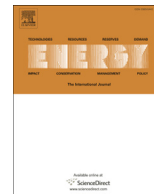




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Too costly to matter: Economics of nuclear power for Saudi Arabia

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ABSTRACT

Saudi Arabia has ambitious plans for nuclear power. Given this context, this paper examines the economics of nuclear power and compares it to two other sources of electricity, natural gas and solar energy. It calculates the costs of electricity generation, water desalination and the opportunity cost associated with forgone oil and gas revenues. A sensitivity analysis is included to account for variations in important parameters within the comparative cost analysis. Our results suggest that for a large range of parameters, the economics of nuclear power are not favorable in comparison with natural gas, even if the currently low domestic natural gas prices in Saudi Arabia were to rise substantially. Further, electricity from solar plants has the potential to be cheaper than nuclear power within the next decade if the rapid decline in solar energy costs in the last decade continue, i.e., before the first planned nuclear power plant would be completed. However, unless the price of oil drops substantially below current values, it would be more economically optimal to export the oil than using it for generating electricity.

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1. Introduction

The leaders of Saudi Arabia have announced that the country is embarking on an ambitious energy diversification plan, including a massive addition of nuclear power. The official reasons for this proposed expansion are laid out in a royal decree from April 2010: “The development of atomic energy is essential to meet the Kingdom’s growing requirements for energy to generate electricity, produce desalinated water and reduce reliance on depleting hydrocarbon resources” [1]. Unlike some neighboring countries, such as Bahrain, Kuwait and Oman, which abandoned their nuclear plans in the wake of the multiple accidents at the Fukushima nuclear plant, Saudi Arabia has reiterated its commitment to the acquisition and expansion of nuclear power. In November 2013, a Saudi spokesperson announced plans to call for preliminary bids for the first nuclear reactor, or set of nuclear reactors, the following year, with the first to start construction in 2017 and be completed in 2022 [2].¹

There is some indication that, while desirous of diversifying their energy production, Saudi policy makers are cognizant of the high costs associated with nuclear energy. It is reported that the finance ministry is wary of the nuclear program’s need for “massive capital outlays and decades of subsidies” [4]. Given these potentially high costs, it is important to assess the economics of nuclear power.

This paper attempts such an assessment by calculating the cost of generating electricity and desalinating water using nuclear power and compares it to two alternate ways of meeting energy demands—natural gas and solar energy—in Saudi Arabia. The cost comparison is supported by a sensitivity analysis to account for any potential changes in the parameters in the future. Prior to that, we explain the historical background to this issue.

2. A brief history

Saudi Arabia has had a long-standing, although limited, interest in nuclear technology. As early as 1978, the country entered into a multi-year Technical Cooperation Project entitled “Nuclear Energy Planning” with the IAEA (International Atomic Energy Agency) [5]. Over the decades, many have advocated Saudi Arabia acquiring nuclear power. Their arguments typically stressed the country’s growing demand for electricity and desalinating water. In some cases, specific niche needs, such as mining and industrial clusters, have also been offered as arguments for constructing nuclear reactors [6]. However, these arguments did not succeed and Saudi

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¹ In contrast, *Nuclear Intelligence Weekly*, a trade magazine, reported in January 2013 that Khalid al-Sulaiman, a senior official in the organization responsible for nuclear development, announced that it would “take 7–8 years before the organization is ready to tender a nuclear program” [3]. This should not be taken as a firm timeline, but as an indication that the Saudi nuclear program is subject to internal domestic disputes.

Arabia's interests were "largely limited to applied nuclear research for industrial, agricultural and medical purposes, and radiation monitoring" [7]. The primary institutional vehicle for these activities was the Atomic Energy Research Institute established in 1988 within the King Abdulaziz City for Science and Technology [7]. According to its website, its mission is to "employ and develop nuclear technology as to serve agricultural, industrial, health, research, economic, security & preventive development" [8].

The current wave of interest came about after a December 2006 meeting in Riyadh during which leaders of the GCC (Gulf Cooperation Council) states announced that they intended to start a joint nuclear energy development program.² Speaking to reporters, Prince Saud al-Faisal, Saudi Arabia's foreign minister, declared "Nuclear technology is an important technology to have for generating power, and the gulf states will need it equally" [9]. The following year, GCC states and the IAEA agreed to cooperate on a feasibility study on regional plans for a nuclear energy program [10]. By late 2007, the IAEA prepared a draft study for the GCC; according to the study, nuclear energy was expected to become operational in the region in 2025 [11]. Among these countries, it was the UAE (United Arab Emirates) that, in 2008, set up an implementing organization and, in December 2009, entered into a contract with South Korea for four APR-1400 nuclear reactors estimated to cost \$20 billion [12,13].

The Saudi nuclear program started to gain momentum in 2010 with founding of the KA-CARE (King Abdullah City for Atomic and Renewable Energy) in Riyadh [14]. The order establishing KA-CARE motivates the action by talking about "an ever-increasing pressure on the country's non-renewable hydrocarbon resources" and the need for "alternative, sustainable and reliable sources of energy for generating power and producing desalinated water" [15]. It went on to say: "Following extensive technical and economic analysis the decision has been taken to introduce atomic and renewable energy for a significant portion of Saudi Arabia's future energy mix. The two sectors will provide substantial capacity, advanced technology, efficient use of resources and will be fully compliant with international best practices, conventions and treaties". Thus, even during its founding, the Saudi nuclear program was conjoined to a renewable energy program.

Shortly thereafter KA-CARE turned to Pöyry, a Finland-based engineering consultancy company, to "help prepare a draft of the national vision and high-level strategy in the area of nuclear and renewable energy applications for Saudi Arabia and help define KA-CARE's strategy, operating model, key short and longer term priorities, and the immediate initiatives and action plan" [16]. The following year, KA-CARE appointed the consulting company WorleyParsons to conduct site surveys and regional analysis to identify potential sites for a planned tender for a nuclear plant [17].³ Saudi Arabia has signed bilateral cooperation agreements on nuclear power with France, South Korea, Argentina and China; agreements with other countries are reportedly under negotiation.

By May 2012 KA-CARE had come out with its first set of projections of nuclear and renewable energy generation capacity for two decades ahead. KA-CARE envisioned that by 2032, out of a total 123 GWe of electricity generation capacity in the country, 18 GWe would be contributed by nuclear power [17]. Others reported that a survey of sites to construct the nuclear reactors now was under way and that ground-breaking for the first nuclear reactor site was to take place in 2014 [18]. KA-CARE also projected ambitious

expansions of renewable energy capacity, with 16 GWe of solar PVs (photovoltaics), 25 GWe of CSP (concentrated solar power), and 4 GWe from geothermal, wind and waste. More recently, wind energy projections have risen to 9 GWe by 2032 [19].

It is not clear if these projections for renewables and nuclear power have been approved by the highest levels of government [20]. Specifically, political support for the nuclear plans appear to be more questionable and some analysts suggest that KA-CARE will likely prioritize renewables in the near term [21,22].

