Saudi Arabia Energy Needs and Nuclear Power

Prepared for the Non-Proliferation Policy Education Center

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1. Introduction

This report, commissioned by the Nonproliferation Policy Education Center, assesses the prospects for Saudi Arabia to meet its energy and environmental requirements without the use of nuclear power.

There are evidently many ways in which those requirements could be defined and met. This study covers the period up to 2040 since this is the period over which the country has defined its current nuclear power target, and with main focus on 2032 given that this was the year for its initial planned mix of nuclear and renewable energy. Reasonable assumptions are made for growth in electricity demand, other industrial energy demand, and transportation, based on official Saudi forecasts with independent checks and scenarios, including those with greater realised energy efficiency. The primary focus is on electricity given that this would be the main output of a civil nuclear power programme, so the other uses of oil and gas in the transportation and industrial sectors are not considered in detail.

Then a comparison is made of the Saudi energy system up to 2040 with nuclear power at current targeted levels; with the current fossil-fuelled mix; and with a number of scenarios with more renewable energy and no nuclear. These three approaches are contrasted on the metrics of economic attractiveness (cost and value); environmental outcomes; reliability and energy security; local economic development. Possible proliferation-related reasons for pursuing civilian nuclear power have been dealt with at length by others[1] and are not considered here.

The main scenarios considered assume that the regional political situation and climate remain broadly similar to today. It is assumed that, over this period, transport (air, land and sea) will remain fuelled primarily by hydrocarbons (oil and possibly natural gas). In all scenarios, mostly current technologies are assumed, with conservative views on improvements in performance and cost. Of course, more rapid advances in renewable energy, unconventional hydrocarbons, carbon capture & storage, advanced energy storage or other technologies would make it easier to meet the country's energy requirements without

nuclear power. Conversely, advances in nuclear power (such as small modular reactors) would make it relatively more attractive.

Environmental requirements are assumed to be, at minimum, compliance with Saudi Arabia's Paris climate change agreement submission, as well as mitigating local environmental impacts of its current energy system.

2. Current situation

2.1. Objectives

Saudi Arabia's oil and gas are its main natural resource, the foundation of its economy and its political system and international role. With that in mind, the key goals of Saudi energy policy can be defined as[2]:

1. Maintain and increase oil and gas output to meet the needs of the domestic population, supply local business with energy and feedstock, and earn export revenues

2. Maintain its role as one of the world's leading oil producers and the dominant force in the Organisation of Petroleum Exporting Countries (OPEC)

3. Secure markets for its oil by investing in assets and relationships in its main customers

4. Diversify the economy by developing hydrocarbon-based and energy-intensive industries, as well as, more recently, non-oil industries, with a view towards the long-term diminution of oil's role in the global economy

5. Build up substantial fiscal reserves to safeguard against oil price volatility

6. Safeguard the security of its energy industry and country generally via hard security measures, relationships/alliances and "soft power"

7. Delay or minimise environmental measures that would reduce the use of oil in the world economy

More recently, two other objectives have risen to prominence, even if they do not yet eclipse the objectives above:

1. Improve energy efficiency, introduce non-hydrocarbon energy sources, and reform subsidies to reduce the fiscal burden on government and preserve oil and gas for industrial and export use, while bearing in mind domestic public opinion and preserving the competitiveness of business

2. Improve environmental performance, including greenhouse gas emissions

2.2. Oil

Saudi Arabia is, of course, one of the world's largest oil producers (12.3 million barrels per day of crude oil, condensate and natural gas liquids in 2016, second in the world behind the USA and ahead of Russia; of this, 10.46 million bbl/day was crude oil), and the world's largest oil exporter (net 8.4 million barrels per day in 2016[3]; of this 7.5 million bbl/day was crude oil and 1.5 million bbl/day refined petroleum products, with 0.6 million bbl/day import of refined products[4]). It is the world's largest holder of conventional oil reserves with an official total of 266.2 billion barrels at the end of 2016[5] (only Venezuela has a larger figure, but the majority of Venezuela's official reserves are extra-heavy oil of uncertain commerciality).

Saudi oil production costs are exceptionally low, probably on the order of $10 per barrel or less (capital plus operating costs). The reserves/production ratio is 59 years, indicating (simplistically) that production could continue at current rates for 59 years from the existing reserves base. Saudi Arabia has aspirations to raise its total recoverable oil substantially, mostly by increasing recovery from the known fields.

Saudi Arabia is also a major oil consumer, refining 2.5 million bbl/day in 2016 and consuming 3.2 million bbl/day[6], the fifth largest figure in the world (behind the US, China, India and Japan). Of this, a large proportion was crude oil burnt directly in power plants. Figure 1 shows oil consumption by month during 2013-16, and it can be seen that it rises some 700-800 000 barrels per day in summer versus winter, mostly due to an increase in the direct burning of crude oil and to some extent fuel oil.

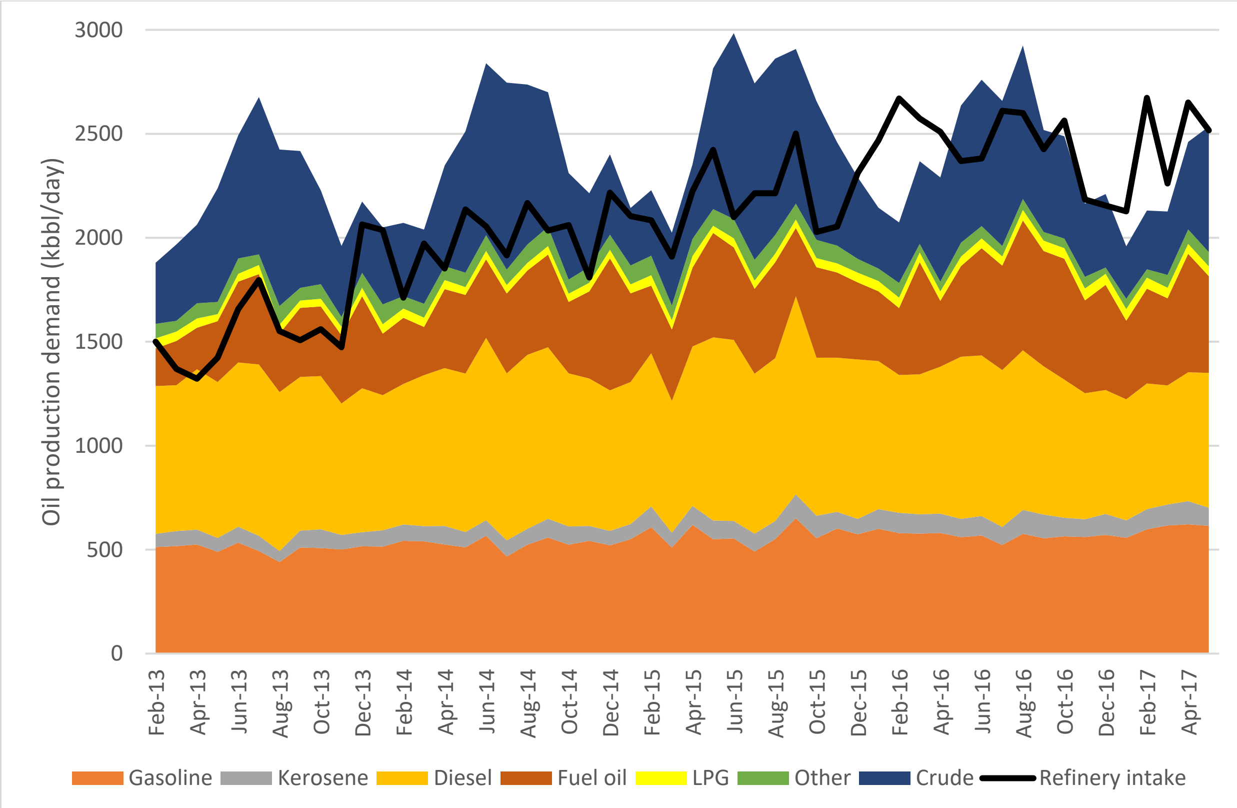

Figure 1 Saudi Arabia monthly oil consumption[7]

All Saudi oil and gas production, apart from that in the Neutral Zone with Kuwait, is operated by Saudi Aramco, the state-owned oil company. Aramco also operates the Kingdom's oil refineries (some in partnership with foreign companies), has a substantial petrochemical and power generation business, and a number of significant international investments in refining and petrochemicals in the US, China, South Korea, Japan and elsewhere. Aramco is respected as a relatively efficient and technically proficient operator. There are plans for an Initial Public Offering (IPO) of 5% of Aramco on the Saudi stock exchange (the Tadawul) and a to-be-chosen international exchange, set for 2018.

2.3. Natural Gas

Saudi Arabia is also an important producer and consumer of natural gas, though not to the same extent as for oil. Official reserves at the end of 2016 were 297.6 trillion cubic feet (the 6^{th}-largest in the world), and marketed production was 10.6 billion cubic feet per day (the 8^{th} largest in the world). All of this gas was used domestically, making the Saudi domestic gas market the world's 6^{th} largest.

A large part of gas production is associated (a by-product of oil production) and is therefore cheap to collect and use but not flexible. The proportion of associated gas, though, has fallen from 42% in 2005 to about 33% in 2015[8]. The reserves/production ratio for gas is 77 years, indicating ample reserves to increase production; however, if oil production remains constant, significant increases in gas production would have to come from non-associated fields. The country has developed its first non-associated fields offshore in the Gulf, Karan and (together feeding the Wasit gas plant) the Arabiyah and Hasbah fields.

Saudi Arabia has significant unconventional (tight/shale) gas resources, estimated at 645 trillion cubic feet[9]. Apart from initial projects in the north-west of the country (Tabuk Basin), shale gas production has consisted only of pilots, with estimates of high production costs ($9/MMBtu in 2012). However unconventional gas production is targeted to reach 4 Bcf/day by 2026[10]. Most versions of hydraulic fracturing, required to produce tight gas, use fresh water, which would require desalination. BP has developed tight reservoirs in Oman's Khazzan field, also in a desert setting, using reverse osmosis desalination plants. Alternatively fracturing fluids using saline water, propane or carbon dioxide could be employed though they may be less effective. In either case, this raises the likely initial cost of tight gas production in Saudi Arabia.

Although it borders two of the world's largest gas resource holders, Iran and Qatar, Saudi Arabia by policy does not import or export gas. Difficult political relations with these two countries (and with another gas-rich neighbour, Iraq, although relations here have somewhat improved recently) make direct imports unlikely. Other than Yemen, whose moderate LNG exports are shut down by the continuing war, its other neighbours – Egypt, Jordan, UAE, Oman, Bahrain and Kuwait – are themselves gas importers or

about to become so[11]. If political conditions did change to allow gas imports from a neighbour, its lower cost might undermine high-cost domestic gas production. It is also possible that Saudi Arabia could at some point import liquefied natural gas (LNG)[12]. In July 2017, Russian energy minister Alexander Novak said that Aramco had been offered a share in Novatek's Arctic LNG-2 project in the north of west Siberia[13].

Energy minister Khaled Al Falih has indicated an aspiration to raise gas from 50% of the "energy mix" to 70%, which probably refers to its share of electricity generation (gas's share of total primary energy use is rather lower, at about 32% in 2016). Under the National Transformation Plan, gas production is intended to rise from a (gross) 12 Bcf/day in 2016 to 17.8 Bcf/day in 2020 and 23 Bcf/day by 2026[14]. Gas production is shown in Figure 2, as well as the projected production in 2020 and 2026, assuming the proportion of shrinkage (removal of natural gas liquids) remains the same (shrinkage figures are not available for 2016). On official figures, flaring and reinjection is minimal although likely to be substantially more in reality. It can be seen that, although marketed gas production has increased by 1.6 Bcf/day from 2011 to 2016, it has to increase by a further 5 Bcf/day by 2020. 2.5 Bcf/day of this will come from the Fadhili processing plant due online in 2019 (which will process 0.5 Bcf/day from the onshore Khursaniyah field and 2 Bcf/day from the second phase of the offshore Hasbah field), and 1.3 Bcf/day from an expansion of the Hawiyah gas plant[15]. 0.075 Bcf/day will be produced from the Midyan field, in a new gas-producing area in the north-west of the country. It is not clear where the remainder of the increase, 1.125 Bcf/day, will come from, although an expansion of the Haradh gas processing plant is also in the works (both Hawiyah and Haradh process gas from the Ghawar field).

