichment plant and financing assumptions.

Plant parameters	Unit	Value
Plant capacity	tSWU/year	Variable
Capacity factor	%	100
Staff size	employee	Variable
Annual salary	$/employee	Variable
Electricity consumption	kW h/SWU	62
Electricity price	$/MW h	100
Financing parameters	**Unit**	**Value**
Inflation adjustment (2008–2016)	%	10
Overnight capital cost	M$	Variable
Discount rate	%	Variable
IDC	%	7.5
Contingency	%	10
Loan amortization	years	30

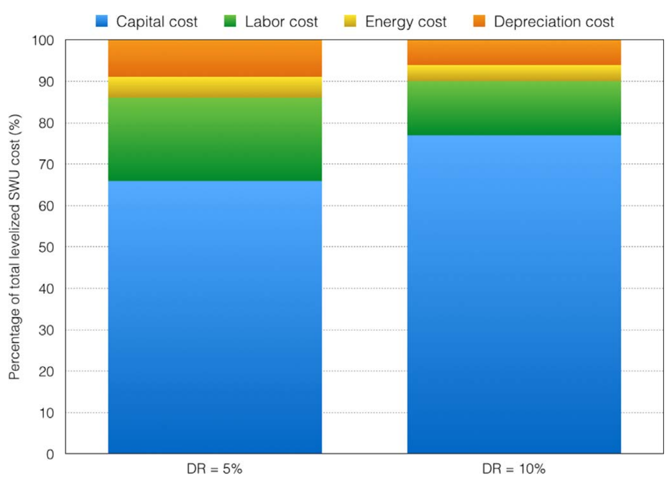

Fig. 4. Elements of the levelized SWU cost at 5% and 10% discount rate.

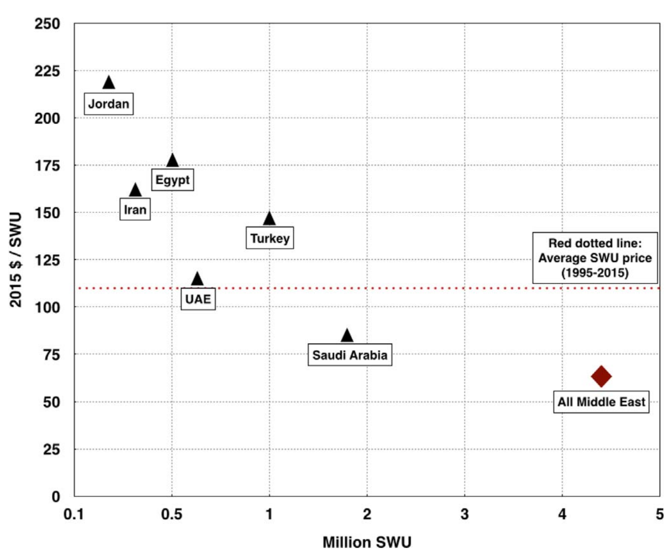

Fig. 5. Levelized SWU cost of countries in the Middle East based on projected nuclear capacity.

costs.

The combined low and high estimates for uranium enrichment of the whole Middle East region by the year 2040 is 1.2 and 4.4 million SWU per year, giving a cost range between 97 and 70 $ per SWU respectively. This shows that, even under conservative nuclear capacity projections, there is still an economic advantage of having a joint enrichment facility compared to having individual programs.

5. Discussion

5.1. Analysis of the global enrichment market

The uranium enrichment market has been volatile during the past two decades. Spot prices have risen since the beginning of the 21st century until they peaked in 2009 at $177 in 2016 dollars. Since then, prices have collapsed at an annual average rate of about 14% to reach below 50 $/SWU.[6] Reasons for the fluctuation in enrichment prices can be mainly attributed to the developments in enrichment technologies and changes in demand and supply of enrichment services (Rothwell, 2009).

According to the IAEA's Nuclear Technology Review, current global enrichment capacity is around 65 million SWU/yr while global enrichment demand is estimated around 49 million SWU/yr (IAEA, 2015). It seems that the commencement of new enrichment plants in the past few years has contributed to this added supply. Since the peak in enrichment prices, both URENCO's project in New Mexico and Areva's George Besse II plant in Tricastin had begun commercial operations and by the end of 2017 they are expected to have a maximum enrichment capacities of 4.6 and 7.5 million SWU/yr respectively. Moreover, the recent downturn in global nuclear capacity caused by the Fukushima disaster had triggered a similar decrease in demand for enrichment services. In this case, producers could have over-estimated demand which would have further contributed to the decrease in enrichment prices as demand did not meet expectations (Kidd, 2014).

