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Investigating Solutions for Peak Electrical Demand in Central Region, Saudi Arabia

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INVESTIGATING SOLUTIONS FOR PEAK ELECTRICAL DEMAND IN CENTRAL REGION, SAUDI ARABIA

by:

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ABSTRACT

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by

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Under the Supervision of Professor David Yu

This thesis studies the electrical power challenges of the Central Region, Saudi Arabia. This includes a look into the geography of Saudi Arabia, to assess the lack of traditional power sources such as coal and hydroelectric. Next, a comprehensive look into the nature of demand in Riyadh, which include the demand types, and comprehensive data about the peak demand and the times associated with it. A problem of very high peak demand that is unique to the region is identified. Then, a study into current electric generation methods to meet this demand, and the associated technologies and fuel costs. This thesis then goes on into discussing the current implemented solutions to reduce peak demand by the Saudi Electricity Company, and then a further discussion about possible further improvements to the system, which includes a study of renewable energy resources, which includes solar and wind. These proposed solutions were evaluated for cost and return on investment, with a particular interest into the price of crude oil.

To

my mother,

my father,

and especially my country

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KWh	Kilowatt Hour
MWh	Megawatt Hour
SEC	Saudi Electricity Company
A/C	Air Conditioning Unit
GW	Gigawatt
CCCT	Combined Cycle Combustion Turbine
SCCT	Simple Cycle Combustion Turbine
O&M	Operation and Maintenance
LCOE	Levelized Cost of Energy
CSP	Concentrated Solar Power
ROI	Return on Investment

ACKNOWLEDGMENTS

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A tremendous thank you to Dr. David Yu, who saw my potential and agreed to take me under his wing. Without his continued support, such a complex and new area of research would have not been undertaken.

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I dedicate this research to my family. To my mother, who has never stopped inspiring me to achieve more in all aspects of life. To my father, who has always been my anchor and my rock no matter what the conditions are. To my brothers and sisters, who stood by me and supported me in this journey. I also dedicate this research to my country and my home, it has been the cause, the inspiration, and the motivation behind completing this project.

Chapter 1: Introduction

The central region of Riyadh, Saudi Arabia faces a set of very unique challenges in terms of electrical grid demand and supply. These issues are almost unique to the area and the region, and not many other grid planners around the world face similar issues. These issues span a wide range of scopes, including geography, demographics, economics, weather, and the hard realities of electrical engineering specifications.

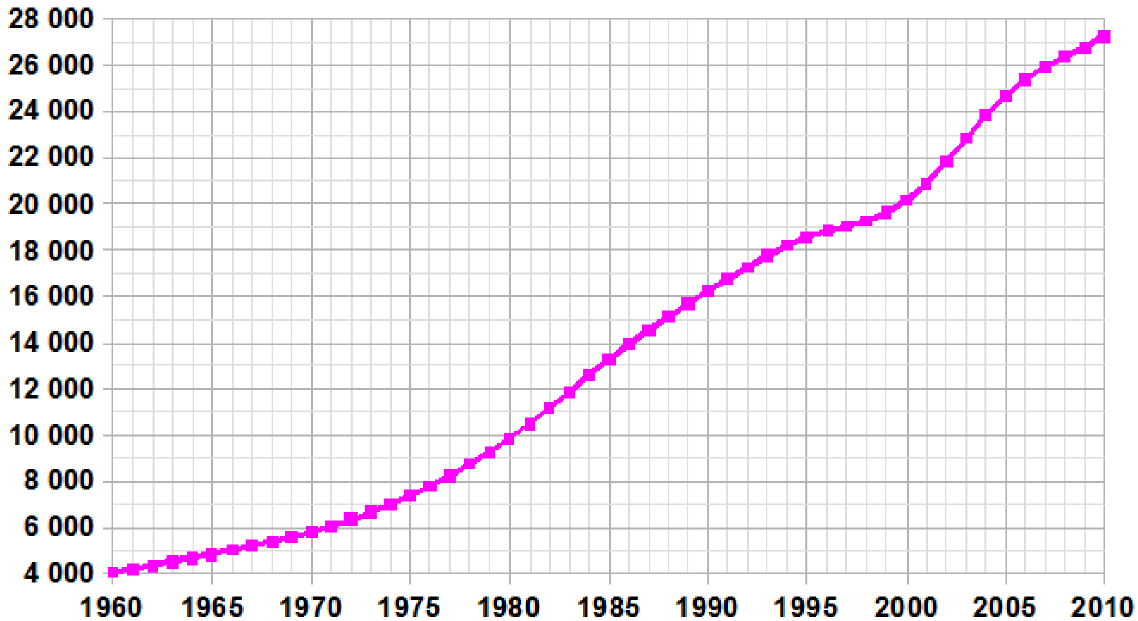
Geography

[Figure 1: Map of Saudi Arabia, Google Maps, 2016]

Riyadh is located in the center of Saudi Arabia, with multiple deserts surrounding it from all sides. It does not have any rivers running next to it, and there are no high-speed winds areas in the region. Also, Saudi Arabia as a country does not have any sources of natural coal. This has many implications on electric power generation, since no rivers or reservoirs means that there are no feasible sources for hydroelectric power. The lack of high-speed winds also limits the use of wind power generation on a big scale. These, combined with the lack of coal in the region, means that electric power generation relies almost totally on natural gas and oil (both crude and oil derivatives). Furthermore, since the region is very dry, water desalination is also operated using these same traditional fossil fuels, which puts a further strain on electric power generation.