Questions aside, these announcements have been welcomed by the nuclear industry, which sees Saudi Arabia as a major potential market for reactors, in part because of the country's considerable financial resources [23]. Companies like Westinghouse and Areva are trying to sell their reactors to the Saudis [24,25]. Likewise, if the solar energy plans were to materialize, Saudi Arabia would likely become the world's largest market for renewable energy [26]. As with nuclear vendors, solar energy companies have also been quick to realize the potential opportunities offered by the plan with companies terming Saudi Arabia as "one of [the] key growth markets" [27]; the consulting company Ernst & Young noted that Saudi Arabia has "quickly made it onto the list of focus markets for investors and technology providers" in the arena of renewable energy [28].

Saudi policy makers do, however, emphasize two requirements for both the solar and nuclear programs: that they have "to be economically viable in the long term... [and have] to make available jobs for the Saudi youth" [2]. For this reason, we examine the relative economic competitiveness of these different sources of energy. Questions about the potential for localization of these technologies are, however, outside the scope of this paper.

3. Motivations

Officially, the primary motivation behind the proposed construction of nuclear reactors is that Saudi Arabia's current sole reliance on oil and gas to generate electricity and to desalinate water is widely perceived to be unsustainable, both economically and politically, in the future. A recent business-as-usual simulation concluded that the Kingdom would become a net oil importer by 2038 [29]. The study also indicated that the global economy will be affected if Saudi Arabia lost its market stabilizing power due to not being able to maintain a sufficient amount of oil export capacity. Several other studies have also discussed the need to diversify energy sources in the GCC in general and Saudi Arabia in particular [30,31].

This situation will likely be affected by the expected increases in production of oil from non-conventional resources, such as shale oil, in various countries, and potential declines in oil prices. These increases could occur in both Saudi Arabia as well as in other countries and will have implications for Saudi nuclear program. As analysts have pointed out, "Renewable and nuclear energy projects and infrastructures are capital intensive and will need a great deal of government subsidies and support to maintain them for many years to come. Should world oil and gas prices experience dramatic declines those countries could find themselves unable to sustain such investments" [32].

In addition to the argument about diversification, Saudi Arabia's interest in nuclear power is also a response to Iran's acquisition of nuclear technology. It has been argued, for example, that "GCC states want to show Iran, their own people, and the broader world that Arabs also have the prowess and power attributed to nuclear technology" [33]. Some go further and assume countries like Saudi Arabia—despite the country being a signatory to the Nuclear NPT (Non-Proliferation Treaty) since 1988 and continued cooperation with the IAEA—are embracing nuclear technology largely due to

² The GCC is a grouping of Arab states bordering the Persian Gulf, namely Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.

³ Such reliance on consulting companies suggests weaknesses in the technical capability of KA-CARE.

security concerns.⁴ Statements by Saudi officials, such as the one by Prince Turki al-Faisal in December 2011 to the effect that the kingdom might consider producing nuclear weapons if it found itself between atomic arsenals in Iran and Israel [34], help boost such concerns. There is ample evidence that “the Saudi leadership is serious about acquiring a nuclear weapon if Iran succeeds in developing one” and the nuclear power program is likely seen as a step towards that goal [35].

3.1. Desalination

Besides electricity generation, nuclear power offers Saudi Arabia the possibility of water desalination to meet growing water requirements. Indeed, Saudi policy makers have been historically more interested in nuclear technology for desalination than for electricity generation, but never actually purchased any reactors because of the availability of hydrocarbon fueled alternatives [36]. Nuclear reactors provide heat with a wide range of temperatures and pressures,⁵ and consequently, offer high flexibility and adaptability to different desalination technologies. Moreover, the heat rejected to the environment during normal reactor operation is suitable for some desalination technologies such as MED (Multiple Effect Distillation) and therefore can be utilized anyway. There is over 150 reactor-years of experience with nuclear desalination, mainly in Kazakhstan, India and Japan [37].

Likewise the potential for renewable energies, especially solar energy, for desalination has been widely explored. Multiple technologies can be used for this purpose; these could be broadly divided into ones that use solar thermal power, wherein the heat produced is used to generate steam to operate an MED system, and ones that use photovoltaics to generate electricity to operate reverse osmosis or electro-distillation system. In the case of solar thermal systems, there is the possibility of using the system for desalination and electricity generation, and if storage is added, dispatchable [38,39].⁶

Desalination can be an important way to deal with varying electricity demands for both nuclear and solar energy. This is because unlike electricity, water can be more easily and economically stored. A nuclear power plant that produces desalinated water based on a co-generation model can be adjusted so that it dedicates a large part of its power for water production during off-peak times and switch back to fully generating electricity during peak times. Likewise, solar energy, particularly, through concentrated solar thermal technologies have been used to generate both electricity and desalinated water in Spain [39].

4. The electricity sector

Before exploring the comparative costs of electricity generation in Saudi Arabia, we outline some basic features of the Saudi electricity sector. There are several electricity-related indicators that can be used to define the average behavior with regards to energy consumption and its relationship to economic activities

and efficiency levels. The following figure (Fig. 1) shows four representative indicators based on 2012 data from the International Energy Agency: Electricity consumption per GDP (energy intensity); electricity consumption per capita; carbon emissions per GDP (carbon intensity); and carbon emissions per capita [40]. The energy intensity indicator is a measure of how energy-inefficient is a country's economy while the carbon intensity indicator reflects the impact of performed economic activities in terms of CO₂ emissions.

In all four indicators, Saudi Arabia has a relatively high score that is generally significantly greater than the global average. When economic performance is evaluated in terms of energy consumption and CO₂ emissions, Saudi Arabia was the least efficient among a cohort of seventeen countries of the Middle East and North Africa [41]. An earlier study calculated that about 63 percent of energy in Saudi Arabia is wasted [42]. There is thus ample scope for instituting energy efficiency and conservation measures. However, given the relatively poor record of implementation of such measures so far, this will not be an easy task [43].

Table 1 below shows the breakup of electricity consumption amongst different end-use sectors. The largest proportion of electricity use is in the residential sector. This is a sector that has been growing rapidly, as also the commercial sector.⁷ The high percentage of electricity consumed by the residential sector highlights the potential for both the utilization of better energy efficiency standards and conservation strategies specific to this sector, as well as increased use of solar photovoltaics because of the overlapping period of demands. Solar photovoltaics can be deployed both on rooftops, which would save some of the costs associated with transmission and distribution, or in utility scale projects. In this paper we only consider the latter.

The trend in Saudi Arabia's strategy for dealing with this growing demand seems to rely mostly on expanding natural gas based generation. As Table 2 shows, nearly 100 percent of installed capacity in recent years is based on natural gas. This is also seen in terms of crude oil consumed for electricity generation in the country, which has been stagnant for the last four years, despite increases in overall electricity demand. There is also significant growth in captive power generation in recent years [45].

While there is general agreement that demand for electricity in Saudi Arabia is expected to grow rapidly over the next decades, there are significant differences in estimates of the expected rate of growth. These differences result mostly from differences in assumptions on expected growth in various underlying factors such as GDP and population,⁸ and improvements in efficiency of energy use, or lack thereof. Ultimately, of course, we do not know what the demand will be in the future, although the choices made by Saudi policy makers today will strongly influence future outcomes.