Future projections for uranium enrichment demand will rely mainly on the future prospects of nuclear power. The IAEA's latest report on the International Status and Prospects for Nuclear Power presents the low and high projections of nuclear power capacity installed by 2030, which are shown in Table 3 (IAEA, 2014). Evidently, current global enrichment capacity can satisfy the IAEA's high projections for global demand in 2025. This could further indicate that current enrichment prices will remain low and stable for the next decade. However, the question of whether global enrichment capacity will grow in the coming decades would depend on the number of new power plants and closures. According to the IAEA, each projection made since 2010 has been lower than previous projections (IAEA, 2014). Moreover, the renewable energy sector is expanding rapidly and gaining increasing generation capacities. These technologies are receiving strong government and private sector support. Moreover, developments in the oil and gas sector, including the expansion of the shale gas industry, have prompted a further decrease in electricity prices in deregulated markets. All these effects are contributing to lowering the economic competitiveness of nuclear power.

Furthermore, the Fukushima disaster has led to a nuclear power phase-out where countries like Germany has decided to permanently shutdown all their reactors by 2021 (The Guardian, 2013). Moreover, Japan had also resorted to shutting down most of its reactors at the time, yet more recently the Japanese government has decided to bring back nuclear power into its energy mix as a way of meeting the country's increasing energy demand and GHG reduction targets. (EIA, 2015) On the other hand, China is currently planning to increase its nuclear generation capacity and will most probably meet enrichment demand using domestic services[7] (WNN, 2016). Globally, however, the demand for enrichment services created by nuclear new build will not necessarily offset the demand lost due closures (Kidd, 2014).

IAEA data trends show an expansion of nuclear power capacity

[6] As of March 2017

[7] China will likely to continue to add the majority of new global nuclear capacity, and by meeting its internal demand of enriched uranium, the potential range of annual future SWU required from nuclear generation capacity additions in the rest of the world is more limited than it might seem

Table 3
World nuclear power and SWU capacities until 2030 based on IAEA's projections.

Year	Nuclear power capacity	SWU capacity
	low-high (GWe)	**low-high (million SWU)**
2020	390–464	41.5–49.4
2025	379–558	40.3–59.4
2030	401–699	42.7–74.4

among developing countries, however, most of these countries might experience delays or suspensions of their current and future plans mainly due to financial challenges (Ahmad, 2015; Sukin, 2016). Aside from the fact that most developing countries are already discouraged to commit to the high up-front investment costs of nuclear power plants, they still have to consider the inflated cost overruns that could eventually deter their projects from being cost-effective. Eventually, it seems that projected nuclear power capacities may in fact be lower than estimated, which means projected enrichment capacities will also be lower.

As discussed above, the likely scenario is that enrichment prices are likely to remain low for the foreseeable future. Consequently, states in the Middle East that aspire to acquire nuclear power would perhaps be better off purchasing enrichment services from an external supplier rather seeking to establish their own enrichment programs. However, political factors and desire to gain access to a secure supply of enriched uranium makes having a multinational enrichment facility in the region a reasonable compromise between the expensive quest of having a domestic enrichment program and the potentially insecure foreign supply of enriched uranium.

5.2. Governance and financing

Should there be a political will and international support to establish a multinational uranium enrichment plant in the Middle East, two main questions would then need to be answered: how the project would be governed and financed* The financing part is perhaps easier to deal with given the financial abilities of key countries such as Iran, Saudi Arabia, Turkey and the UAE. Additionally, some international investors, governments or commercial entities, might be also interested in buying equity in the project. According to the model used in this paper to estimate the levelized SWU costs, the overnight capital cost of a 4 million SWU/yr enrichment plant to be about 3 billion USD. Assuming no research and development costs, i.e. relying on an external supplier of centrifuge technology, the level of investments required look reasonable, especially with multiple equity holders. Furthermore, since the needs for enriched uranium is expected to gradually increase as more nuclear reactors are built across the region, the plant can be expanded and centrifuges can be installed incrementally. This would offer the advantage of a reduced construction risks.