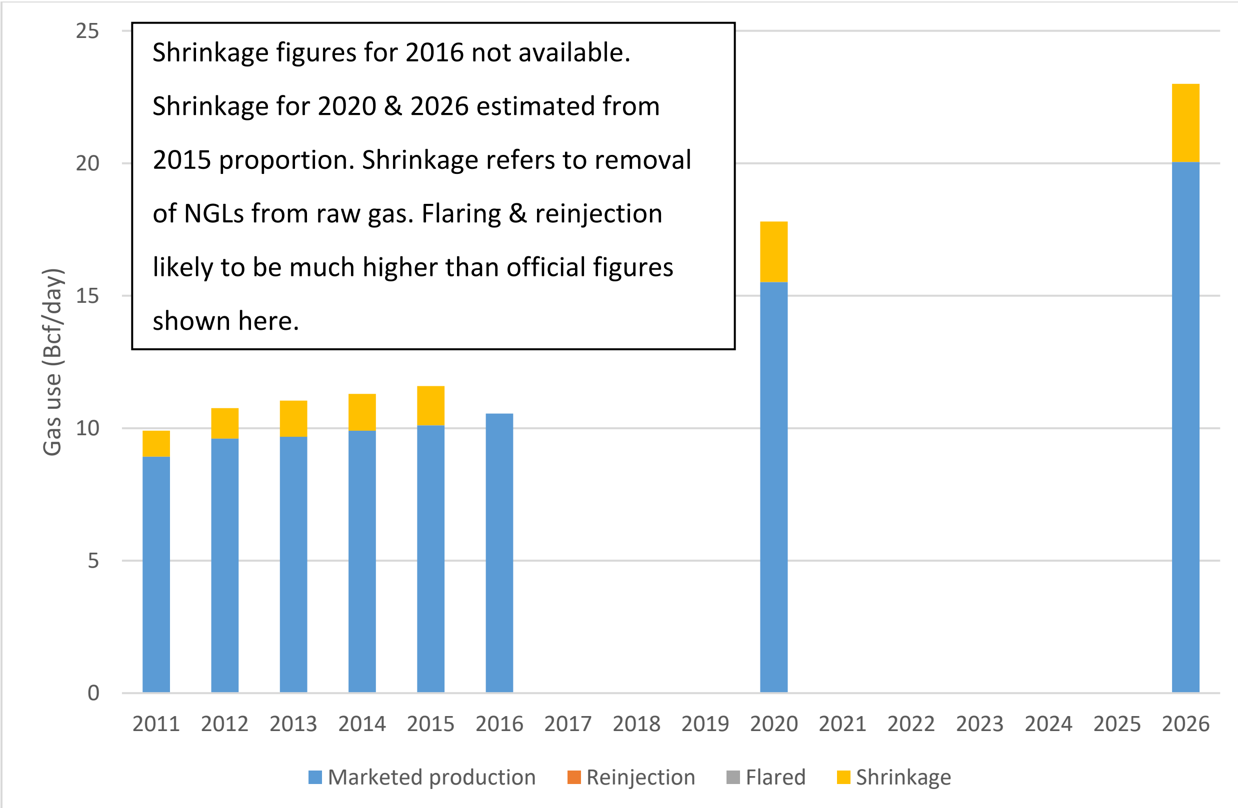

Figure 2 Gas production[16]

The International Energy Agency has become progressively more sceptical on Saudi Arabia's gas output targets. In 2014, it forecast production would be approaching 13 Bcf/day by 2019, but in subsequent editions of its Medium Term Gas Outlook, it reduced that down to just over 9 Bcf/day by 2019 and about 10 Bcf/day by 2022[17].

Gas consumption by sector is shown in Figure 3. The power sector is about 56% of total gas consumption. (Note that there is an unexplained discrepancy between the IEA figures, used here, and the OPEC and BP figures for total production which are significantly higher, while Saudi Electricity Company (SEC)'s figures for generation use are significantly *lower* than those of the IEA). 26% of the country's petrochemical feedstock is methane (the main constituent of natural gas) and 46% is ethane (primarily derived from natural gas)[18].

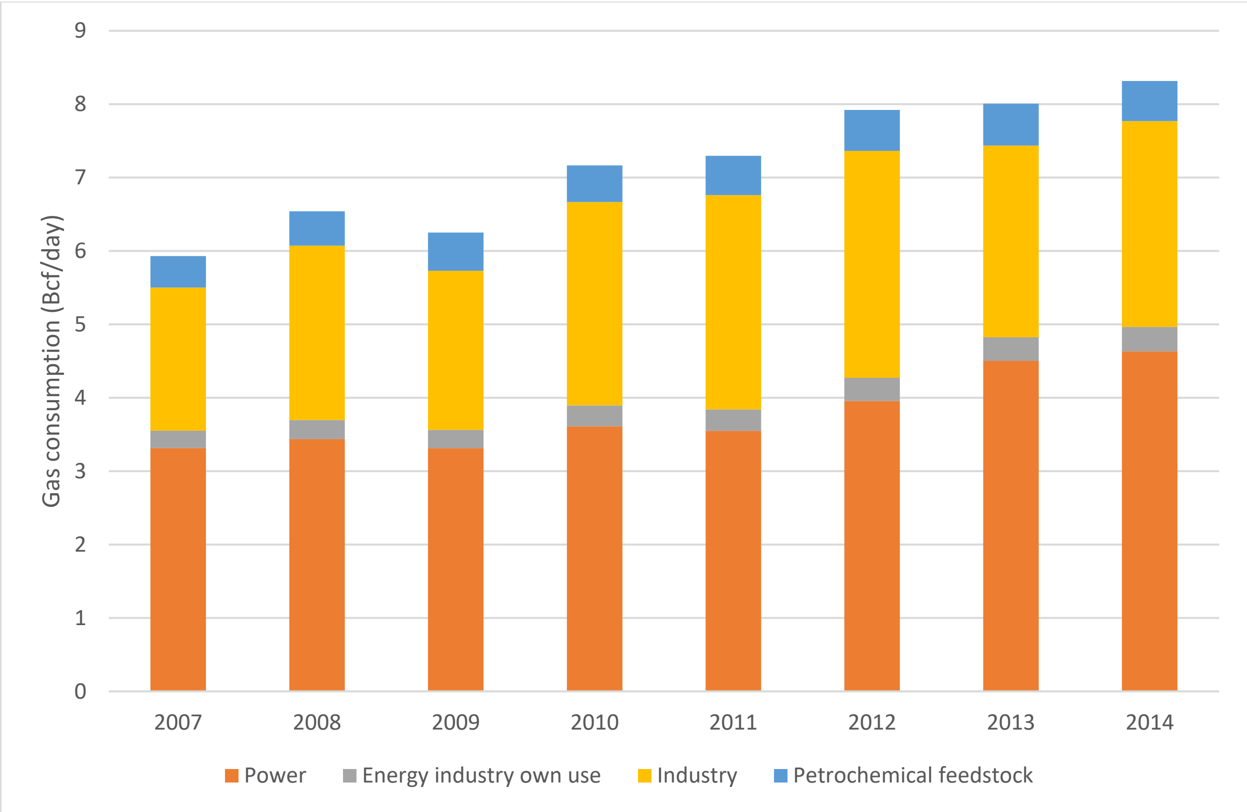

Figure 3 Gas consumption by sector[19]

Gas prices are regulated by the government and are very low by global standards, being raised in 2016 from $0.75 to $1.25/MMBtu, and for ethane (used in petrochemicals) from $0.75 to $1.75/MMBtu[20]. These are still well below the price that would be paid for imported LNG, or the cost of developing domestic unconventional gas.

2.4. Electricity

Electricity demand has been rising rapidly, at an annual average rate of 6.2% in the ten years 2006-16, spurred by the economic boom (up to 2014), rising population and low, subsidised tariffs. However, with

an economic slowdown and an increase in tariffs, demand grew by only 0.7% in 2016. It remains to be seen whether this slower growth becomes the norm, but without efficiency measures the government expects demand growth to be 4-5% annually[21].

Total generating capacity attached to the national grid was 74.3 GW at the end of 2016 (up from 69.2 GW a year earlier), of which 55 GW was provided by the state-owned Saudi Electricity Company and the rest by industrial companies with their own grid-connected power plants. The highest reported load was 62.26 GW in August 2015 although that may be exceeded this year[22]. The reserve margin is therefore almost 20% which would be considered adequate (SEC's target is 12%). Power plants receive fuel at prices fixed by the government which are far below world market levels: $1.25 per MMBtu for natural gas, $4.4 per barrel for heavy fuel oil, $11.7 per barrel for diesel, and $5.94 per barrel for crude oil (these are the prices after a sharp increase ordered in January 2016; they were even lower before)[23].

Figure 4 shows Saudi power generation by source. It can be seen that virtually all comes from oil (crude oil and refined products) and natural gas (the breakdown of generation for 2015 and 2016 is not available from IEA). A very small proportion (0.083 TWh out of total generation of 330.46 TWh in 2016, or 0.03%) is provided by solar photovoltaics (PV), with current installed capacity of 85 MW[24]. Saudi Arabia's first wind turbine (2.75 MW) was installed in January 2017[25] and it does not currently make use of any other form of renewable electricity production[26], nuclear power or coal. Saudi Arabia is constructing three integrated solar combined cycle (ISCC) plants, using small amounts of solar thermal to boost the efficiency of combined-cycle plants: Duba 1 (43 MW solar out of total 605 MW), Waad Al Shamal (50 MW solar out of total 1390 MW) and Taiba (180 MW solar out of total 3600 MW)[27].

KA CARE's 2013 strategy foresaw total generation capacity by 2032 of 123 GW. This would be met by 60 GW of hydrocarbon power (oil and gas), 18 GW of nuclear, 41 GW of solar (16 GW PV and 25 GW CSP), 3 GW of waste-to-energy and 1 GW of geothermal. A further 9 GW of wind power would be used for desalination, with the intermittency presumably managed by other generation and/or water storage.

80% of the renewable and 60% of the nuclear expenditure would be in-country (local content). By 2020, 17.35 GW of solar and 6.5 GW of other renewables would have been installed.

However, very little progress was made on this plan, due to bureaucratic infighting and unclear lines of responsibility[28]. In 2016, the new National Transformation Plan intends that 3.45 GW of renewable energy should be introduced by 2020 (4% of the energy mix) and that the renewable share would reach 9.5 GW[29] by 2023 and 10% by 2030 (instead of almost 50% in the KA CARE plan). In April 2017, companies were shortlisted for a 300 MW solar plant and 400 MW wind farm. The wind power, originally intended to be at Midyan in the north-west Tabuk region, will now be in Al Jouf in the north[30], and by July 2017 was already five months behind its original target. By the fourth quarter of 2017, the country intends to tender another 620 MW of solar PV and 400 MW of wind. If all awarded and built, this would amount to 1.7 GW, which, sustained annually, would be a sufficient pace to meet the 2020 and 2023 targets.

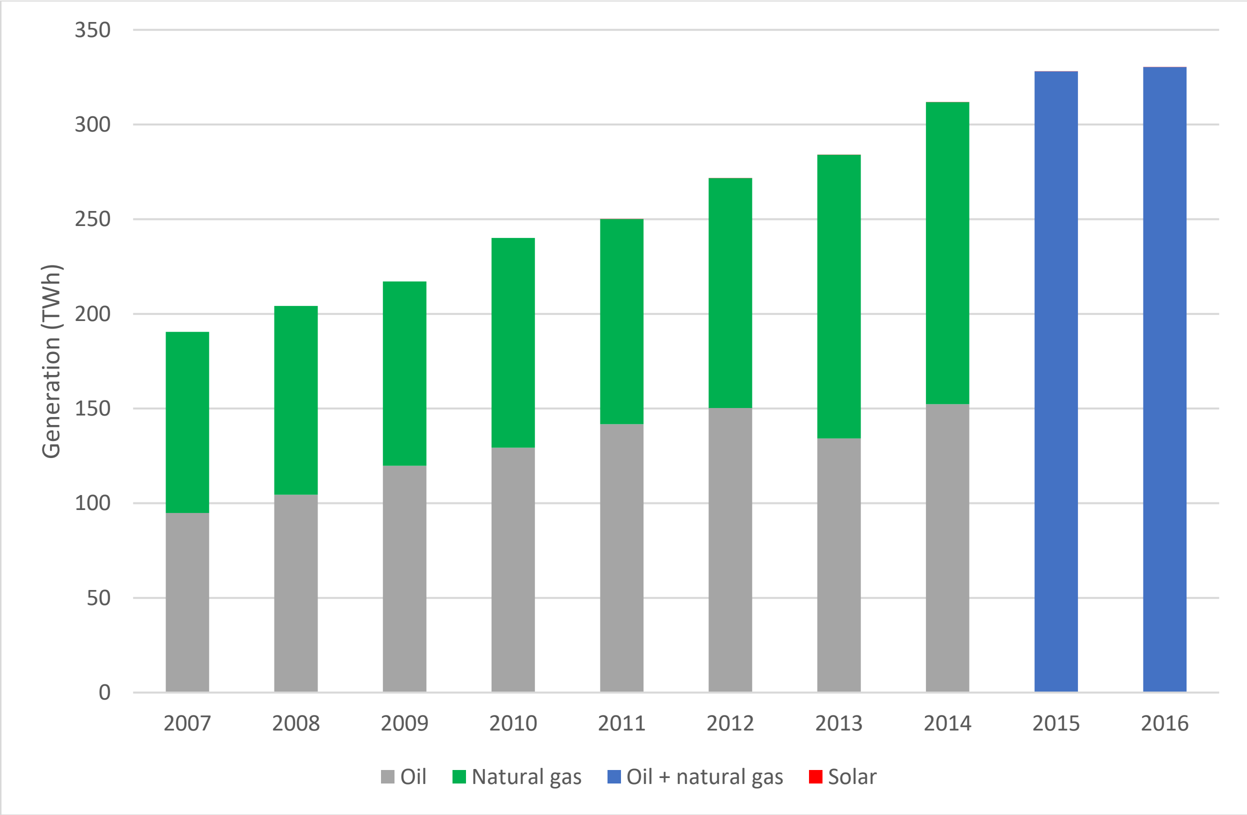

Figure 4 Saudi Arabia electricity generation by source[31]