Fig. 2 shows the actual electricity demand until 2012 (solid blue line) and three representative projections based on different AAGR (average annual growth rate): 7.7 percent [47], 5.1 percent [48], and the projection of 5.3 percent according to the Saudi Electricity Company's 2012 annual report. Note that the Saudi Electricity Company's projections only go up to 2016. Other estimates typically

⁴ For example, the International Institute for Strategic Studies argued that the GCC's joint nuclear program “could serve as a hedging option [against Iran]. Although it would not confer a nuclear-weapons capability or breach their non-proliferation obligations, a civil nuclear program could allow Gulf states to respond to an Iranian nuclear threat in the long term, while in the short term their conventional deterrent is bolstered through large purchases of Western armaments” [7].

⁵ Note that the heat and pressure of the coolant that come out of the reactor is constant but the heat transferred to secondary systems can be adjusted.

⁶ Between 2002 and 2008, the greatest average annual increase was in the commercial sector at 13.4%, followed by the residential sector at 7.9% [44].

⁷ For an example, see Ref. [46].

⁸ In comparison, the International Energy Agency projects global electricity demand growth at 2.6 percent over the next quarter century under a current policies scenario; the demand in just the Middle East region is projected to grow at 3.5 percent [49]. So rates of the order of 5–8 percent are very high.

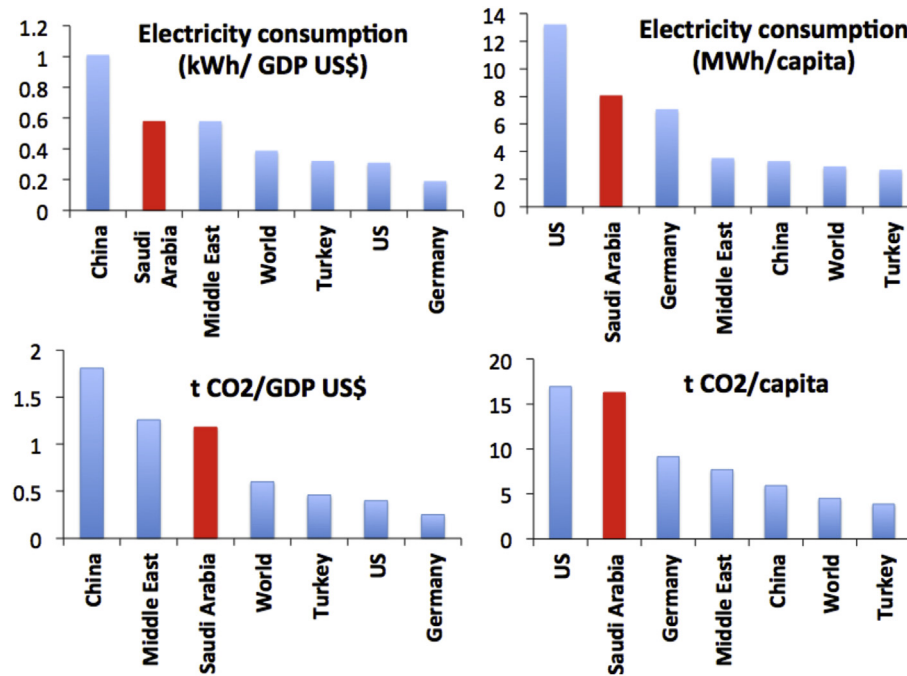


Fig. 1. Comparative electricity and emission Figures.

fall in the range between 5 and 8 percent.⁹ A difference of 3 percent might seem small, but over a period of 20 years the difference between these estimates can be as high as 330 TWh. Over-estimating the demand could result in enormous over-expenditure or misdirection of investment.

One reason for these relatively large increases in energy use is the practice of subsidizing energy use. The role of historically low energy prices in both driving consumption trends and inhibiting energy efficiency measures has been commented on widely [29,50]. In part as a response to these, the Saudi government started a NEEP (National Energy Efficiency Program) in 2003 whose objective is to promote “efficient and rational consumption patterns” [43]. In 2008, the National Energy Efficiency Program put together a plan that aims to cut the electricity intensity by 30 percent between 2005 and 2030 and the growth in peak demand by 50 percent compared with the average 2000–2005 increase [51].

There is a further complication. Electricity demand is not constant throughout the day and increased demand during peak periods has been a major problem in the country. Electricity peak demand times in Saudi Arabia occur yearly on weekdays (i.e., Saturday to Wednesday), typically from 1:00 pm to 5:00 pm during the months from June to September. In addition, electricity demand increases significantly during the holy lunar months of Ramadan and Dhul-Hijjah [52]. This demand pattern overlaps substantially with solar insolation patterns [53]; therefore the use of solar photovoltaics to meet this peak demand does have technical merit.

The value of the electricity generated at those peak times in the Saudi market could be considerable. While electricity rates in Saudi Arabia do not vary over the day and night, one pilot program that introduced time-of-use tariffs found that the optimal ratio of tariffs during times of peak demand to off-peak times was 4:1, which resulted in about 10 percent of the peak demand being shifted to off-peak periods [44]. Thus, even if the cost of generating solar energy is higher, it would be economical for the supplier to use this

source of electricity. The comparison between generation costs that we have carried out does make solar power look less favorable than it would appear if the overlap between solar generation and peak demand is methodologically included [54].

In 2012, the maximum peak load was 51.939 GWe [55]. The annual average load is about 65% of the peak load [56], or about 34 GWe. This high peak to average load difference offers significant potential for solar energy.

5. Water demand and trends

Unlike its plentiful hydrocarbon resources, Saudi Arabia faces a severe shortage of water and relies on desalination to get about 50 percent of its drinking water [50]. Saudi Arabia's risk has been

Table 1

Sector-wise electricity consumption in Saudi Arabia.

Year	Residential	Industrial	Government	Commercial	Other	Total electricity delivered (TWh)
2012	120.2	41.7	30.3	39.3	8.8	240.3
2011	109.3	42.1	27.5	32.5	8.3	219.7
2010	108.6	28.6	24.5	29.3	21.3	212.3
2009	100.8	34.7	22.2	23.6	12.1	193.4
2008	96.7	32.4	20.4	21.4	10.2	181.3

Sources: [44] [Numbers rounded to the nearest tenth]

Table 2

Installed electricity generation capacity by Year.

Year	Generating capacity based on gas added (MW)	Fraction of Gas (%)	Generating capacity based on oil added (MW)	Fraction of oil (%)
2012	2039	100	0	0
2011	989	45.5	1191	54.5
2010	2918	100	0	0
2009	3510	100	0	0
2008	1704.5	100	0	0

Source: Annual Reports of Saudi Electricity Company

⁹ There are numerous other designs that are potentially available for sale but we do not list any designs that have so far not been constructed or under construction.

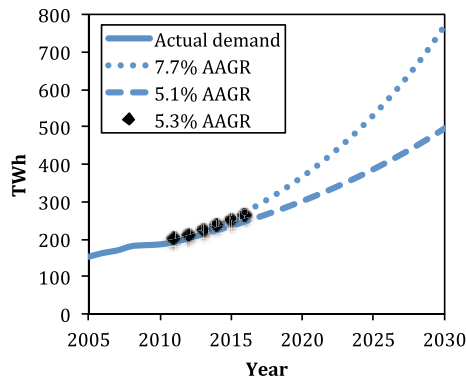


Fig. 2. Impact of assumed growth rate on demand projections.

classified as “extreme” and is ranked among the most water stressed countries [57]. To make matters worse, the demand for water in Saudi Arabia has been increasing with an annual average growth rate of 3.8 percent from the year 2000 until 2012; this is expected to increase even further to 4.3 percent according to projections until 2020 [50] (Fig. 3). A primary cause of this shortage is the fact that water is given away at rates that the Saudi Minister for Water and Electricity called “almost free”, while admitting that there is no incentive for limiting water consumption [58].