On the other hand, addressing the governance question seems more challenging since it will have to be based on a high level of political and technical cooperation required between the involved states. A Princeton study, that mainly examined limiting access to fissile material in the Middle East, also discussed possible ways to promote regional cooperation and enhancing verification and transparency measures between states in the region (Hippel et al., 2013). These measures could play an important role to improve regional dialogue and promote trust.

5.3. Multinational enrichment and the political context of the Middle East

Beyond the economic benefits of multinational versus national enrichment, the primary rationale for a multinational arrangement is the added assurance that Iran's nuclear program will remain peaceful. In the Middle East today, existing security structures are collapsing due to weak states and overlapping revolutions, but the prospect of additional states seeking the option of acquiring nuclear weapons in reaction to Iran would make the region's security challenges even more complicated to manage. While the exact structure and management of a multinational facility is beyond the scope of this paper, focus on the political factors that could shape the incentives for multinational enrichment deserve attention. The political acceptance of such a facility in the region should primarily be viewed as a confidence-building measure within the context of other security challenges.

A precedent for multinational enrichment exists with Urenco, a multinational company that combined the national enrichment programs of Germany, the Netherlands, and the United Kingdom in 1970.[8] While Urenco today is the world's second largest provider of enrichment services behind Russia, Urenco was in part originally established due to concerns that Germany may want to acquire nuclear weapons. A multinational facility established in Iran today could allow international access to facilities previously controlled by Iran and a say in how they are managed. Any management could be designed to control access to proliferation-sensitive knowledge and technology by the workers in the plant.

Regardless of whether regional powers feel they need an additional secure source of fuel from a multinational facility for their nuclear energy programs, many – including members of the P5+1 – will want further assurance of Iran's intentions beyond the JCPOA if Iran expands its enrichment capacity to fuel its Bushehr-I reactor. This would require an enrichment capacity of at least 100,000 SWUs and would only require about a week with 3.5% enriched uranium feedstock to produce enough highly-enriched uranium (HEU) for a bomb.[9]

For instance, Israel has no current plans for civilian nuclear energy, but would almost certainly have an interest in further assurance about Iran's program as more centrifuges are added and the flow of enriched uranium increases at Natanz. Alternatively, Saudi Arabia has very ambitious nuclear energy plans, but may never consider any dependence on a facility located within the territory of its main regional adversary for reactor fuel. They would likely need greater confidence in Iran's intentions, however, and the same would presumably be true for P5+1 states. Absent sufficient assurance, Iranian control over a facility capable of producing a significant quantity of bomb material in about a week may produce another crisis.

Such a prospect adds a different economic consideration into how regional powers may respond. As shown in Fig. 5, national enrichment plants only provide economic benefits compared to purchasing enrichment services on the international market when a country uses over 1 million SWU annually (perhaps less for UAE), a capacity for about 8 GWe of nuclear power. Yet such an enrichment capacity may be considered a bargain if states imagine that national enrichment plants provide them with security benefits. In 2014, Saudi Arabia's defense budget was $ 80 billion, Turkey's $17 billion, and Egypt's $5 billion (SIPRI, 2015). A 1 million SWU plant costing $150 million per year in the case of Turkey (Fig. 5) would allow for the production of enough HEU for 200 nuclear weapons per year. Some states could view such plants as allowing for enormous savings in defense spending in reaction to a reduction in concerns about Iran's program. The case of Saudi Arabia is different as the bulk of their defense spending goes to the U.S. defense industry in exchange for security commitments, but they may decide that spending a small portion of that budget on a national enrichment plant would provide them with security benefits

[8] Treaty of Almelo, 1970. “Agreement between the United Kingdom of Great Britain and Northern Ireland, the Federal Republic of Germany, and the Kingdom of the Netherlands on Collaboration in the Development and Exploitation of the Gas Centrifuge Process for Producing Enriched Uranium.”

[9] Ten years after implementation of the JCPOA, there are no restrictions on Iran's enrichment capacity, but the enrichment level must not exceed 3.67% for 15 years (JCPOA, 2015).

they believe they are not receiving. Such a decision would most likely be made if they begin to question their reliance on and commitment from the U.S. for security given Iran's future nuclear program and expanding role in the region.