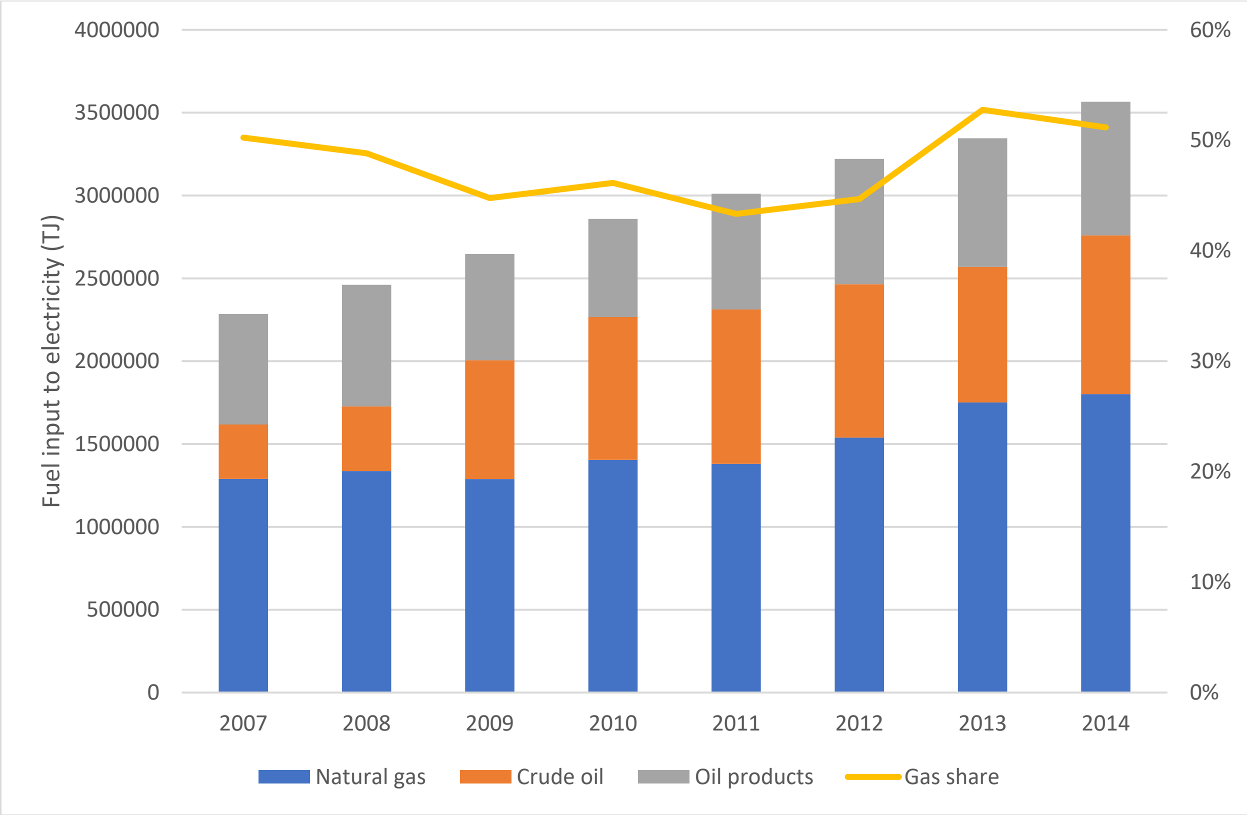

Figure 5 Fuel to electricity generation[32]

Figure 5 shows a breakdown of fuel supply to power generation. 1801750 TJ of gas supplied in 2014 is equivalent to about 4.6 Bcf per day. The share of gas in the fuel mix has hovered a little below 50%, rising a little in 2013 and 2014 as new gas supplies became available. Saudi Arabia is almost unique globally for the large-scale direct use of crude oil in power generation, which averaged about 450 kbbl/day during 2014 and reached 1 million bbl/day at times during the summer months when demand for air-conditioning peaks.

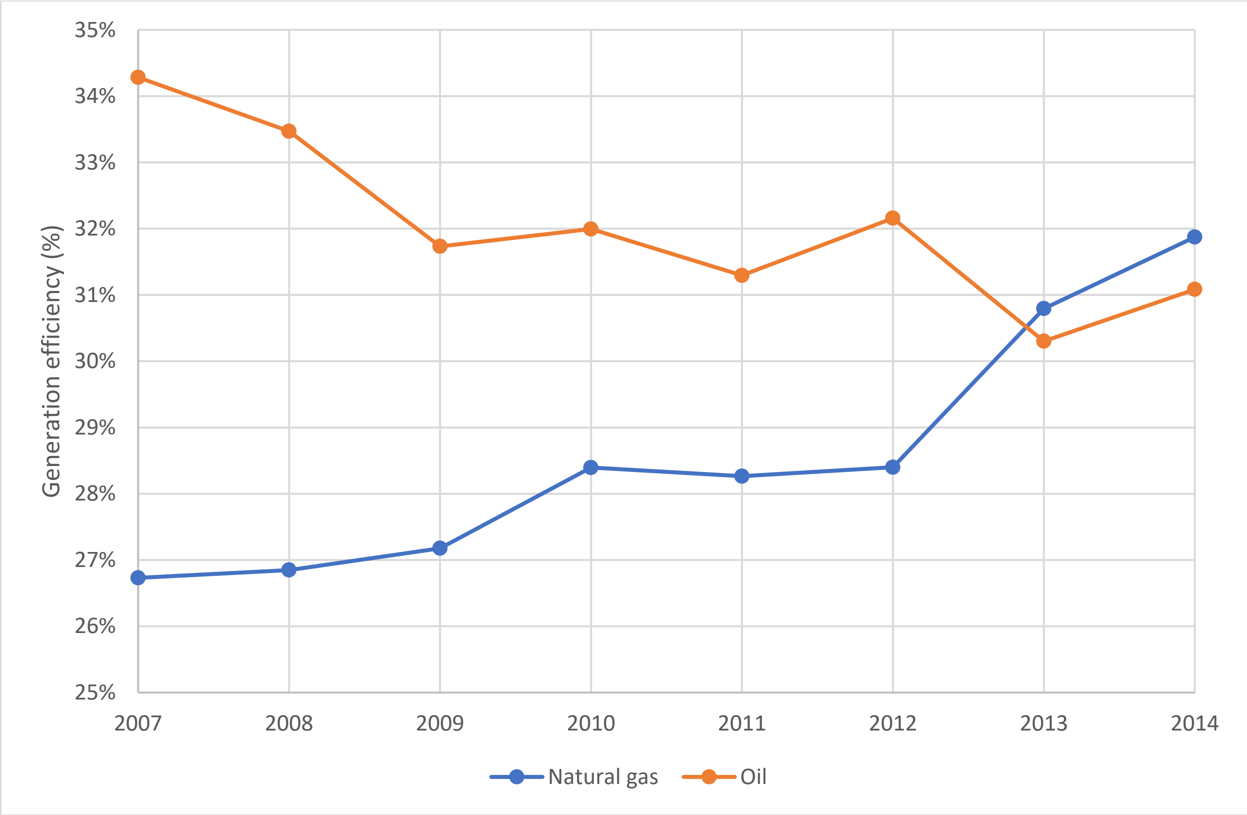

Figure 6 Power generation efficiency by fuel[33]

Figure 6 shows gross power generation efficiency for oil (crude and products) and natural gas. The efficiency of gas-fired power plants has risen somewhat over time while that for oil-fired power plants has declined. But the overall efficiency of both is low. SEC claims that the efficiency of its plants was 35.6% in 1Q 2017, compared to 34.5% in 1Q 2016[34], although as this period is cooler it would be expected that efficiency would be higher than later in the year. Nevertheless as this figure is higher than the overall efficiencies shown in Figure 6, this implies that the non-SEC power generation has low efficiency.

The hot and (along the Red Sea and Gulf coasts) humid climate, the highly seasonal load profile (peak demand in summer), and, for cogeneration plants, the requirement to co-produce desalinated water, all reduce efficiency from its theoretical maximum. Nevertheless, these efficiency factors are still very low, with over 50% achievable in realistic Gulf operating conditions for a modern combined-cycle plant running on natural gas.

Demand is highly seasonal due to air-conditioning loads (Figure 7), with a peak daytime summer load of about 60 GW, a summer night-time load of about 50 GW, contrasting to about 35 GW daytime and 25 GW night-time in winter.

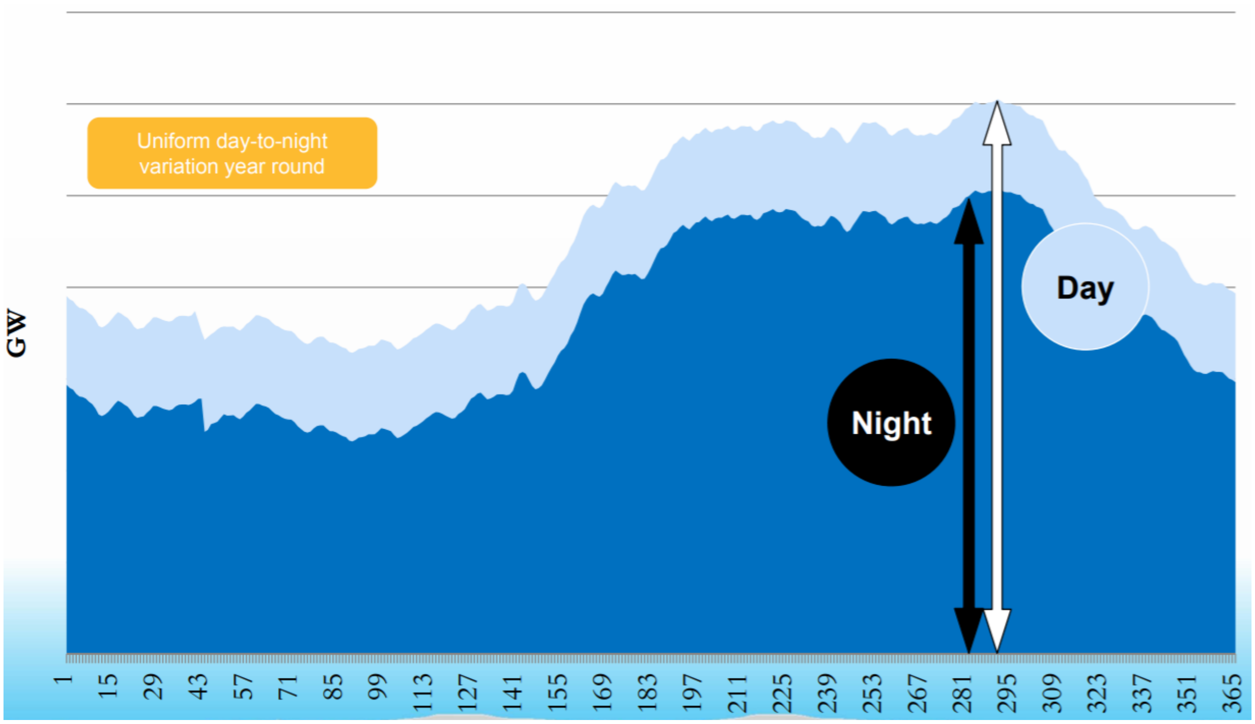

Figure 7 Annual demand pattern, day and night[35]

The daily demand pattern is shown in Figure 8. The peak in summer is reached in mid-afternoon, with maximum temperatures and hence air-conditioning load, exacerbated by poor insulation, inappropriate building techniques (e.g. glass-panelled office buildings) and use of inefficient air-conditioning units. There is a second peak around 20-21:00 when temperatures remain high and demand is driven by residential use as people return from work. Even at night consumption does not drop much, as temperatures remain high, falling only by around 6 am.

Figure 8 Forecast daily load pattern, 2032[36]

As noted, Saudi electricity prices to consumers are highly subsidised. In 2015, the average countrywide price was 2.09 US₡/kWh, with tariffs tiered by consumption, from the lowest band of 2000 kWh up to amounts in excess of 10 000 kWh. Price rises in 2016 increased the price in the main band by 20%, to 4.3 US₡/kWh[37]. However, this remains well below international benchmarks and the cost of generation (if fuel were valued at international prices). These low prices encourage wasteful consumption and make energy efficiency investments or small-scale renewable energy (such as rooftop solar panels) unattractive. SEC is vertically-integrated, and so it is not clear what proportion of its costs relate to transmission and distribution (T&D), or how the end-user subsidy is distributed between generation and T&D. Tariffs do not vary by location, and therefore remote areas are effectively being undercharged for T&D. If all costs were transparently accounted for, local renewable energy may be more cost-competitive for such localities.