Water shortage is strongly linked to the energy challenge, because desalination is an energy intensive process. They are also linked because some desalination plants in Saudi Arabia are based on a co-generation model and produce water and electricity. Thus, dealing with rising electricity demands can go hand in hand with adding more desalination capacity. The SWCC (Saudi Saline Water Conversion Corporation) produces around 3.5 million cubic meters of desalinated water per day, 30 percent of world's total, and contribute 5 GWe of electricity to the national grid [59].

Currently, three different desalination technologies are operating in the Kingdom: 86 percent of desalinated water produced by MSF (Multi-Stage Flash), 12 percent by RO (Reverse Osmosis) plants and 2 percent by MED (Multiple-Effect Distillation) plants [59]. Linking these three technologies with a power plant using a co-generation model reduces energy requirement for desalination by half and that is the model Saudi Arabia is following. There are other proposed desalination technologies that operate at low temperatures and offer the potential to better utilize solar energy [60]. In this paper, we do not explore these because they have not yet been commercialized on a large scale.

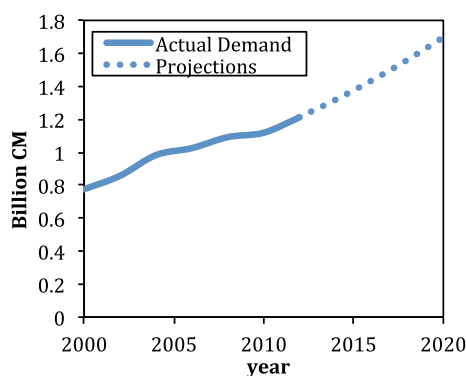


Fig. 3. Actual and projected water demand in Saudi Arabia.

Table 3

Some reactor designs available for import.

Brand	Country	Technology
VVER	Russia	Pressurized water reactor
APR-1400	South Korea	Pressurized water reactor
ABWR	GE-Hitachi	Boiling water reactor
AP-1000	Westinghouse	Pressurized water reactor
EPR	Areva	Pressurized water reactor

6. Nuclear technologies

The demand for energy for both electricity and desalination of water can be met through a variety of technologies. The main focus of this paper is nuclear power. However, any economic analysis of the nuclear option has to compare it with other technologies. The technologies we consider here are the currently two dominant sources in the country—oil and natural gas—and the other technology that is being pursued by KA-CARE—solar energy. Other technologies such as wind turbines have also been proposed [52,61,62], but we do not evaluate those here. Though we do not carry out the analysis here, it has become common to compare the costs of energy efficiency improvements and the resulting cost per unit of electricity saved on the same footing as new generation. Because of the high potential for energy efficiency improvements in Saudi Arabia, there are likely many low cost possibilities.

There are multiple reactor technologies at different stages of readiness available for the export market. Some of the technologies that have already been sold and are being operated or under construction are listed in Table 3 below alongside their corresponding exporting vendor or country.¹⁰ More detailed technical descriptions of reactor technologies and their relevance to the Middle East can be found in the literature [63].

There does not seem to be much clarity on what technologies Saudi policy makers are interested in importing, and reports suggest their being interested in diverse nuclear technologies. Perhaps the most intriguing of these is an expressed interest in small modular reactors [64,65], which are being developed by multiple countries. However, regulatory authorities are yet to license most of these [66], and none have been commercialized so far.¹¹ Among more standard large reactors, KA-CARE is reported to be evaluating both pressurized and boiling water reactors [68,69].

The economic cost of nuclear power has been a key barrier to the construction of new reactors around the world. As the influential interdisciplinary study conducted at the MIT (Massachusetts Institute of Technology) more than a decade ago stated, “Today, nuclear power is not an economically competitive choice” [70]. In large part, this was a result of the high capital cost associated with constructing a nuclear reactor. The problem posed by high construction costs is compounded by uncertainty. Historical analyses of reactor construction and operation cost show significant variations amongst different reactors [71,72].

¹⁰ For their part, companies developing such reactors have also been actively wooing Saudi Arabia and advertising various features of their products; for example, one selling point used by Babcock and Wilcox, the company developing the mPower design, has been the potential for cooling the reactor with either water and air [65]. Technically, cooling with air would result in a slight loss of efficiency; in one early design variant, mPower was capable of generating 136 MWe of electricity if the condenser was cooled with water, but only 125 MWe if cooled with air [67].

¹¹ In the United States, for example, several reactors have been prematurely shut down because they cannot compete with the low natural gas prices [74]. A former member of the Nuclear Regulatory Commission has argued that nuclear power has become so uncompetitive that market forces will all but phase out the U.S. nuclear fleet by midcentury [75].

Another problem has been a history of time and cost overruns. A recent study of the economic feasibility of nuclear power in Spain came to the conclusion that it “could be competitive only for the nuclear projects with the lowest projected costs... and most importantly, if there are no cost overruns” [73].

The last decade has seen a further decline in the relative competitiveness of nuclear power.¹² Whereas the MIT study assumed a capital cost of \$2000/kW as their base case, in the case of the Vogtle project, where two AP1000 reactors are being constructed in the U.S. state of Georgia, a senior official from the utility building the reactor estimated in 2012 that the unit capital costs were \$6100/kW, roughly 2.5 times the cost estimate assumed in the MIT study even after allowing for inflation [76].¹³ This cost for the Vogtle reactors includes the benefits that result from a variety of government subsidies, including tax-exempt bonds, a potential federal loan guarantee, and favorable rules that shift financing costs and risks onto current rate payers [78]. Since then cost estimates for Vogtle have further increased because of delays and difficulty in meeting quality standards [79]. Likewise, the estimated costs of constructing a EPR (European Pressurized Reactor) in Western Europe or North America range from around \$5000 to \$7300 per kW, or about \$6100 on average [80–82].

Cost escalation in the EPR projects in Western Europe illustrate dramatically how initial estimates may have nothing to do with the final figures. The best example is in Finland, where the country's parliament approved the construction of a fifth nuclear unit in 2002 [80]. After a tendering process involving seven designs, in December 2003, the Finnish utility TVO (Teollisuuden Voima Oy) signed a turnkey deal with Areva for a 1600 MW EPR at a cost, including interest during construction and two fuel charges, of €3 bn. The reactor was to commence electricity generation in 2009. The latest estimates for Olkiluoto amount to €8.5 bn (\$7000/kW) and the reactor is expected to be completed in 2016, seven years late [83,84]. The case of Flamanville in France is roughly similar, although that reactor is only four years late.

The 2013 deal in the United Kingdom for the Hinkley Point suggests that these high construction costs may not be attributed to first-of-a-kind reactor projects. For Hinkley Point where two EPRs are to be constructed, the agreed construction cost is £16 bn [85]. This translates to €19.4 bn or about \$8000/kW, which is higher than current estimates for both Flamanville and Olkiluoto. Electricity from this project is to be purchased at £92.5/MWh (or about \$150/MWh), but even this price was a result of very favorable terms offered by the United Kingdom (80% loan guarantees and a 35 year power purchase contract).