If Iran intends to expand its enrichment capacity to fuel Bushehr-I, it should seek an arrangement that provides additional assurance of peaceful use. Such an expansion under its own control may trigger other regional powers to begin their own national enrichment programs, and would likely bring another crisis with P5+1 countries, particularly the United States. The nature of the crisis and its prospects for escalation will depend on both the future security context and the actions Iran has taken to fulfill its regional ambitions, but the United States will need to decide what role it will take in managing the region's security as well. The evolution of the U.S.–Iran relationship will therefore greatly affect whether Iran sees its own interest in allowing a multinational overlay to its nuclear program, and the actions of both countries may determine whether other states in the region consider options for obtaining nuclear weapons.

Other regional states could also advocate for a multinational overlay to Iran's program if they agree to forgo any national enrichment ambitions. One feared consequence of the JCPOA was that its recognition of Iran's program would spur Iran's neighbors to pursue their own weapons programs, either by building indigenous enrichment plants or by acquiring weapons from current nuclear powers. Fortunately, according to a recent study by the Brookings Institution, the evidence suggests that such outbreaks of proliferation appear unlikely (Einhorn and Nephew, 2016). However, concerns about the effectiveness of the JCPOA over the next 10–15 years and unsatisfactory peaceful assurances after the expiration of its restrictions could change this prospect. Rather than risk a cascade of proliferation in the Middle East by pursing their own enrichment programs, regional powers should advocate for a multinational arrangement to Iran's program that assures their doubts. An added benefit for Iran is that a multinational uranium enrichment plant, supplying multiple countries in the region, is much less likely to be attacked.

The challenges in designing an effective multinational facility are dependent on whether Iran, regional powers, and the P5+1 mutual accept such a structure. Beyond assuring customers of a secure supply of enriched uranium for their nuclear reactors, a multinational arrangement should improve timely verification of HEU production and further complicate the establishment of a parallel, clandestine facility. A multinational workforce in Natanz would need to provide assurance that hidden arrangements in the cascades that could speed up HEU production are absent, and that the alarm provided following a decision by Iran to produce HEU would allow more time for an effective response than currently possible with IAEA safeguards. Additional assurance against clandestine HEU production would involve multinational control over proliferation-sensitive technology and knowledge within centrifuge R & D and manufacturing facilities. The most proliferation-resistant arrangement in this case would likely be supplying centrifuges to the plant in a "black-box" format as now done at all Urenco plants. It is doubtful that Iran's political leadership would accept replacing Iranian centrifuge technology, but other arrangements that incorporate Iranian technology may be more acceptable.

Of additional concern is whether the plant should be designed to be economically profitable. As this paper makes clear, there are economies of scale, but the goal of making a profitable plant may change the incentives that Urenco may have to become a partner as well as which countries may be willing to join the multinational workforce. This would also affect the size and duration of monetary subsidies until the plant became profitable, and how to incorporate a desire for and the benefits of profitability with assurances of peaceful use may prove challenging. Additionally, Germany (a P5+1 country) and the Netherlands (two Urenco countries) may be the most trusted as partners in a multinational facility due to their commitment to the nonproliferation regime and lack of conflicting political interests in the region. It should be noted that Russia's state nuclear energy company Rosatom has nuclear fuel supply and "take-back" in its current supplier contracts with Middle Eastern countries, and Russia's interests in preserving this aspect of their business model may need to be accommodated. In short, profitability, nonproliferation, and Russia's fuel-supplier interests must be sufficiently balanced to the satisfaction of all states involved.

The arrangements of any multinational facility will therefore be subjected to complex political factors with equally complex technical questions about what provides adequate assurance of continued peaceful use. If it is agreed that some multinational arrangement is a goal that would provide an important confidence-building step towards stabilizing the region's security, managing the political questions in getting there will likely prove more salient than the economic benefits of multinational versus national enrichment.

6. Conclusion and policy implications

The JCPOA agreed to by Iran and world powers in July of 2015 established constraints on Iran's nuclear program in return for lifting economic sanctions. These constraints will remain in place over the coming decade as other countries in the Middle East advance their own civilian nuclear power programs, which are projected to include the construction of new reactors. While the current status of most national programs in the region are expected to include vendor contracts that both supply reactor fuel and take it back for waste storage, the concern that states may decide to acquire their own enrichment programs needs to be carefully addressed. These programs would provide states with the implicit option of building nuclear weapons, making the region's security concerns vastly more challenging to manage.

This paper demonstrated that the idea of converting Iran's uranium enrichment program to a multinational one could offer significant economic benefits such as reduced capital and operational costs, benefiting from economies of scale and higher utilization of efficient enrichment technologies, as well as lower fiscal risks due to having a set of equity holders. Additionally, in the context of political division in the Middle East, a joint enrichment facility could improve transparency and promote cooperation between Iran and its neighbors.