Saudi Arabia has an extensive electricity grid that covers essentially the entire country apart from some uninhabited parts of the Rub' Al Khali (Figure 9). Some remote or rural areas are served by unconnected local generation (usually diesel generators) but all of the population has access to electricity. As can be

seen from the map, the east-west connections are limited with only two in operation, but more are under construction or planned.

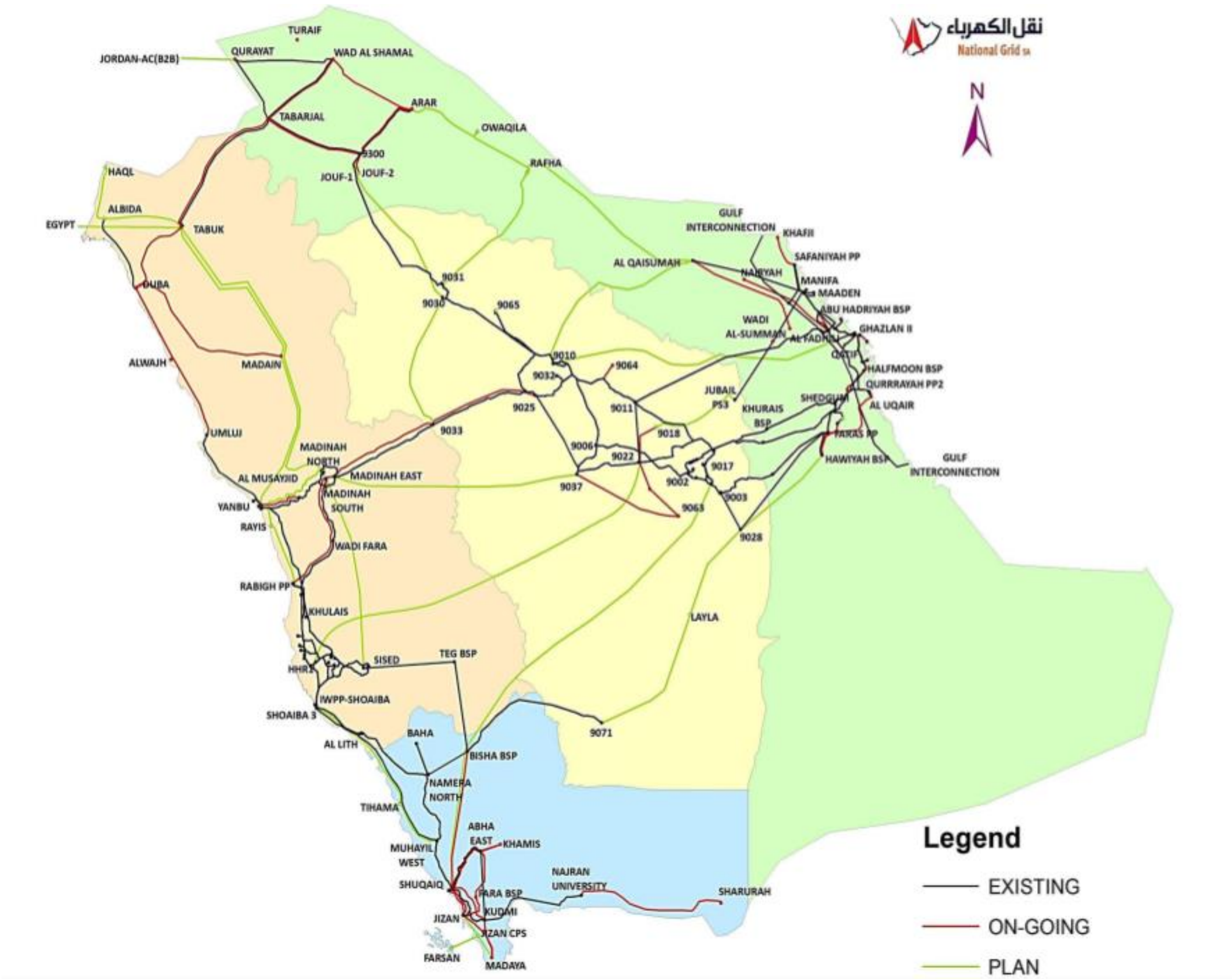

Figure 9 Saudi electricity grid[38]

Saudi Arabia is connected to the five other Gulf Cooperation Council (GCC) states via the GCC Interconnection for electricity. This has a capacity of 1200 MW to Kuwait, 1200 MW from Saudi Arabia into the interconnection, 600 MW to Bahrain, 1200 MW to Qatar and 1400 MW to the UAE (with 400 MW to Oman through the UAE)[39]. Construction of a 3000 MW interconnection with Egypt is also underway with first operations scheduled for 2019 and a connection to Jordan is under discussion.

3. Nuclear power in Saudi Arabia

Saudi Arabia's most recent interest in nuclear power dates back to December 2006, when the GCC states (Saudi Arabia, Bahrain, Kuwait, Oman, Qatar and the United Arab Emirates) announced the commissioning of a study on civil nuclear power. A number of different plans have emerged since then, as described below[40]. This list is not exhaustive and other agreements have also been concluded on research, training, etc. However, Saudi Arabia has not concluded a "123 agreement" which is required for US companies to export nuclear equipment or materials to it[41].

August 2009 – Government announcement of a national nuclear power programme

2009 – Safeguards agreement in place with the IAEA, but no Additional Protocol

April 2010 – Royal Decree announces the establishment of the King Abdullah Centre for Atomic and Renewable Energy (KA-CARE) to supervise nuclear and renewable programmes.

2011-13 – Various plans and targets announced, including site selection for reactors at Jubail on the Persian Gulf and Jizan and Tabuk on the Red Sea.

June 2011 – Plans for 16 reactors over the following 20 years (likely of ~1 GW each), costing $80 billion, generating 20% of Saudi Arabia's electricity, with smaller reactors used for desalination.

April 2013 – KA-CARE proposes 17 GW of nuclear power by 2030, plus renewable energy (see separate section). Construction was to begin in 2016.

September 2013 – GE Hitachi Nuclear Energy signed a contract with Exelon Nuclear Partners to pursue construction of its Advanced Boiling-Water Reactor (ABWR) and (ESBWR), while Toshiba/Westinghouse signed a deal with Exelon to pursue its AP1000 and ABWR reactors with KA-CARE.

January 2015 – Nuclear target date moved to 2040.

March 2015 – Korea Atomic Energy Research Institute (KAERI) signs an agreement with KA-CARE to assess building two or more SMART reactors (up to 100 MW each), including integrated desalination, with a cost for the first unit of up to $1 billion. Construction was to begin in 2018.

April 2015 – Government adviser Maher Al Odan says the country has a target of 6-7 GW of nuclear power by 2032 and 17 GW by 2040[42].

November 2015 – Announcement at a conference that Saudi Arabia has identified a number of possibly commercial uranium deposits in its territory. These include volcanic, black shale, evaporite and possibly pegmatite deposits[43].

January 2016 – KA-CARE signs with China Nuclear Engineering Corporation (CNEC) for a high-temperature reactor to be built in Saudi Arabia, based on the HTR-PM being built in China by CNEC.

September 2016 – Russia's Rosatom announces that it is ready to build 16 nuclear reactors in Saudi Arabia at a cost of $100 billion[44].

October 2016 – Saudi energy minister Khalid Al Falih announces that sites for the first nuclear plant will be chosen within the next 12 months.

January 2017 – Al Falih says that the first two nuclear reactors, totalling 2.8 GW, were in the early stages of feasibility and design studies[45].

March 2017 – Further agreement signed with CNEC on localisation of the nuclear supply chain in Saudi Arabia. Saudi Arabia announces an investment fund for its neighbour and ally Jordan, which includes uranium mining[46].

May 2017 – Program framework agreement signed with IAEA; KA CARE holds discussions with China.

24th July 2017 – National Panel for Atomic Energy established[47]. KA CARE said to be undertaking a technical study for the location of two large and two small reactors, and to explore for uranium for mining and processing its own fuel[48].

As can be seen from this timeline, Saudi Arabia's nuclear plans so far have changed frequently and involve numerous outside parties without clear progress, and with unrealistically fast timelines. However, this is not unique to its nuclear sector, as the renewable energy programme championed by KA-CARE has made similarly limited progress. Some recent activity may indicate that the pace of both the nuclear and renewable programmes is finally picking up, but it remains to be seen how effectively the new 'super-ministry' of energy and industry, under Khalid Al Falih, will be able to coordinate these complex activities while managing other initiatives such as the IPO of part of Saudi Aramco, the development of the mining sector, and the privatisation of Saudi Electricity Company.

4. Environment

Saudi Arabia's Intended Nationally Determined Contribution (INDC)[49] under the 2015 Paris climate agreement seeks to mitigate up to 130 million tonnes of CO_2 equivalent by 2030[50]. This is to be achieved by economic diversification, energy efficiency (including the conversion of single-cycle power plants to combined cycle), the use of renewable energy, carbon capture and storage, increased use of gas (by implication, to replace oil), reducing flaring, water management, public transport, reduced desertification and other measures.

The submission does not give a figure for estimated business-as-usual emissions by 2030, but estimated CO_2 emissions (excluding other greenhouse gases) from fuel combustion alone were 589.0 million tonnes in 2014 and 621.8 million tonnes in 2016[51]. The proposed mitigation is therefore about 21% of 2016

emissions. For electricity generation only, CO_2 emissions in 2014[52] were approximately 101 million tonnes from natural gas, 70 million tonnes from crude oil and 61 million tonnes from oil products, totalling 232 million tonnes[53]. In other words CO_2 emissions from electricity generation were about 40% of the total in 2014.

5. Energy Outlook

5.1. Forecasts

5.1.1. Demand

Total demand was 330.46 TWh in 2016[54] and peak load was 60.88 GW (including 2.285 GW from remote, non grid-connected locations)[55]. As noted, peak load is assumed by KA CARE to grow to 123 GW in 2032 plus another 9 GW required for desalination. Including the desalination load, that is an implied growth rate of 5% annually. The growth rate over the past ten years has been 7.4% annually[56]. However a slower rate of growth in future is reasonable given increases in electricity tariffs, efforts to promote efficiency, and the slowing of economic growth due to lower oil prices.

If the pattern of demand has not changed by 2032, then that implies total required generation would be 716.5 TWh, peak daytime summer load would be 132 GW, night-time summer load would be about 110 GW, daytime winter load would be about 77.8 GW and night-time winter load about 56.1 GW. This ignores the possibility of switching the desalination load between different periods.

5.1.2. Generation mix

Estimated generation costs for various generation technologies under Saudi conditions are shown below (Figure 10). These do not include transmission and distribution costs nor the cost of backup for intermittent resources. The fuel price assumed is $7 per MMBtu and the thermal efficiency assumed is 50% for combined-cycle gas turbines (reasonable for current best-in-class under Gulf conditions), 31% for steam turbines and 25% for gas turbines. For the purpose of calculating fuel requirements and CO_2 emissions, thermal plants are assumed to burn exclusively natural gas.

The prices for solar CSP (with 8 hours of storage) and solar PV are consistent with bids received in the UAE for recent projects, with Dubai's first CSP project attracting a bid of 9.45 ₡/kWh for 200 MW, lowered to 7.3 ₡/kWh for an expanded 700 MW plant with 11-15 hours of storage. However, since the bid cost of solar CSP at 7.3-9.45 ₡/kWh is well below previous projects (such as Morocco's Noor 3 at 15.67 ₡/kWh, despite excellent site conditions[57]), it should be regarded with caution – the project in Dubai has not yet been built or even awarded. Assumed capital cost for CSP is $3.6 million per MW, while the reported cost for the Duba and Waad Al Shamal ISCCs is $1.6 million per MW, albeit providing only a small amount of the plant's total capacity. The solar PV prices are more reliable given that there have been several bids around that level, as well as other sunny countries in Africa and Latin America.

There is little information on Saudi geothermal resources and costs were therefore taken for a typical US project; the planned capacity is small anyway so makes little difference to the analysis.

The cost for nuclear, at about 9.1 ₡/kWh, is consistent with reported costs for the UAE's nuclear programme, although given likely cost escalation and some delays, it is probably an underestimate. It is also questionable whether Saudi Arabia would be able to plan and execute a nuclear programme as quickly and cost-effectively as the UAE, particularly given its ambitions for local content. The reported capital costs are well below those for US reactors, and may represent a combination of low (or zero) land costs, lower permitting and legal costs, the absence of public opposition, lower costs for land and possibly

some materials, low (government-backed) financing costs, aggressive bids from suppliers, and over-optimism.

Advanced nuclear designs may achieve costs significantly below this[58], with a (wide) range from 3.6-9 ₡/kWh and an average of 6 ₡/kWh. Some designs for small modular reactors, being investigated by Saudi Arabia in cooperation with KAERI as noted above, are included in the study quoted, and also have potential to provide nuclear power at more competitive costs. Cogeneration of desalinated water using waste heat could also improve the overall economics. However, these plants are still in design and commercial demonstration plants are a decade away, at least. The cost estimates are also for nth-of-a-kind (NOAK) plants, i.e. incorporating substantial learning from several prior constructions, and the first-of-a-kind (FOAK) plants would cost more.