The outlook for the future is not bright either. An expert elicitation study involving 30 European and 30 U.S. nuclear technology experts found that on average, under a business as usual scenario, current (Gen. III/III+) designs were expected to be somewhat more expensive in 2030 than they were in 2010, and the next generation of designs (Gen. IV) were expected to be even more expensive as of 2030. Projected costs of proposed SMRs (small modular reactors) were similar to those of Gen. IV systems [86].

At the same time, there is also a long history of systematic under-bidding in nuclear projects. The case of the South Korean sale to the UAE of four APR-1400 nuclear reactors at an estimated cost of just \$20 billion [13]. This was estimated at being about 20

percent beneath the industry average [87]. Such underbidding or offering special deals is especially true in the case of countries with ambitious nuclear programs. The best example in recent years has been China, where a number of foreign governments offered various forms of inducement to promote reactors designed by vendors from their country [88]. Because it has proposed a large expansion of nuclear power, Saudi Arabia may well be offered reactors at prices below recent costs seen in Western Europe and the United States. However, this sort of subsidization can be done only for the first one or two projects, and cannot be the basis of a large-scale expansion.

7. Electricity cost analysis

A conventional way to compare the cost of electricity generated by different sources is to calculate the LCOE (levelized cost of electricity).¹⁴ This follows from the standard discounted cash flow methodology, which accounts for the time-value of money [89]. We use this methodology to calculate the life cycle cost of producing electricity. The levelized cost is the ratio of the total cost to the benefits (in this case the electricity produced) with all figures being discounted to the same baseline year.

The costs of electricity that we calculate are all busbar costs delivered to the grid; i.e., they take into account auxiliary or in-plant consumption of electricity but do not include transmission and distribution costs. Any large scale expansion of nuclear power or utility scale solar energy would require an expansion of transmission infrastructure. We do not include those costs here, even though it could be significant.

The cost of electricity generated as well as water produced by desalination from any technology depends on a number of parameters. An important factor is the discount rate. For our base case, we assume that the discount rate is 5 percent; to test the dependence on this assumption, we use 10 percent in our sensitivity analysis [90]. Note that this is a real discount rate, and inflation is implicitly taken into account. This choice may seem somewhat low, but many studies do indeed adopt discount rates of around 5 to 5.5 percent in their evaluations of electricity economics in Saudi Arabia [91,92]. Studies specific to neighboring Oman adopt a discount rate of 7.5 percent [93].

Another key factor is the construction period. The Nuclear Energy Agency observes, “Managing risks of construction costs may be the greatest challenge facing nuclear expansion. The high up front investment costs also make construction time a critical factor for nuclear long term competitiveness” [90]. According to the IAEA's figures for construction periods [94], the global weighted average reactor construction time is 96.6 months, or about eight years. In these figures, the construction period is defined as the time between the “first pouring of concrete to the connection of the unit to the grid” [94].

However, some costs that are incurred before the first pour of concrete—for example, money spent on ordering components that take a long time to manufacture. If one were to include those as well, there would be cash flows from a project initiator for about ten years. Note that this could be an under-estimate. In France, the last four reactors commissioned in the late 1990s had an average construction time, between first pour of concrete and grid connection, of 124 months [94], or more than ten years.

¹² For more information on the evolution of cost estimates over the last decade, see Ref. [77].

¹³ We are aware of the pitfalls of using LCOE to compare an intermittent source of power like solar energy with nuclear power. However, as mentioned earlier, this methodology makes solar power look less favorable than if the methodology could incorporate the benefits of the overlap between solar generation and peak demand.

¹⁴ The use of data from the EIA implicitly offers a subsidy to nuclear power in Saudi Arabia, because the costs associated with nuclear regulation in the United States are spread out over about a hundred nuclear reactors, whereas in Saudi Arabia they would, at least initially, all spent on a few reactors.

Table 4

Cumulative distribution of construction expenditures.

Year	0	1	2	3	4	5	6	7	8	9	10
Cumulative Fraction	0	0.03	0.125	0.25	0.375	0.5	0.625	0.75	0.875	0.97	1

The cost of electricity depends not just on the number of years but also the precise distribution of annual capital expenditures. When listed in terms of cumulative expenditure, this distribution is termed an S curve because of its shape. Because of the lack of experience with nuclear construction in Saudi Arabia, we have assumed a nearly even distribution of costs, with equal annual expenditures during most of the years except for the first and last year. Table 4 shows the distribution of costs we assume for nuclear reactors.

For natural gas and CSP, we assume that the expenditure is equally divided into two years, whereas for solar photovoltaics, we assume that all of the expenditure is incurred in one year [90].

A third factor that affects the relative economics of different energy technologies is the capacity factor, the ratio of the energy produced in a given year to the amount that could have been produced if the power plant were to operate at full power all the time. We will assume an average capacity factor of 25 percent for solar PV [95], 35 percent for solar CSP [38], and 90 percent for nuclear and gas.

For capital costs we use figures from the U.S. Department of Energy's Energy Information Administration [96]. The EIA assumes a capital cost estimate for nuclear reactors of \$5530/kW, much lower than the average cost of nuclear reactors under construction.¹⁵ In contrast, its solar cost estimates are likely too high [97]. Further, the cost of solar power has been dramatically declining. This is particularly relevant because of the long construction period of nuclear projects, a decade in our assumptions. Even assuming that a Saudi nuclear power project is given the go-ahead in 2014, it will likely be 2024 by the time it starts generating electricity.

In 2012, based on solar industry experts, other research groups, the EIA and various company web sites, analysts from the McKinsey Consulting Company projected that "the cost of a commercial-scale [solar] rooftop system could be reduced by 40 percent by 2015... and by approximately another 30 percent by 2020—to nearly \$1.20 per Wp" [98]. In all, therefore, the reduction is about 70 percent relative to 2010. Another study projected roughly 40 percent declines in capital costs for both PV and solar thermal [38]. We use the latter figure, i.e., 40 percent, in capital costs for solar PV and CSP but start with the EIA's current estimate for both costs.¹⁶

This is a cautious assumption and there is good reason to expect even greater declines in prices. The U.S. DOE (Department of Energy), for example, has initiated the SunShot Initiative, which seeks to make solar energy cost-competitive with other forms of electricity by the end of the decade. It expects to do this by reducing the total installed cost of solar energy systems to \$0.06 per kWh, or \$60 per MWh, by 2020 [100]. By February 2014, the costs had declined sufficiently for DOE to declare that 60 percent of the target had been reached [101]. However, our approach in this paper is to consider assumptions that are relatively favorable to nuclear power in Saudi Arabia. Therefore, for our base case, we only assume a 40 percent decline in solar prices. We do explore the case of solar power having even lower costs in the sensitivity analysis.

We use EIA costs for natural gas plant of the advanced type. For the gas prices, we use the Saudi domestic gas price of \$0.75/mmBTU. To account for the possibility that this cost might escalate in real terms (i.e. not due to inflation), we also assume a 400 percent increase to a cost of \$3/mmBTU.¹⁷ We discuss the difference between the domestic and international gas prices while estimating opportunity costs. The various parameters used throughout this section are listed in Table 5 below.

Fig. 4 shows the LCOE of the four energy sources with two different cases for PV, CSP and natural gas.