To achieve such a high level of technical cooperation, as required to establish a joint uranium enrichment facility in the region, it is imperative that the involved states possess a high level of commitment toward reducing tension, and have a strong political will to overcome serious differences. The current rift between Iran and Saudi Arabia poses a serious challenge to start a debate on such initiatives. However, this rift also highlights the importance of promoting cooperation between states in the region as a vehicle to promote trust. Such trust could be cultivated if nations start viewing the venture as a means to guarantee Iran's peaceful enrichment plans beyond the JCPOA.

The added assurances could eventually contribute to soften the heightened alertness currently present among regional states and possibly lead them to reduce their defense spending. Nevertheless, certain technical challenges, such as safeguard arrangements, will need to be thoroughly studied to address the issue of proliferation-sensitive technology and knowledge. Moreover, challenges involving the potential competitiveness of the multinational facility within the enrichment market should be assessed such that the interests of potential shareholders like Russia and URENCO are accommodated.

The 10–15 years freeze of Iran's nuclear program, as agreed in the JCPOA, offers a good time margin to attempt to improve relations between states in the region. However, reaching mutual political understanding could prove more challenging than providing economic incentives for multinational enrichment in the Middle East.

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References

Ali, Ahmad, Snyder, Ryan, 2016. Iran and multinational enrichment in the middle east. Bull. At. Sci. 72, 52–57.

Ali, Ahmad., 2015. Economic risks of jordans nuclear program. Energy Sustain. Dev. 29, 32–37.

EIA, 2015. Japan Plans to Restart Some Nuclear Plants in 2015 after Fukushima Shutdown. URL ⟨https://www.eia.gov/todayinenergy/detail.cfm*Id=19951⟩ (Accessed on 26 April 2016).

Einhorn., Robert., Nephew., Richard., 2016. The Iran Nuclear Deal: Prelude to Proliferation in the Middle East* Technical report, The Brookings Institution 2016.

Fahmy., Omar., Alsharif., Asma., Baker., Luke., Lawson., Hugh., 2016. Egypt, Russia Sign Deal to Build a Nuclear Power Plant. URL ⟨http://www.reuters.com/article/us-nuclear-russia-egypt-idUSKCN0T81YY20151119⟩ (Accessed on 21 April 2016).

Glaser, Alexander, Mian, Zia, Mian, Frank von, 2015. After the iran deal: multinational enrichment. Science 348, 1320–1322.

Hippel., Frank N., von., Mousavian., Seyed Hossein., Kiyaei., Emad., Feiveson., Harold A., Mian., Zia., 2013. Fissile material controls in the middle east: Steps toward a middle east zone free of nuclear weapons and all other weapons of mass destruction. Technical report, International Panel on Fissile Materials, 2013.

IAEA, 2014. International status and prospects for nuclear power. Technical Report GOV/INF/2014/13-GC(58)/INF/6, IAEA. URL ⟨https://www.iaea.org/About/Policy/GC/GC58/GC58InfDocuments/English/gc58inf-6_en.pdf⟩.

IAEA, 2015. Nuclear technology review. Technical report, IAEA. URL ⟨https://www.iaea.org/sites/default/files/ntr2015.pdf⟩ (Accessed on 4 April 2016).

International Atomic Energy Agency. 2014. Iaea mission concludes peer review of jordans nuclear regulatory framework. URL ⟨https://www.iaea.org/newscenter/pressreleases/iaea-mission-concludes-peer-review-jordans-nuclear-regulatory-framework⟩ (Accessed on 21 April 2016).

Irish., John., Clercq., Geert De., John., Mark., Regan., James., 2015. France and saudi arabia inch closer to civil nuclear deal. URL ⟨http://uk.reuters.com/article/uk-france-saudi-contracts-idUKKBN0P41IP20150624⟩ (Accessed on 21 April 2016).

Islamic Republic News Agency, 2016. Rosatom: Construction of Bushehr II, III N. power plants to start. URL ⟨http://www.irna.ir/en/News/81970820/⟩ (Accessed on 12 April 2016).

James., Acton., Bowen, Wyn, Q., 2008. Atoms for peace in the middle east: The technical and regulatory requirements. URL ⟨http://www.npolicy.org/article_file/Atoms_for_Peace_in_the_Middle_East-The_Technical_and_Regulatory_Requirements_(FINAL).pdf⟩ (Accessed on 21 April 2016).