The costs do not include any future cost reduction from research and development, and therefore the costs of solar and wind in particular can be anticipated to fall; as noted nuclear costs might fall if advanced designs are developed. Saudi Arabia's initial large PV tender shortlisted two bidders at 2.342 ₡/kWh and 2.66 ₡/kWh, rejecting the lowest bid of 1.79 ₡/kWh for having insufficient local content. This shows that despite the relatively smaller size (300 MW) of its plant and the fact it was its first tender, it can receive bids similar to, even slightly lower than, those achieved in the UAE. These prices are anyway amongst the very lowest offered anywhere in the world. If Saudi Arabia seeks to achieve high local content targets, which was a major component of the original KA CARE plan, this would raise costs, although achieving wider development goals. On the other hand, its CSP conditions in the north-west are superior to the UAE's.

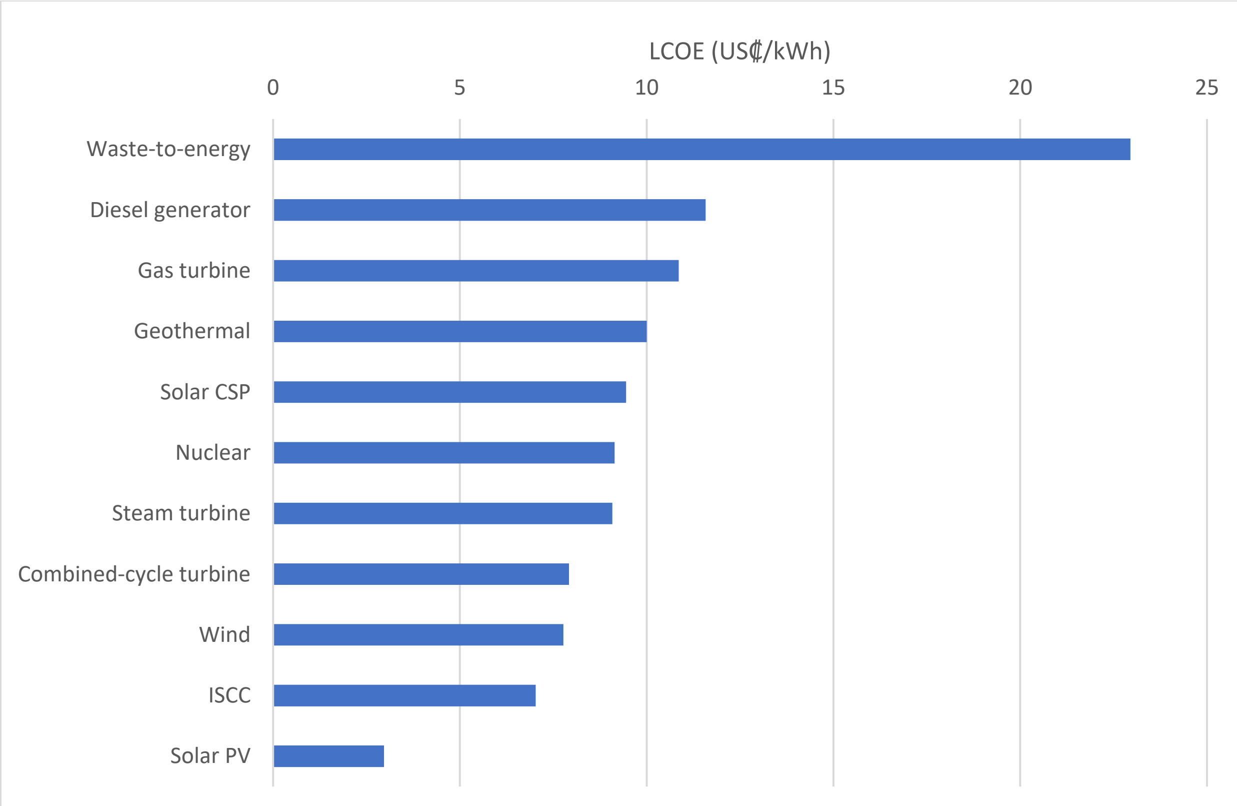

Figure 10 Generation costs under Saudi conditions[59]

These costs cannot be viewed simplistically in isolation, because a realistic generation mix, as discussed below, requires a blend of generation methods. However, it does indicate that, at the relatively high fuel prices assumed (comparable to current LNG prices, and well above current regulated Saudi domestic prices), high-efficiency combined cycle gas turbines are still cheaper than nuclear or solar CSP, which have very similar costs in this view. If the lower CSP prices seen in Dubai could be replicated, or even reduced given the favourable resources in Saudi Arabia, much more CSP could be included, given its capability for night-time storage. The CSP portion of ISCC plants, serving to boost their efficiency, is cheaper than a conventional CCGT and could be considered for inclusion in all suitably-located new CCGTs. Solar PV is extremely cheap, even if considered only as a means of saving fuel.

60% of household water consumption comes from desalination, with the remainder from groundwater, and desalination demand is growing at 14% per year[60]. This study has not assessed the provision of

desalination in detail. One study[61] has concluded that reverse osmosis plants driven by solar PV or CSP would be slightly cheaper than reverse osmosis driven by nuclear power, and that in any case all the reverse osmosis methods are much cheaper than the multi-effect distillation or multi-stage flash which currently predominates (and which is energy-intensive). It can also be observed that reverse osmosis is more flexible as it can be run when surplus electricity is available and hence function as a kind of energy storage/demand-shifting. Thermal desalination methods can be run using the waste heat from fossil fuelled or nuclear generation, but with some loss of efficiency in electricity generation.

Possible options for the 2032 generation mix are shown below. Some gas turbines have been added to the KA CARE plan to assure that peak summer daytime demand plus that the National Transformation Plan's stated 12% reserve margin can be met. Figures here assume conservatively that no wind power can be counted as firm capacity, that the GCC interconnection is not expanded, that no additional pumped hydro storage nor other storage is added, and that the Egypt interconnector is not usable to meet peak demand[62]. Coal is not considered as an option due to its polluting nature, the lack of domestic or indeed regional resources, and the energy security consequences of importing it (although some studies have been carried out, there are no plans for coal use in the country).

Only CO_2 emissions from fuel combustion are considered, not life-cycle emissions for construction and fuel production. Waste-to-energy is assumed to be carbon-neutral (its contribution in any case is small and it does not vary across the scenarios considered).

The options are constructed so that daytime and night-time summer and winter demand can be met with a minimum 12% margin, and that total generation over the year is sufficient to meet total demand. Assumed maximum annual capacity factors are 90% for all thermal, nuclear, waste-to-energy and geothermal generation; 40% for solar CSP; 20% for solar PV; and 30% for wind. CSP is assumed to have 8 hours of storage so that it can meet the early evening demand peak.

The options considered are as follows:

1) KA CARE plan as described above

2) KA CARE plan but with 18 GW of combined-cycle gas turbines replacing the planned 18 GW of nuclear

3) KA CARE plan but with an additional 21 GW of CSP (taking the total to 46 GW) replacing the planned 18 GW of nuclear

4) KA CARE plan but with no nuclear, more CSP as in option (3) and with solar PV increased from 16 GW to 74 GW

5) KA CARE plan with 18 GW of nuclear and with solar PV increased from 16 GW to 64 GW of solar PV (this saturates winter daytime demand)

6) Current system expanded to meet demand with only combined cycle oil/gas generation and currently-tendered renewables

7) Maximum build-out of nuclear to meet the minimum load (winter night-time) with CCGT meeting the rest

Capacity (GW)	**Current fleet**[63]	**2032 fleet**						
		(1) KA CARE	**(2) KA CARE, CCGT replaces nuclear**	**(3) KA CARE, CSP replaces nuclear**	**(4) KA CARE, CSP replaces nuclear; more PV**	**(5) KA CARE; more PV**	**(6) Current system expanded**	**(7) High nuclear**
Steam turbine	32	0	0	0	0	0	32	0
Gas turbine	38	21.64	21.64	18.64	10.34	13.33	38	23.8
Diesel generator	1	0	0	0	0	0	1	0
Combined-cycle turbine	10	60[64]	78	60	60	60	73.2	68
Solar PV	0.085	16	16	16	74	64	0.3	0.3

Solar CSP	0	25	25	46	46	25	0.111	0.111
Wind	0.00275	9	9	9	9	9	0.4	0.4
Geothermal	0	1	1	1	1	1	0	0
Waste-to-energy	0	3	3	3	3	3	0	0
Pumped hydro	0	2[65]	2	2	2	2	2	2
Nuclear	0	18	0	0	0	18	0	52
GCC Interconnection	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2

These scenarios are, of course, simplistic and ignore issues such as the finer scale of demand, seasonal correlations between wind and solar generation, the geographic location of generation and demand, and the time for plants to ramp up and down. They are conservative in ignoring options for storage (other than the planned pumped hydro and CSP), some level of firm wind capacity, new interconnections, or demand response.

The generation mixes are shown graphically in Figure 11, along with the peak summer daytime and night-time demand (plus the desired 12% reserve margin). Demand is shown with a business-as-usual case, and a case with Oliver Wyman's projected 27% decrease in demand through efficiency measures by 2032. It can be seen that the efficiency measures save about 40 GW of peak summer daytime required capacity and 33 GW of peak summer night-time required capacity. The two cases with large amounts of solar PV (4 and 5) have higher overall capacities because of the lower capacity factor of solar and the requirement for back-up generation at night.

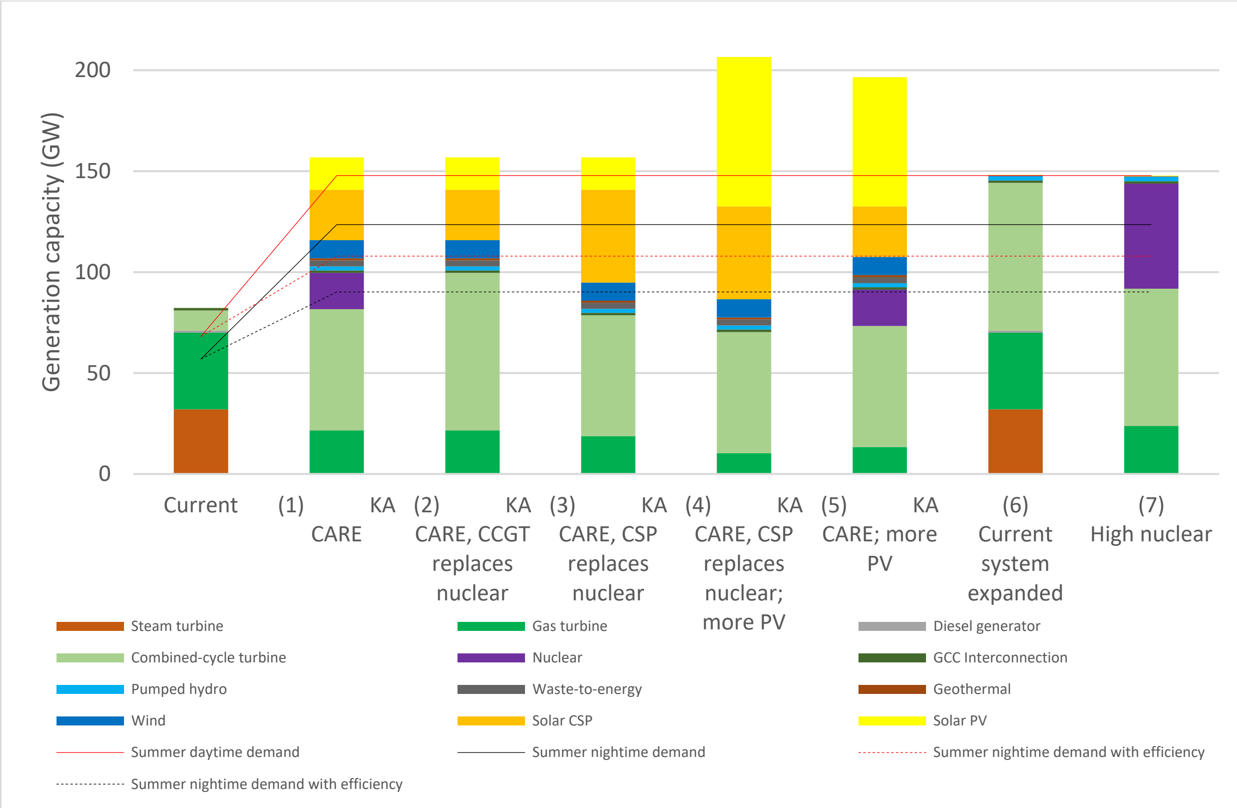

Figure 11 Generation mixes of different options

Average cost per year of the electricity generated (fuel, operating and capital cost amortisation) is shown below, along with the average gas consumption. Note that costs exclude transmission and distribution. The fuel price assumed is $7 per MMBtu as a reasonable estimate of long-term LNG import prices or the cost of producing domestic unconventional gas. This assumes the Saudi gas market is reformed so the marginal gas supply sets the price. In this case, industrial gas demand would probably fall (or at least not rise so quickly), making more gas available. Electricity tariffs would have to be increased to avoid incurring a large subsidy burden, and this would also restrain demand. However, these additional effects have been ignored at this stage for the simplicity of comparison.