Our calculations show that for Saudi Arabia gas is by far the most cost effective electricity production option today compared to the other sources. Given the cost of electricity at the end user level in Saudi Arabia is 30\$/MWh, gas is the only option that does not require a direct subsidy. Saudi gas-fired power plants not only benefit from much lower capital cost compared to the other options but also very cheap domestic gas prices. It is possible that this price may be increased over the next few decades. However, even assuming a four-fold escalation in the domestic gas price, the cost of gas-based electricity is only 45% of the cost of nuclear electricity. The cross-over between nuclear and gas occurs at domestic gas prices of about \$9.50/mmBTU, over 12 times the current price.

At today's prices, nuclear-generated electricity is roughly 55% of the cost of electricity from solar PV. However, as we have noted earlier, solar prices have been declining sharply and are expected to decline by about 40% by the end of this decade. At those solar costs, nuclear power is only about 10% cheaper than solar. If this trend were to continue, then it is very likely that solar electricity would be cheaper than nuclear power well before any nuclear reactor starts generating electricity.

Our estimates of solar electricity generation cost are roughly comparable to other values in the literature for utility scale projects [103]. Further, although we do not consider the possibility of storage, it has been suggested there are latent storage thermal systems that can be developed over the next decade that might be able to produce electricity at below \$60/MWh [104].

The lowest cost scenario would presumably include only natural gas. However, there may be concerns about inadequate availability of natural gas as well as a desire to diversify electricity sources. In that case, clearly the optimal choice would be to use solar power for meeting peak demand, which as we have noted earlier is a large fraction of the total demand, and natural gas to meet the remaining demand. We address the question of depletion of gas resources and the potential time frames during which this may become significant below.

7.1. Desalination cost

As mentioned earlier, water desalination is another important and growing source of energy demand. An obvious strategy to deal with both electricity generation and desalination is to implement a co-generation model. We consider the three water desalination processes—MSF (Multi Stage Flash), MED (Multiple Effect Distillation) and RO (Reverse Osmosis)—the ones currently deployed in

¹⁵ The cost assumed for PV includes all the other components—for example, blocking diodes, power conditioners and inverters/converters [99].

¹⁶ This is reported to be at the upper end of the numbers being discussed as the potential result of an imminent review of the domestic gas price [102].

¹⁷ MSF works well even with high salinity levels and has a larger production capacity compared to other technologies.

Table 5
Assumed parameters and cost estimates.

	Nuclear	Gas (domestic price)	Solar (CSP)	Solar (PV)
Unit capital cost (\$/kW)	\$5530	\$1023	\$5067	\$3873
O&M cost ratio			1.33%	0.65%
Assumed reduction in capital costs by 2020			40%	40%
2020 capital cost (\$/kW)			\$3040	\$2324
Fixed O&M (\$/kW-y)	\$93.28	\$15.37	\$40.43	\$15.10
Variable O&M (\$/MWh)	\$2.14	\$3.27	0	0
Heat rate (BTU/kWh)		6430		
Gas used (mmBTU/MWh)		6.43		
Gas cost (\$/mmBTU)		\$3.00		
LEU fuel cost (\$/kg)	\$3211		0	0
Fuel consumption (kg/kWh)	3.15E-06			
Fueling costs (\$/MWh)	\$10.11	\$19.29	0	0
Economic life	60	40	25	25
Capacity factor	90%	90%	35%	25%
Auxiliary consumption	8%	8%	0.25%	0.25%
Discount rate	5%	5%	5%	5%
Total levelized cost (\$/MWh)	\$76	\$34	\$86	\$82

Source: EIA 2013 and authors' calculations and assumptions

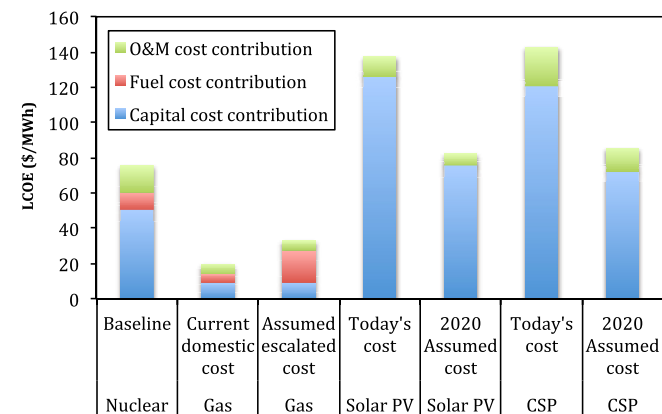


Fig. 4. Levelized costs of electricity generation.

Table 6
Parameters used to calculate cost of desalination.

Parameter	Nuclear	Gas	Solar-CSP	Solar-PV
Nominal power (MWe)	1000	400	100	150
Efficiency	33%	40%	20%	20%
Water capacity (CM/day)	100,000	50,000	50,000	5000
Plant cycle	Steam	Combined cycle	Steam	N/A

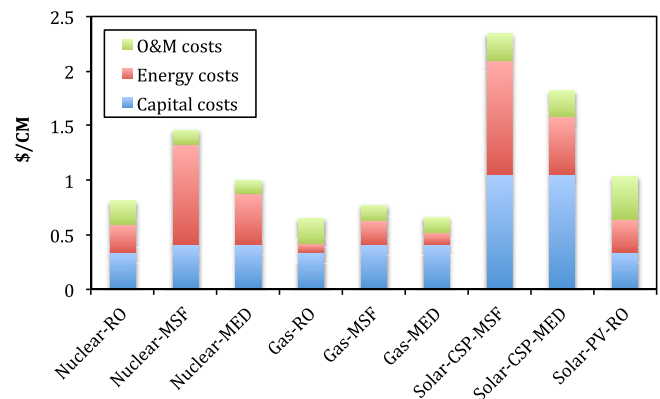


Fig. 5. Costs of desalination.

technology because it uses much less energy than MSF and MED which are based on thermal processes. As far as desalination cost is concerned, nuclear power offers a clear advantage compared to solar CSP and PV particularly in the MSF, the most used technology in Saudi Arabia.¹⁸

The difference between the economics of desalination and electricity using solar power is primarily because desalination plants using solar thermal power are roughly an order of magnitude smaller in capacity compared to desalination plants that use waste heat from nuclear plants. Thus, solar desalination plants suffer from diseconomies of scale relative to nuclear power.

7.2. Opportunity cost

Consuming oil and gas domestically to generate electricity has an opportunity cost associated with forgone export revenues. In the case of Saudi Arabia, the difference between domestic and international prices for both gas and oil are quite substantial and the opportunity cost, particularly when oil prices have increased significantly, is a major rationale for energy diversification.

Currently Saudi Arabia neither imports nor exports natural gas. If the kingdom were to increase its domestic output and start exporting gas, it will most likely be in a liquefied (LNG) form. Consequently, the costs associated with building infrastructure, liquefaction and shipping should be taken into account. A study on the future of natural gas conducted by the Massachusetts Institute of Technology estimates the cost of liquefaction at \$2.15/mmBTU, shipping of LNG at \$1.25/mmBTU, and regasification at \$0.7/mmBTU [106].