JCPOA, 2015. Joint Comprehensive Plan of Action. URL ⟨http://collections.internetmemory.org/haeu/content/20160313172652/http://eeas.europa.eu/statements-eeas/2015/150714_01_en.htm⟩ (Accessed on 14 September 2016).

Kidd., Steve., 2014. Uranium enrichment whats happening today*. URL ⟨http://www.neimagazine.com/opinion/opinionuranium-enrichment-whats-happening-today-4311115/⟩ (Accessed on 27 April 2016).

Kramer., Andrew., 2015. Russia expands sanctions against turkey after downing of jet. URL ⟨http://www.nytimes.com/2015/12/31/world/europe/russia-putin-turkey-sanctions.html*_r=0⟩ (Accessed on 12 April 2016).

McAuley., Anthony., 2015. Russia plans to supply fuel to iranian nuclear plant this month. URL ⟨http://www.thenational.ae/business/energy/russia-plans-to-supply-fuel-to-iranian-nuclear-plant-this-month⟩ (Accessed on 12 April 2016).

Nuclear Intelligence Weekly, 2016. September 16, 2016.

PressTV. 2016. Iran says has nuclear plans for neighbors, 2016. URL ⟨http://www.presstv.ir/Detail/2016/04/11/460194/Iran-nuclear-cooperation-neighbors-Persian-Gulf-states-Kamalvandi/⟩ (Accessed on 12 April 2016).

Ramana, M.V., Ahmad, Ali, 2016. Wishful thinking and real problems Small modular reactors, planning constraints, and nuclear power in jordan. Energy Policy 93.

Rosatom. 2015. Russia and egypt signed and intergovernmental agreement on nuclear power plant construction. URL ⟨http://www.rosatom.ru/en/presscentre/highlights/c5ad7a804aa37da1b1fcbf8d686b7041⟩ (Accessed on 4 April 2016).

Rothwell, G., 2009. Market power in uranium enrichment. Sci. Glob. Secur. 17, 132–154.

Russia Today. 2015. Russian contractor denies halt to turkish nuclear power plant project. URL ⟨https://www.rt.com/business/325249-russia-turkey-nuclear-station/⟩ (Accessed on 21 April 2016).

Shamseddine., Reem., Kim., Brian., Gamal., Rania El., Neely., Jason., 2015. Saudi arabia, South Korea sign mou on nuclear power. URL ⟨http://www.reuters.com/article/saudi-south-korea-nuclear-idUSL5N0W61GM20150304⟩ (Accessed on 26 April 2016).

SIPRI, 2015. Sipri military expenditure database. Technical report, Stockholm International Peace Research Institute. URL ⟨https://www.sipri.org/sites/default/files/SIPRI-Milex-data-1988-2015.xlsx⟩.

Sukin, Lauren, 2016. Beyond iran containing nuclear development in the middle east. Nonproliferation Rev. 22, 379–400.

The Guardian, 2013. Goodbye nuclear power: Germany*S renewable energy revolution. URL ⟨http://www.theguardian.com/sustainable-business/nuclear-power-germany-renewable-energy⟩ (Accessed on 27 April 2016).

Ulgen., Sinan., 2016. Is this the end of moscow-ankara nuclear cooperation* URL ⟨http://www.thebulletin.org/end-moscow-ankara-nuclear-cooperation9059⟩ (Accessed on 21 April 2016).

WNA, 2016a. Nuclear power in jordan. URL ⟨http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/jordan.aspx⟩ (Accessed on 4 April 2016).

WNA, 2016b Nuclear power in united arab emirates. URL ⟨http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/united-arab-emirates.aspx⟩ (Accessed on 4 April 2016).

WNA, 2016c. Nuclear power in saudi arabia. URL ⟨http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/saudi-arabia.aspx⟩ (Accessed on 4 April 2016).

WNA, 2016d. Nuclear power in turkey. URL ⟨http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/turkey.aspx⟩ (Accessed on 4 April 2016).

WNN, 2016. Nuclear growth revealed in china*S new five-year plan. URL ⟨http://www.world-nuclear-news.org/NP-Nuclear-plans-revealed-in-Chinas-new-Five-Year-Plan-2303166.html⟩ (Accessed on 27 April 2016).