If instead Aramco's average cost of supply is used, this would be significantly lower given the contribution of low-cost associated gas as well as large non-associated conventional fields. This would

make gas-fired generation appear cheaper, but at the cost of a (hidden) subsidy from Aramco to the power sector.

Scenario	(1) KA CARE	(2) KA CARE, CCGT replaces nuclear	(3) KA CARE, CSP replaces nuclear	(4) KA CARE, CSP replaces nuclear; more PV	(5) KA CARE; more PV	(6) Current system expanded	(7) High nuclear
Average gas consumption (Bcf/day)	7.55	10.2	8.83	6.93	5.98	14.93	5.69
Annual cost ($ billion)	62.1	60.4	61.5	56.5	58.0	58.3	61.7
Average cost of electricity	8.67	8.43	8.58	7.88	8.09	8.14	8.62

supplied (₡/kWh)[66]							
Annual CO_2 emissions (million tonnes)	153.3	207.1	179.2	140.6	121.3	303.9	115.8

Gas consumption is higher in all cases than current levels, since oil burning for power is assumed to be completely phased out. However, from all the options 1-5 the highest estimated gas use, in option 2, is equivalent to about 4 million TJ, while total 2014 consumption of natural gas, crude and oil products for power generation was about 3.6 million TJ. Therefore even the most fossil-fuel intensive option only has a moderate increase in consumption while doubling generation. By contrast, the option 6, relying on the current path of fossil-fuelled generation, has much higher gas (and/or oil) consumption at about 5.75 TJ.

It is not clear what proportion of the planned increase in natural gas production is intended to be devoted to the power sector. 2014 marketed production was 9.9 Bcf/day (on OPEC/BP figures; as noted, the IEA is lower) of which 4.6 Bcf/day goes to power generation, or 47% (as noted, on the IEA's figures, the share is 56%). An increase to 23 Bcf/day gross gas production by 2026, if then held constant to 2032, with an implied 20 Bcf/day of marketed gas, would mean that in the above options 1-5, power generation would consume 30-51% of available gas, while all current oil consumption for power would be freed up for export or other uses. Available gas for industry or other uses would increase from about 5 Bcf/day in 2014 to 10-14 Bcf/day in 2032, which seems sufficient to meet substantial growth. Therefore all these scenarios seem reasonable in terms of gas use, assuming the production targets are met, or domestic production is supplemented with imports. By contrast, option 6 would consume 75% of marketed gas, leaving little for industry.

If gas production only remained constant at current levels, then it could be supplemented with oil for power. Combined-cycle gas turbines would in principle have to run on clean fuels (diesel) which is significantly more expensive. However the total quantities of liquid fuels burnt in options 1-5 would be less than today's quantities except in option (2) where they would be slightly larger and (3) where they would be similar. In the fossil-fuelled current path with gas production at today's levels, oil burning would reach about 1.8 million barrels per day.

It can be seen that the five renewable/nuclear options are all rather similar in cost, since the estimates used here for CCGT (at $7 per MMBtu gas), CSP and nuclear are very close. However, adding additional PV does bring down the total cost by saving gas, given its very low costs. Adding more wind, which would also contribute at night, would also reduce gas consumption and total costs. These options are vulnerable to CSP costs, given the uncertainty in its price levels and that it is relied on to contribute to meeting summer evening peak demand. If it turned out to be significantly more expensive, then more gas-fired and/or nuclear generation would be required. Arguably about 6-7 GW of CSP is possible at low cost by hybridisation with combined-cycle gas plants, if suitable land is available near the plants. The fossil-fuelled option (6) is also similar in cost, assuming that the required volumes of fuel are available. The nuclear-heavy option (7) has a somewhat greater cost given the higher (but still probably over-optimistic) cost of nuclear assumed.

All the renewable/nuclear plans represent substantial reductions in CO_2 emissions compared to the estimated 232 million tonnes of electricity-related emissions in 2014, despite much higher total generation. This is achieved by switching entirely to natural gas instead of oil, using more efficient combined-cycle gas turbines almost exclusively, and introducing low/zero-carbon generation. Savings range from 25-112 million tonnes of CO_2 per year versus 2014, while the high nuclear (7) produces slightly less CO_2 than the most aggressive renewables option. The fossil-fuelled option (6) sees a substantial rise in CO_2 emissions, despite the use of high-efficiency CCGTs and the (assumed) replacement of all oil-fuelled generation with gas. If insufficient gas were available, the use of oil would raise emissions further.

Replacing nuclear with CCGT or solar CSP raises CO_2 emissions significantly (since solar CSP has a lower assumed load factor and hence the CCGTs run more). However, the option with much more solar PV is not only cheaper overall but has somewhat lower emissions than the KA CARE case with nuclear. Lowest emissions of all are achieved in the case with both nuclear and increased PV.

All these options would also greatly reduce most other pollutants, notably sulphur oxides from heavy fuel oil, assuming that the primary fuel is gas.

The pace of generation construction in the options presented amounts to 3.6-8.9 GW of renewables per year during 2018-2032, and up to 1.8 GW of nuclear per year (assuming a 2022 start) in the KA CARE case. This would be a significant acceleration on the current tenders for 1.7 GW of renewables. Solar capacity added in Germany per year reached a maximum of about 7 GW between 2010-12[67]. The UAE began constructing its 1.4 GW reactors in 2012 and the first is due online later in 2017. The high nuclear option (7) would require 52 GW of nuclear to be installed in 10 years (France has 63 GW total installed), a pace comparable to installing almost the UAE’s entire nuclear programme (5.6 GW) every year from 2022 to 2032. This appears completely implausible, and therefore the option is shown only for illustration.

Therefore while the renewables and the lower nuclear installation rates appear plausible, they are challenging and would require a quick start with a minimum of bureaucratic delay. More reliance on local content would also slow the programme. However, both renewables and nuclear appear to face similar challenges in terms of installation pace.

All these options assume a quite rapid conversion of current generating plant to combined-cycle operation and/or the construction of new CCGTs. The current fleet of 32 GW of steam turbines, 38 GW of gas turbines and 10 GW of CCGT has to be converted to 60-78 GW of high-efficiency modern CCGT by 2032 plus 10.3-21.6 GW of gas turbines for peaking use. If older plants are retained in service or not converted, the efficiency would be lower and hence more oil/gas fuel would be required. This study has not assessed how much of the existing fleet would be suitable for conversion to CCGT. However, even if all the additional CCGT capacity had to be newly-built, the rate of 3.5 GW per year is still feasible as thermal generation capacity has been rising at about this rate historically.

5.1.3. Efficiency

Energy use in Saudi Arabia is highly inefficient by global standards. At 6.7 tonnes of oil-equivalent per capita in 2013, the 13th-highest in the world, it was slightly behind the US (7 toe/capita) but well ahead of the EU (3.2 toe/capita) and the world average (1.9 toe/capita). As opposed to most countries, whose energy intensity has been falling, Saudi energy intensity has been rising and reached 137 toe per $1000 of GDP in 2011, ahead of 95 toe per $1000 of GDP in the EU[68].

Saudi Arabia has launched the Saudi Energy Efficiency Center, to develop the Saudi Energy Efficiency Policy, an inter-agency effort. This is focussed on industry, buildings and transport, primarily by means of benchmarking and standards. Studies have been conducted for a national District Cooling Company and a national Energy Services Company (ESCO). The programme's overall aim is to increase electricity efficiency by 30% by 2030. Building codes have been strengthened, though this will take a long time to have an impact on the existing stock, and monitoring and compliance is likely to be lacking initially.

Areas for gains in efficiency include air-conditioning, in particular, as by far the biggest user of electricity. District cooling use is low in Saudi Arabia, at less than 5%, versus 30% in Dubai[69]. More efficient air-conditioners, better maintenance and improved insulation are being targeted (70% of existing buildings are not insulated)[70]. Other promising areas include public transport such as the Riyadh Metro, under construction; appliance and vehicle efficiency standards; more efficient lighting; solar water heating; and heat pumps which could drive absorption chillers as well as providing space- and water heating.

One KAPSARC study suggests that a building retrofit programme could save 3.7-22.9 GW of peak electricity capacity, depending on the level of retrofit, with reasonably attractive payback periods, depending on the electricity price[71], though the payback periods are rather long for the higher levels of ambition.

An Oliver Wyman study[72] concluded that efficiency could cut 27% of electricity demand from the 2030 baseline (with technical feasibility up to 56%), at an assumed electricity price of 10 ₡/kWh (comparable to the numbers calculated above, particularly when transmission and distribution costs are added). If the drop in peak demand by 2032 is proportionate, then it would be reduced from 132 GW to 96 GW; i.e. the annual growth rate would fall from 5% to 2.5%.

Such efficiency gains would substantially improve the feasibility of meeting Saudi Arabia's electricity demand without nuclear power, as they would reduce the required pace of renewable and/or CCGT construction, and save on fuel demand and CO_2 emissions. Achieving efficiency gains is, though, very dependent on continuing to reform and reduce subsidies, as the low electricity and water prices do not encourage energy-saving behaviour or the use of efficient construction and equipment, and replacing them with a more targeted form of social support.

5.2. Solar

Saudi Arabia has among the best conditions for solar power in the world. Global horizontal irradiance (relevant for photovoltaic power) in Riyadh is 2242 kWh/m^2 per year (Figure 12), while direct normal irradiance (relevant for concentrating solar thermal power, CSP) is 2116 kWh/m^2 per year (Figure 13). For comparison, San Diego has 1964 kWh/m^2 and 2242 kWh/m^2 respectively. The western parts of Saudi Arabia are superior for CSP as the climate along the Gulf can be hazy and dusty.

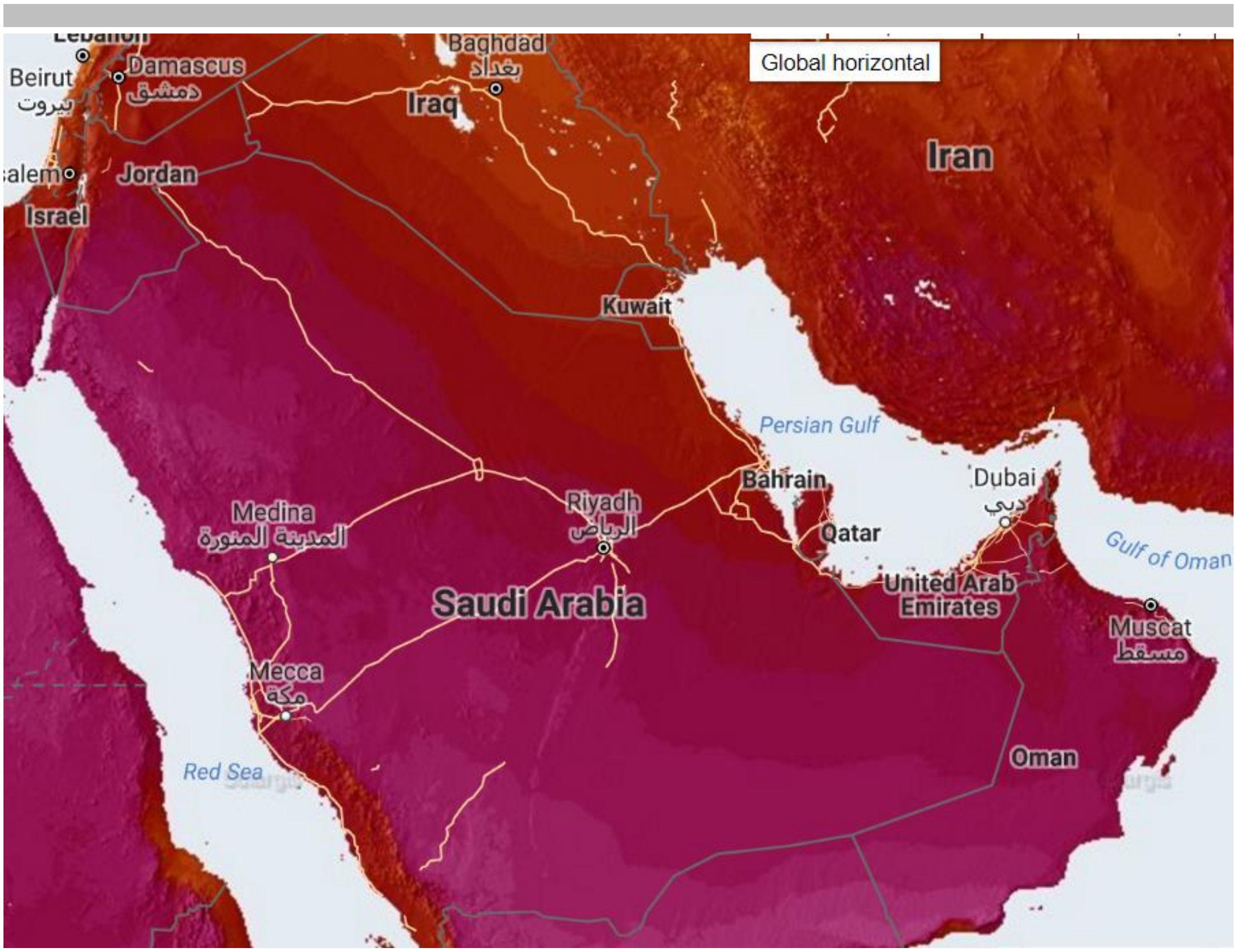

Figure 12 Global horizontal irradiation[73]