We calculate the opportunity cost for gas as follows. First, we evaluate how much revenue could be generated by exporting the amount of gas used to generate 1 MWh of electricity and

¹⁸ Because we are not including storage in the case of solar power, we do not consider any opportunity costs associated with its use.

substituting nuclear power to generate the same amount of electricity.¹⁹ The amount of gas used to generate 1 MWh is 6.43 mmBTU. The extra cost associated with using nuclear power is about \$56/MWh. Second, we calculate the necessary natural gas price at which this extra cost can be justified. Once the costs associated with conversion to LNG are included, we find that there would be a positive opportunity cost only if Saudi Arabia can procure a price of \$13.6/mmBTU for exported (and shipped) LNG.

Prices for natural gas vary widely, both spatially and temporally. The price of \$13.6/mmBTU is high compared to spot prices in the United States, whereas it is smaller compared to the spot prices in Japan, which has had often had to pay the most for natural gas in recent years.²⁰ Given the many countries that are interested in exporting natural gas, and the expansion of natural gas production from shale that is happening around the world, it is not clear if Saudi Arabia can be confident of procuring this high price for the many decades it would have to take to justify the significantly higher electricity costs associated with nuclear power.

Since opportunity cost is linear with fuel prices, both gas and oil profiles are very similar. If one assumes that no new oil plants are built, the only comparison is whether to run an existing oil plant to generate electricity or to export the oil and generate the same amount of electricity using nuclear power. The cost of 1 MWh of nuclear power is \$76. Following the U.S. DOE's EIA, we assume that the amount of oil used is 1.8 barrels per MWh of electricity [107]. The domestic price charged to Saudi Electric Company for oil is reported to be \$0.73 per mmBTU [108], or \$4.1 per barrel. Thus, the fueling cost of oil-based power is \$7.4/MWh. In addition there will be the O&M costs, which we assume to be the same as for natural gas plants: \$5.39/MWh. Therefore, the additional cost of nuclear power is about \$63. Thus, as long as the available price for a barrel of oil is higher than about \$38, it would be more economically optimal to generate electricity using nuclear power and export the oil. This has been the case for many years. Likewise, at current oil prices, it would be economically justified to replace oil-based electricity with solar power.

However, natural gas remains a more economical source of electricity generation. Indeed, as we have noted earlier, Saudi policy makers are no longer expanding oil based generation, focusing primarily on natural gas based electricity.

7.3. Saudi gas reserves

The question that might follow from our assessment that natural gas offers the lowest cost electricity generation and desalination in Saudi Arabia is whether the country will run out of natural gas if all, if not most, of the future electricity generation capacity is based on natural gas. The current production level for natural gas is about 100 billion cubic meters per year [109]. All gas produced is consumed domestically with 42 percent used for electricity generation. According to the EIA's latest estimates, Saudi Arabia's total gas reserves are about 8.15 trillion cubic meters, 57 percent of which are in associated fields [109].

These are sizeable reserves. Even if one assumes that electricity demand grows at an average rate of 6.5 percent—roughly the mean of the two growth rates assumed earlier—and all of these are met using natural gas, our calculations show that Saudi Arabia will run out of gas only in 2056. This assumes that between now and 2056, no additional natural gas resources are discovered. In other words,

even under conservative assumptions, there is no imminent danger of shortage of fuel. And if there were improvements in domestic energy efficiency, this depletion date could be extended even further out.

Further, the estimate of reserves is almost definitely a lower bound. According to Saudi Aramco, the state-owned national oil company, only 15 percent of Saudi Arabia has been explored for gas [110]. More dramatic increases are expected if Saudi Arabia starts exploiting unconventional and shale gas fields. In March 2013, Saudi Oil Minister Ali Al-Naimi announced that their rough estimates of such gas amounts to “over 600 trillion cubic feet” or over 17 trillion cubic meters, more than twice the conventional gas reserves, and that seven test wells were to be drilled [111]. However, the cost of recovery from such reserves might be higher than from conventional gas reserves or as a by-product of oil production [102].

8. Sensitivity analysis

Our results in the previous sections are, of course, dependent on the assumptions about costs and other parameters. We now perform a sensitivity analysis to see how strong this dependence is and whether qualitatively different answers emerge when other reasonable assumptions are used.

8.1. Capital cost

In the case of both solar and nuclear power, the primary components of the electricity costs are the capital costs of the installation. In the case of natural gas plants, depending on the cost of the gas, it could be either the fueling cost or the capital cost. Because domestic gas prices in Saudi Arabia are so low, the capital cost is again the dominant element.

To quantify the sensitivity of our results to our assumptions, we assume that the unit cost of each of these technologies is 30 percent lower and 30 percent higher. For example, for a nuclear reactor the high and low scenarios would involve capital costs of \$7200/kWe and \$3870/kWe. The results of these variations are shown in the figure (Fig. 6) below. As expected, the costs of nuclear and solar power vary strongly with capital cost.

While our sensitivity range is symmetric, the likelihood of the upper and lower ends of this capital cost range is highly unsymmetric. In the case of nuclear power, current capital cost estimates for many proposed reactors are in the vicinity of \$7200/kWe, but one cannot seriously envision any project costing \$3870/kWe. In contrast, most analysts expect solar costs to continue on the current downward trend and the 30 percent lower scenario is a more realistic variation to explore.

One scenario where these higher costs for nuclear power might be applicable is if Saudi Arabia acquires small modular reactors, which is of some interest to Saudi policy makers [64,65]. Detailed and carefully conducted elicitation showed that even experts drawn from, or closely associated with, the nuclear industry, expect these reactors to cost more per kW of capacity than currently operating reactors [112]. Other expert elicitation comes to similar conclusions [86]. In other words, it is quite likely that solar power would be a cheaper source of electricity than SMRs.

8.2. Discount rate

The results of our calculations depend on the choice of discount rate. Though the discount rate is a crucial variable, there is no clear consensus on what it should be and different studies use different values. Our baseline calculations were made using a discount rate of 5 percent. As a variant, we also use a 10 percent discount rate to be consistent with other such studies [90] (Fig. 7).

¹⁹ The spot price is that which is offered in the market by customers without a long-term contract.

²⁰ For a comprehensive list of subsidies to nuclear power in the United States, see Ref. [118].

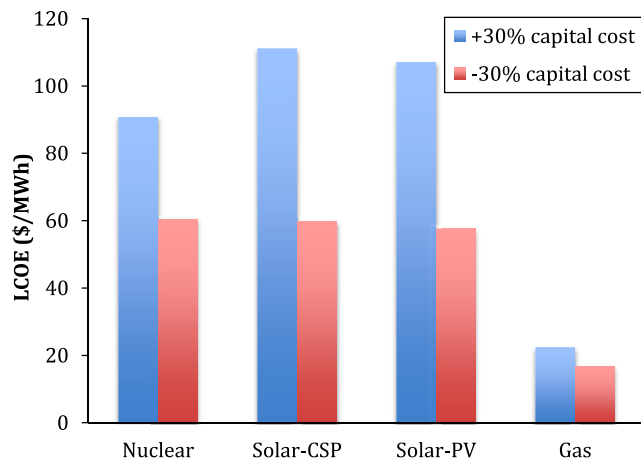


Fig. 6. Variation of levelized costs with capital cost.

As expected the costs of both nuclear and solar technologies go up sharply with discount rate, while gas is relatively stable. However, nuclear costs are more sensitive because of the long construction period over which the expenditures are incurred.