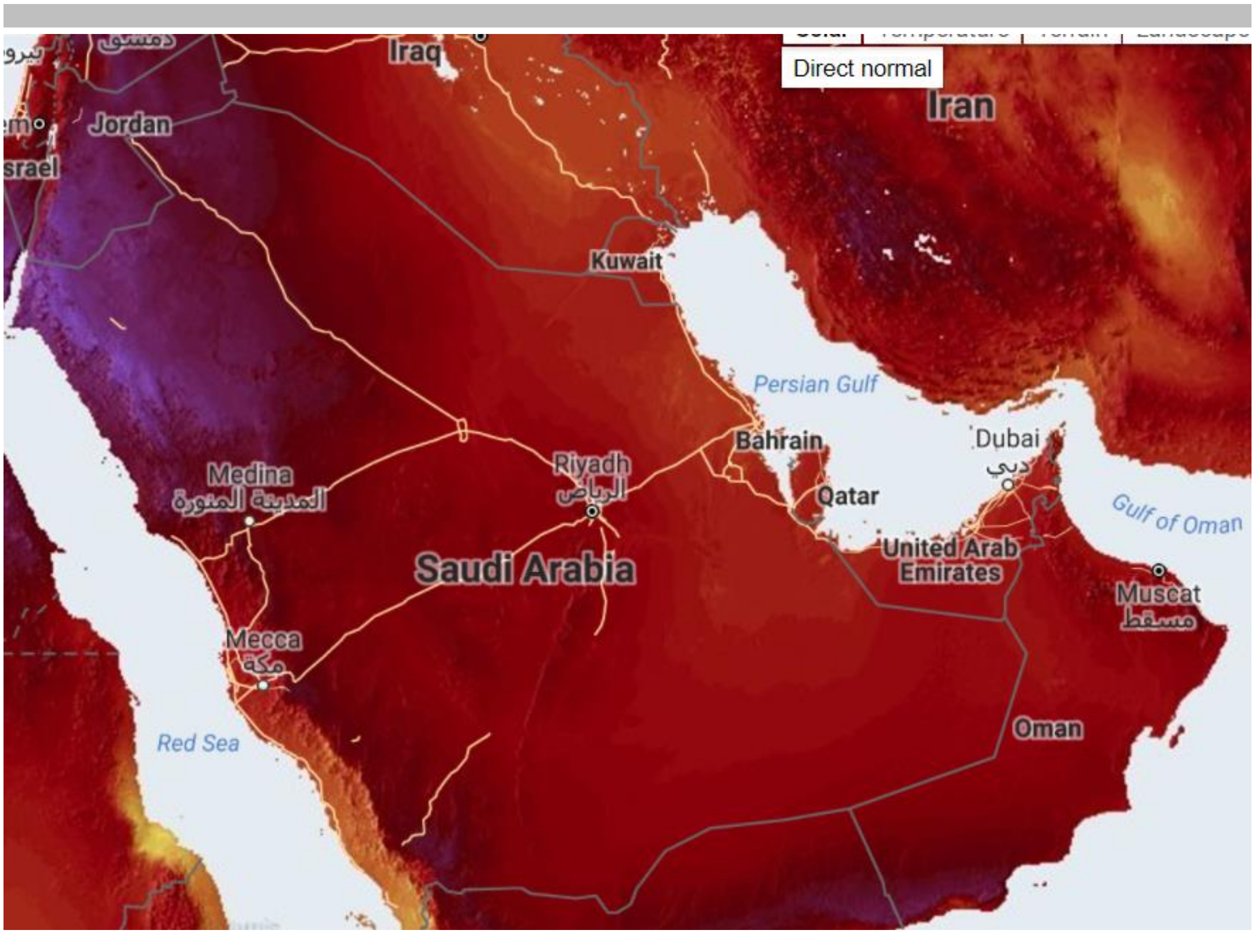

Figure 13 Direct normal irradiation[74]

As can be seen from the maps, conditions for solar PV in Saudi Arabia are at least as good as in the UAE which has launched several very successful and cost-competitive solar projects to date. Conditions in the west of the country actually appear to be superior. Conditions for CSP are similar to those in the UAE, except in the north-west where they are superior.

Concerns are often raised about the impact of dust and blown sand on the effectiveness of solar PV in the Gulf. Experience in the UAE suggests that these issues are manageable with a careful cleaning schedule and do not add significantly to operating costs[75]. Given low population densities in much of the country, and large tracts of arid land with little alternative use, finding suitable cheap land for large solar installations should not be problematic although some transmission costs may have to be incurred.

The Saudi population is concentrated on the east coast (around the oil and industrial centres of Dammam, Dhahran and Jubail), the centrally-located capital Riyadh, and the west coast with the holy cities of Makkah and Madina, the port of Jiddah and industrial city of Yanbu' (Figure 14 – this is for the year 2000 so the population has grown substantially but the overall pattern remains similar). Current demand is roughly evenly split between east, centre and west (~16 GW peak demand each) with a remaining ~10 GW in the south and Yanbu' Industrial City[76].

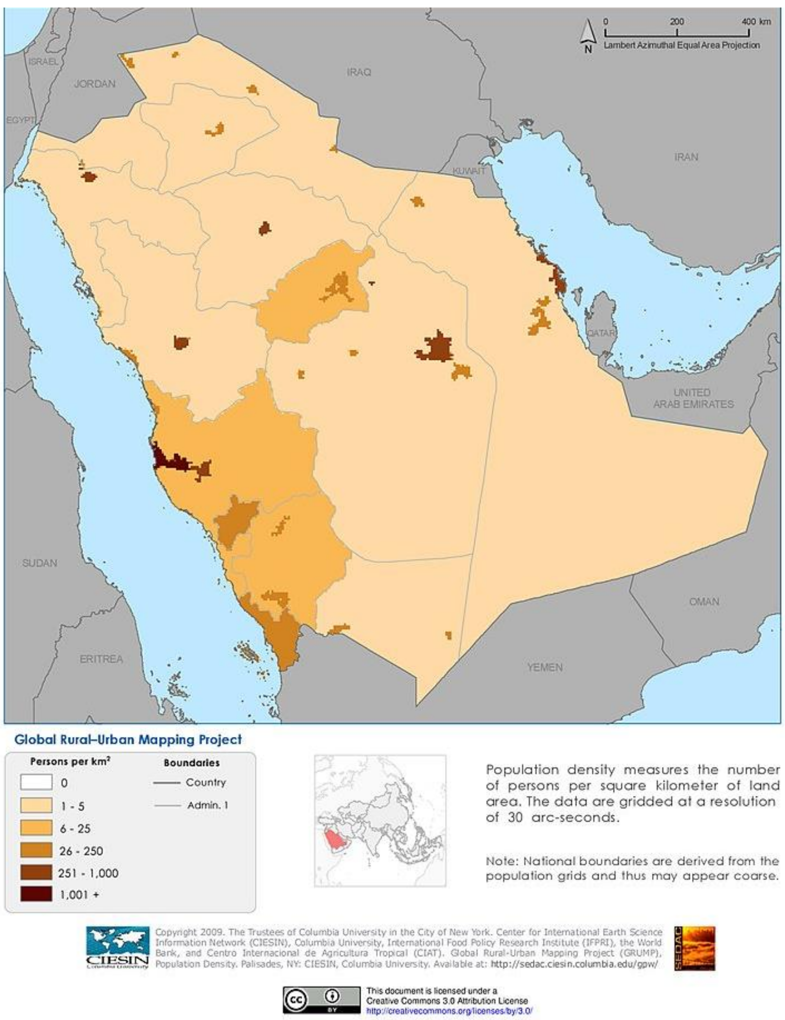

Figure 14 Saudi Arabia population density (2000)[77]

The difference in sunset times between Dammam on the east coast and the industrial city of Yanbu' on the west coast is about 40 minutes in summer. There is thus some scope for solar generation in the west to

serve the east's early-evening peak demand. The large concentration of population in the west would, however, require another solution. This could be via the new interconnector to Egypt, if surplus capacity is available there at the right time.

5.3. Wind and other renewables

The best Saudi wind resource is located on the west (Red Sea) coast, especially in the north-west around Tabuk (Figure 15). In most sites investigated, wind speed does not show much monthly variation[78].

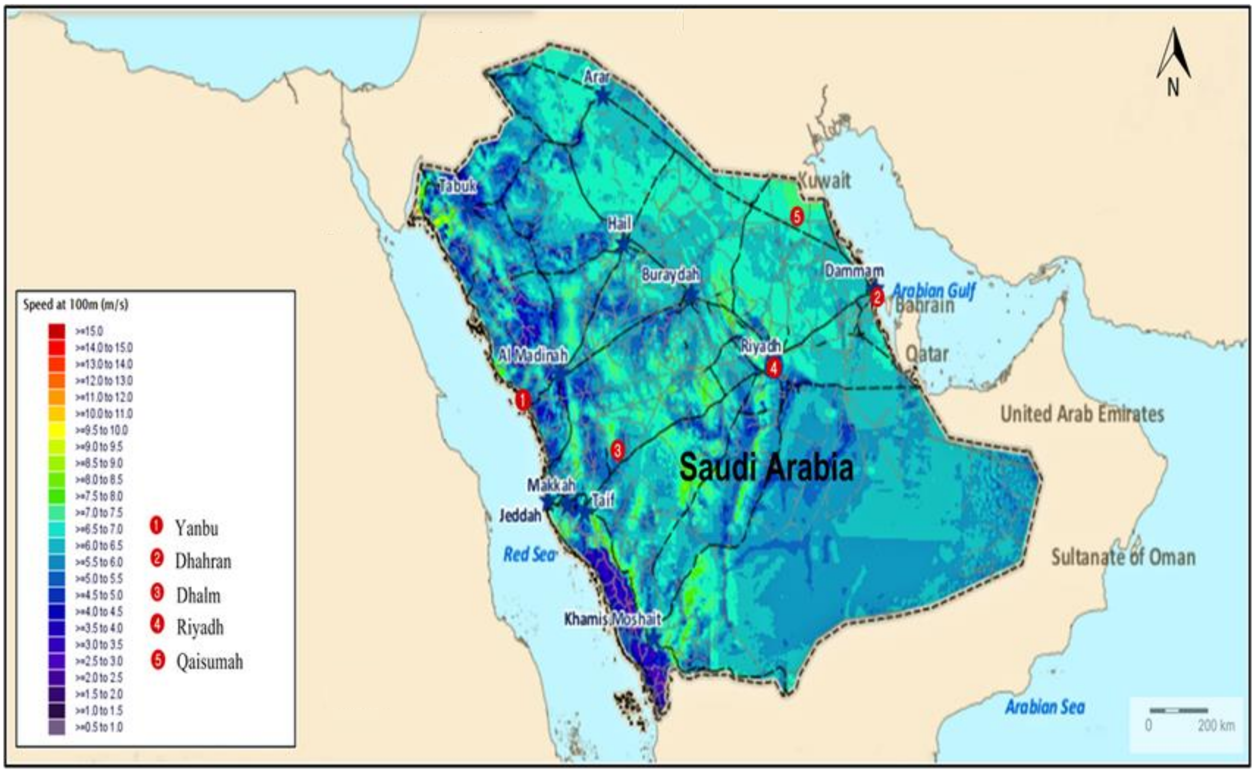

Figure 15 Map of Saudi wind resource[79]

It is assumed here that the 9 GW target given by KA CARE is feasible in terms of total capacity of suitably windy sites. No information was identified as to the ultimate wind power potential in Saudi

Arabia. With relatively low wind speeds over most of the country, larger amounts of wind power may be possible but with higher costs.

Geothermal potential is present around Jizan in the south-west where there are hot springs[80], and in various granites in the west of the country with high heat-flow[81]. Lower-temperature resources may be useful for thermally-driven cooling or desalination. Estimated potential generation is 3-5 GW and hence it is assumed here that the KA CARE target of 1 GW by 2032 is feasible.

Different studies estimate waste-to-energy potential by 2032 of 1.447-2.074 GW[82]. However a recycling policy would substantially reduce this potential (though it would be better for life-cycle emissions). The KA CARE target of 3 GW may therefore be somewhat ambitious and up to 1-3 GW of other generation may be required instead. However the KA CARE target has been used here as the impact is relatively small and it does not vary between scenarios.

5.4. Energy storage

Saudi Arabia is currently constructing two 1000 MW pumped storage facilities on the west (Red Sea) coast, one using seawater and the other desalinated water[83], with storage of 8 hours (implying 8000 MWh). Additional sites have been identified and so more storage could probably be installed if required[84].

As noted, integrated thermal storage was also assumed for the CSP plants included in the generation mix above.