While we have assumed the same discount rate for all technologies, there are good reasons to use of a higher discount rate specifically for nuclear power plants. Several economists have argued for such higher discount rates because nuclear projects are financially more risky [113]. This is primarily because these have higher fixed costs as compared to, say, coal plants that have higher operating costs. For plants with higher fixed costs, the systematic risk is higher [114–116]. In our analysis, however, we use the same discount rate. This assumption amounts to an implicit subsidy to nuclear power. If the discount rate for nuclear power were to be increased by even 1 percent relative to the discount rates for other technologies, to 6 percent, the LCOE for nuclear power increases to \$87/MWh, up from \$76/MWh.

8.3. Carbon costs

Even though Saudi Arabia does not have any pricing for carbon emissions so far, it is possible that some form of carbon emission pricing could be introduced over the coming decades, either because of a purely domestic decision or because of a global agreement on carbon pricing. This would, obviously, impact only natural gas; nuclear power and solar energy are conventionally treated as zero carbon sources.

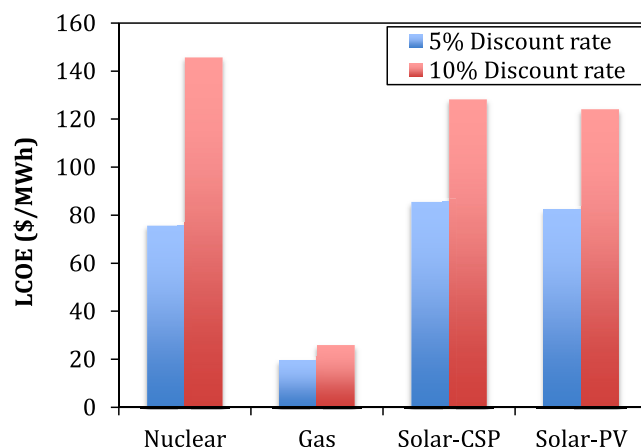


Fig. 7. Variation of levelized costs with discount rate.

Advanced and future gas-fired power plants are estimated to emit about 0.4 ton CO₂ eq/MWh [117]. The carbon price, if and when introduced, will likely vary regionally but increase with time. The International Energy Agency assumes between \$10 and about \$90 per ton of CO₂ in its various scenarios in different regions [49]. We therefore assume \$50/tCO₂, a figure in the middle of this range. For this carbon price, the levelized cost of electricity from natural gas plants is about \$39/MWh, \$20/MWh (0.4t/MWh × \$50/t) more than the \$19 figure shown in Fig. 4. Since there is a linear relationship between carbon price and electricity cost, the appropriate increase for different carbon prices is easy to calculate. At current natural gas prices, the carbon price has to exceed \$150/tCO₂ for the levelized cost of electricity from natural gas plants to overtake that from nuclear reactors.

8.4. Other costs associated with nuclear power

Our calculations can justifiably be accused of being overly partial towards nuclear power since they omit a number of costs specific to that technology.²¹ For example, spent-fuel management and decommissioning costs have been completely excluded from these cost-calculations. These can be significant. One recent estimate, based on the U.S. Department of Energy's Nuclear Waste Fund Fee Adequacy Assessment Report, finds the costs of managing spent nuclear fuel are in the range of \$10 to \$20 per MWh [119].

Another factor specific to nuclear power that we have omitted is they needed to be loaded up fully with fuel (full core loading) before the reactor starts operating. For example, Areva's EPR reactor core requires 241 fuel assemblies with each assembly contains 527.5 kg of uranium, resulting in an initial core loading of 127 tons of uranium [120]. At the LEU price we have assumed, that adds roughly half a billion dollars to the initial capital cost, or about \$250/kWe.

We have also not included any provisions for costs associated with dealing with nuclear accidents. Even discounting the impacts on human health, Fukushima has shown how large the financial implications of a catastrophic accident are. Despite advances in nuclear technology, it is still not possible to categorically rule out the possibility of such accidents.

There has been a longstanding debate over the extent of the subsidy provided by policies such as the Price Anderson Act in the United States wherein there is a cap on the extent of the liability taken on by the operator of a nuclear power plant in the event of an accident, with the government taking on the responsibility of dealing with any expenditures in excess of this cap [121–123]. These figures will have to be updated following the Fukushima accident because of its implications for both the estimates of the cost of a nuclear accident and the probability of one occurring. Since Saudi Arabia is still in the early stages of setting up its nuclear program, it is not clear how it will handle nuclear liability. Therefore, we cannot estimate how much of a subsidy it would offer, or how it would affect the cost of nuclear electricity generated.

There are other costs that we have not included in the case of nuclear power. In the case of the United States, these subsidies have been studied in detail [118]. It is not clear what kinds of subsidies the Saudi government will extend to nuclear power, and thus we cannot quantify these.

9. Conclusion

The global future of nuclear power is uncertain [124]. There are some who feel that nuclear power "is a critical component to meeting future global energy needs and reducing the emission of greenhouse gases" [63]. Others are dismissive arguing that "nuclear energy is not a solution to our energy worries but part of the

problem” [125]. Regardless of these varied perceptions, Saudi Arabia does have ambitious plans regarding nuclear power.

This paper has examined the economic prospects for nuclear power in Saudi Arabia and found that they are not favorable in comparison with natural gas, even if the currently low domestic natural gas prices in Saudi Arabia were to rise substantially. As shown by our sensitivity analysis, this is a robust conclusion. The comparison with solar power is contingent upon future variables, in this case the capital costs of solar photovoltaics and concentrated solar power generation equipment. Given the rapid declines in solar costs that have been witnessed in the last decade, electricity from solar plants has the potential to be cheaper than nuclear power within the next decade. If the U.S. Department of Energy’s Sunshot goals for 2020 are reached, for example, solar power would certainly be cheaper than nuclear power by 2020. The relative economic advantage of solar power has added relevance because of the coincidence between the peak demand and solar insolation in Saudi Arabia. This coincidence also implies that the LCOE measure that we have used undervalues solar power. However, this will be partially or wholly compensated by the costs of technologies needed to deal with short term variability of solar insolation.

Our analysis suggests that a focus on solar energy is indeed justified, even if storage technology is still quite expensive and solar power cannot as yet be used to meet nighttime electricity demand economically. This is not the case for desalination, wherein nuclear power is more expensive than natural gas based plants, but is clearly cheaper than solar CSP and PV.

Through our sensitivity analysis, we confirmed that the potential of solar power to produce relatively cheaper electricity compared to nuclear power for a wide range of possible parameter values. This includes both higher discount rates and capacity factors. In the case of solar power, the baseline values of the capacity factor are relatively low compared to what is projected by many analysts for the coming decades.

Though nuclear power is sometimes justified because Saudi Arabia could export its natural gas instead of burning it to produce electricity, this opportunity cost is positive only if Saudi Arabia can procure a price of \$13.6/mmBTU for exported (and shipped) LNG for the several decades it would take to recover the high construction cost of nuclear reactors. However, in the case of oil, global prices are much higher than domestic oil prices and it would be economically optimal for Saudi Arabia to export some of the oil and substitute with any of the other forms of power we discussed.

The high costs of nuclear power suggests that, despite impressive projections of a rapid and massive construction of reactors, economic considerations would limit the role nuclear power will play in meeting Saudi electricity demand. As the *Economist* magazine observed famously, “nuclear power, which early advocates thought would be ‘too cheap to meter’, is more likely to be remembered as too costly to matter” [126].

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