Other storage options, such as batteries, have not been evaluated here, but could be useful in balancing demand and renewable output. Particularly appropriate to the Saudi climate is thermal storage, mainly for air-conditioning given its large share of load, which would be more effective if building insulation is improved. Thermal storage can include pre-cooling buildings before the hottest part of the day; or making

ice in low-demand periods (typically at night) to provide cooling during the day. Thermal storage can be integrated with district cooling plants, which are anyway inherently more efficient than individual cooling units. Another option is to use reverse osmosis plants for desalination in low-demand periods, and store the water, as noted above.

6. Security

Despite some terrorist incidents, the physical security of Saudi Arabia's oil installations has been assured by extensive defensive measures. There is therefore no unusual security risk to relying on domestic oil and gas output for energy, except in case of a total breakdown in national security (which would also badly affect demand). Large, dispersed renewable energy sites do not present a single point of failure and hence would also not be particularly vulnerable to security threats, although long-distance transmission lines could be threatened.

Any strategy depending on imports of natural gas, LNG (or coal) could be vulnerable to various supply disruptions such as boycotts, sanctions, unrest in exporting countries, or threats to maritime supply routes through the Gulf and Red Sea.

Nuclear power plants would, like the oil facilities, likely be highly fortified and built to withstand some level of plausible attacks or natural disasters. Of the sites proposed so far, Jizan is near Yemen and may be problematic given the continuing war there and some cross-border incursions and reported missile attacks. Jubail is in the Eastern Province, with a large Shi'ite Muslim population which has often complained of discrimination and where unrest is frequent. It is also relatively close to Iran with whom Saudi Arabia has poor relations at present. The third site, at Tabuk in the north-west, is relatively close to Israel, which presumably would be expected to agree tacitly to a Saudi civil nuclear endeavour, but otherwise does not present any obvious security concerns.

7. Conclusions

Saudi Arabia's fast-growing energy demand and heavy reliance on oil and gas for power generation have led to investigations of nuclear power as one component of its future energy mix. Nuclear power has been under consideration for a long period, with frequent changes of plan. Both nuclear and renewable energy have made little headway, but several tenders for solar and wind projects have recently been launched.

This study has assessed options for meeting Saudi Arabia's future energy mix, primarily considering electricity. Based on the original KA CARE plan, a number of plans with varying mixes of renewables, nuclear and fossil fuels are considered. These scenarios suggest that the 2032 demand can be met with a mix of gas-fired (highly efficient CCGT) and renewable energy at a cost comparable to, indeed slightly lower than, options including nuclear. Proposed renewable build-out rates are ambitious but should be achievable. The proposed renewable mix is primarily solar (CSP and PV), for which Saudi Arabia has excellent resources. Both the renewable and nuclear mixes deliver substantial declines in CO_2 emissions, with most oil eliminated from the power sector, and moderate increases in gas demand that should be achievable within Aramco's gas production targets.

These options do not assume significant gains in energy efficiency, which would further reduce costs, CO_2 emissions and required construction pace, nor do they optimise energy storage, or allow for continuing cost reductions in renewable (or nuclear) energy.

Nuclear power may have other strategic, technological or development-related attractions for Saudi Arabia. However, overall, it appears that it would be economically, practically, environmentally and organisationally feasible for it to meet its energy needs without resort to nuclear power.

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[1] Ref

[2] Author's interpretation based on observable Saudi policies, official statements and development plans such as Vision 2030

[3] BP Statistical Review of World Energy 2017, 'Oil – proved reserves', 'Oil Production – Barrels', 'Oil Consumption – Barrels'

[4] OPEC Annual Statistical Bulletin 2017, p8
[5] OPEC Annual Statistical Bulletin 2017, p8
[6] OPEC Annual Statistical Bulletin 2017, p8
[7] Qamar Energy graph from Joint Organisations Data Initiative (JODI)
[8] http://www.jadwa.com/en/download/natural-gas-and-the-vision-2030/gdp-report-16-6-2-1-3-3-2-1-1-1-1-1-1-1-1-1-1, p3
[9] Baker Hughes, quoted in http://www.oilandgasnewsworldwide.com/Article/34799/Work_starts_on_shale_production
[10] http://www.epmag.com/saudi-shale-drive-powers-850356#p=full
[11] Oman exports LNG but the plant runs below capacity because of a shortage of feedstock; it is negotiating with Iran for gas imports. Egypt may again become a marginal gas exporter with development of its Zohr field, but any excess is likely to be exported through currently mothballed LNG plants on the Mediterranean coast.
[12] http://www.reuters.com/article/us-saudi-plan-saudi-aramco-gas-int-idUSKCN0YS2MS
[13] https://www.reuters.com/article/us-russia-saudi-novak-idUSKBN19R1RF
[14] http://www.epmag.com/saudi-shale-drive-powers-850356#p=full
[15] http://www.reuters.com/article/us-aramco-gas-idUSKBN1541PK
[16] OPEC Annual Statistical Bulletin 2016, http://www.opec.org/opec_web/static_files_project/media/downloads/publications/ASB2016.pdf ; BP Statistical Review of World Energy 2017 for year 2016
[17] International Energy Agency, Medium Term Gas Report 2014, 2015, 2016, 2017; Middle East Economic Survey volume 60 number 28 (14th July 2017), p2
[18] http://www.jadwa.com/en/download/natural-gas-and-the-vision-2030/gdp-report-16-6-2-1-3-3-2-1-1-1-1-1-1-1-1-1-1
[19] http://www.iea.org/statistics/statisticssearch/report/?year=2014&country=SAUDIARABI&product=NaturalGas
[20] http://www.oxfordbusinessgroup.com/news/saudi-arabia-plans-diversify-power-sources
[21] http://www.oxfordbusinessgroup.com/news/saudi-arabia-plans-diversify-power-sources
[22] Saudi Electricity Company
[23] Middle East Economic Survey (8th January 2016), Volume 59, Number 1, p8; Walid Matar and Murad Anwer (October 2017), 'Jointly reforming the prices of industrial fuels and residential electricity in Saudi Arabia', Energy Policy, Volume 109, p747-756
[24] http://www.mesia.com/wp-content/uploads/MESIA-Outlook-2016-web.pdf
[25] http://www.saudiaramco.com/en/home/news-media/news/first-wind-turbine.html
[26] There are some solar hot water systems
[27] http://tracker.newenergyupdate.com/technology/saudi-arabia%E2%80%99s-first-iscc-plant-set-record-low-csp-cost
[28] https://www.apricum-group.com/saudi-arabia-announces-9-5-gw-renewable-energy-target-new-king-salman-renewable-energy-initiative/
[29] https://www.pv-magazine.com/2017/01/17/wfes-2017-saudi-arabia-announces-new-energy-master-plan/, http://www.reuters.com/article/us-saudi-plan-renewable-idUSKCN0XM2AD
[30] https://www.thenational.ae/business/energy/saudi-arabia-looks-past-oil-and-re-starts-wind-ambitions-1.609330
[31] BP Statistical Review of World Energy 2017, 'Solar Consumption – TWh', 'Electricity Generation'; International Energy Agency http://www.iea.org/statistics/statisticssearch/
[32] Data from International Energy Agency http://www.iea.org/statistics/statisticssearch/
[33] Calculated from data from International Energy Agency http://www.iea.org/statistics/statisticssearch/
[34] Saudi Electricity Company
[35] https://www.irena.org/DocumentDownloads/masdar/Abdulrahman%20Al%20Ghabban%20Presentation.pdf
[36] King Abdullah Centre for Atomic and Renewable Energy (KA CARE)
[37] http://www.jadwa.com/en/download/natural-gas-and-the-vision-2030/gdp-report-16-6-2-1-3-3-2-1-1-1-1-1-1-1-1-1-1
[38] https://www.se.com.sa/en-us/Lists/NGReports/Attachments/2/NG_2016_AR.pdf, p33 (in Arabic)
[39] http://www.epcc-workshop.net/Presentations/EPCC2015-Presentation13_Al-Shahrani-GCCIA.pdf

[40] Material in this list is based primarily on http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/saudi-arabia.aspx, with other sources noted where used.
[41] https://www.nei.org/Issues-Policy/Exports-Trade/Nuclear-Export-Agreements
[42] https://www.bloomberg.com/news/articles/2016-10-20/saudi-arabia-to-select-nuclear-power-plant-site-very-soon
[43] http://www-pub.iaea.org/mtcd/meetings/PDFplus/2009/cn175/URAM2009/Session%203/05_88_Howari_USA.pdf
[44] http://www.arabianbusiness.com/russia-s-rosatom-says-ready-build-16-saudi-nuclear-power-stations-644543.html
[45] http://fortune.com/2017/01/16/saudi-arabia-renewable-energy-program/
[46] http://www.thenational.ae/world/middle-east/saudi-arabia-to-set-up-3bn-joint-investment-fund-for-jordan
[47] http://www.arabnews.com/node/1134776/saudi-arabia
[48] Middle East Economic Survey Volume 60, Number 30, p.7
[49] http://www4.unfccc.int/Submissions/INDC/Published%20Documents/Saudi%20Arabia/1/KSA-INDCs%20English.pdf
[50] Including carbon dioxide, and other gases such as methane and nitrous oxides at their CO_2-equivalent warming potential.
[51] BP Statistical Review of World Energy 2017, 'Carbon Dioxide Emissions'
[52] 2014 is considered since IEA figures are not available for 2015 and 2016, and there is a considerable unexplained discrepancy between EIA and Saudi Electricity Company figures
[53] Author's calculation from IEA consumption figures and emissions factors from IPCC, https://www.ipcc.ch/meetings/session25/doc4a4b/vol2.pdf
[54] BP Statistical Review of World Energy 2017, 'Electricity Generation'
[55] http://www.ecra.gov.sa/en-us/DataAndStatistics/NationalRecord/StationCapacities/Pages/Home.aspx
[56] BP Statistical Review of World Energy 2017, 'Electricity Generation'
[57] https://www.thenational.ae/business/24-hour-solar-power-is-possible-for-mena-1.40805
[58] http://innovationreform.org/wp-content/uploads/2017/07/Advanced-Nuclear-Reactors-Cost-Study.pdf
[59] Qamar Energy research; EIA
[60] https://www.ifri.org/sites/default/files/atoms/files/note_arabie_saoudite_vf.pdf
[61] http://www.aub.edu.lb/ifi/publications/Documents/policy_memos/2016-2017/20170215_solar_nuclear.pdf
[62] This is on the grounds that, as the sun sets in western Saudi Arabia and solar output falls, Egypt would be entering its own peak evening demand period.
[63] 2015, http://www.ecra.gov.sa/en-us/MediaCenter/DocLib2/Lists/SubCategory_Library/Statistical%20Booklets%202015.pdf
[64] Assumed that all thermal generation in KA CARE plan would be combined-cycle burning either gas or diesel
[65] Not explicitly in the KA CARE plan, but under construction today
[66] Excluding transmission & distribution costs
[67] http://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/zeitreihen-zur-entwicklung-der-erneuerbaren-energien-in-deutschland-1990-2015.pdf
[68] https://www.ifri.org/sites/default/files/atoms/files/note_arabie_saoudite_vf.pdf
[69] http://www.swedishepa.se/Documents/konferensdok/hfc2016/04-saad-saudi-presentation-updc-focus-areas-r.pdf
[70] https://www.iea.org/policiesandmeasures/pams/saudiarabia/name-147402-en.php
[71] https://www.kapsarc.org/wp-content/uploads/2016/10/KS-1655-DP049A-Evaluating-Building-Energy-Efficiency-Investment-Options-for-SA_web.pdf
[72] http://www.oliverwyman.com/content/dam/oliver-wyman/global/en/files/archive/2013/Energy_Efficiency_inMiddleEastFINAL.pdf
[73] https://solargis.info/imaps/#c=25.918526,41.813962&z=5
[74] https://solargis.info/imaps/#tl=GeoModel:dni_yr_avg&c=24.806682,42.604978&z=5
[75] First Solar and Masdar personnel, personal communication
[76] https://www.irena.org/DocumentDownloads/masdar/Abdulrahman%20Al%20Ghabban%20Presentation.pdf
[77] http://sedac.ciesin.columbia.edu/data/set/grump-v1-population-density/maps/6
[78] http://www.ijastnet.com/journals/Vol_5_No_3_June_2015/2.pdf

[79] https://www.researchgate.net/figure/306068825_fig17_Fig-2-Wind-speed-in-Saudi-Arabia-at-the-height-of-100-m

[80] http://www.thinkgeoenergy.com/saudi-arabia-eyeing-geothermal-energy-for-future-energy-mix/

[81] http://www.bu.edu.eg/portal/uploads/Science/Geology/3501/publications/Aref%20Adel%20Ahmed%20Elaraby%20Lashin_01014.pdf

[82] http://www.sciencedirect.com/science/article/pii/S1364032116300223, Ouda, O.K.M. 'Assessment of Waste-to-Energy Potential in Saudi Arabia as Electricity Source & Environmental Protection Measure' Prince Mohamed Bin Fahd University

[83] http://www.afconsult.com/en/newsroom/press-releases/all/2015/af-is-awarded-a-new-contract-for-consulting-services-for-pumped-storage-hydro-power-plant-in-saudi-arabia/, http://www.isaet.org/images/extraimages/P1215236.pdf

[84] https://www.slideshare.net/SNC-Lavalin/130715-hydrovision-paper-v3