Demographics:

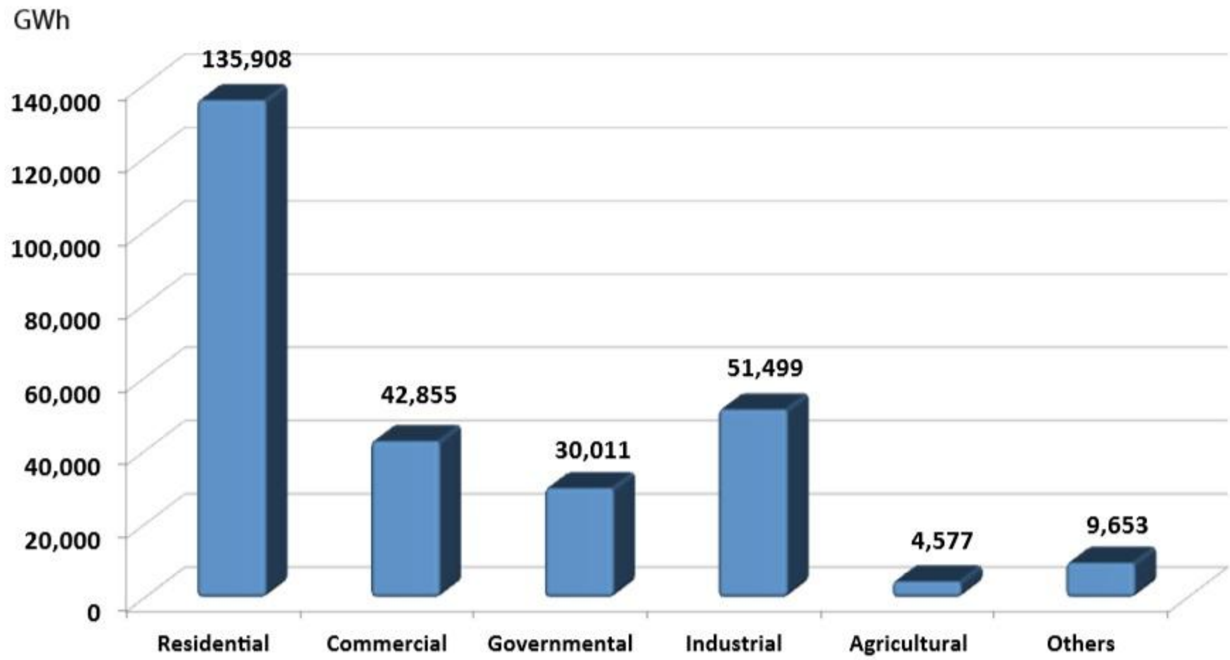
The central region is home to Riyadh; the capital city of Saudi Arabia and the largest city in the country. The region's population is estimated to be 6.77 million [2010 Census]. The region's population is also young, with an average age of 26 years [2010 Census]. This is also coupled with the fact that most of region is very urbanized, with very little rural or semi-rural communities surrounding the city. In terms of the electric grid, this translates into a very high electric demand per-capita, averaging around 8,741 KWh per year, compared to the United States of 12,988 KWh per year [CIA Fact book 2014]. The region is growing extremely rapidly as well, with an average increase of overall electric demand of 6.5% per year [SEC Electrical data 2000-2014].



[Figure 2: Demographics of Saudi Arabia, Data of FAO, year 2005; Number of inhabitants in thousands.]

Economics:

Saudi Arabia is an oil-producing nation primarily, and while per-capita income is relatively high (GDP PPP is 55,229$ compared to the United States of 59,407$ [IMF, 2016]), most of the economic activity happens near the oil wells and at the coast away from the capital Riyadh. While Riyadh is the biggest city, and the most prosperous, the economic activity there is of the nature of managerial and office work, instead of factories or hard industry. In terms of the electrical grid, this translates into home and office loads on the network, and little production or factory demands. Since office and home loads happen primarily in the morning, and it is not possible to shift those loads to night time, the bulk of the demand concentrates during that time.



[Figure 3: Consumption types in 2014 for Saudi Arabia, SEC Electrical Data 2000-2014]

Weather:

Since the city is located in a desert region, the temperature in the summer reaches 49+ C (120+ F). This, combined with the fact that the city is highly urbanized and well-off economically, means that most of the population use A/C units quite extensively in the summer. In terms of electrical demand, that results in a very sharp peak during mid-day in the summer months.

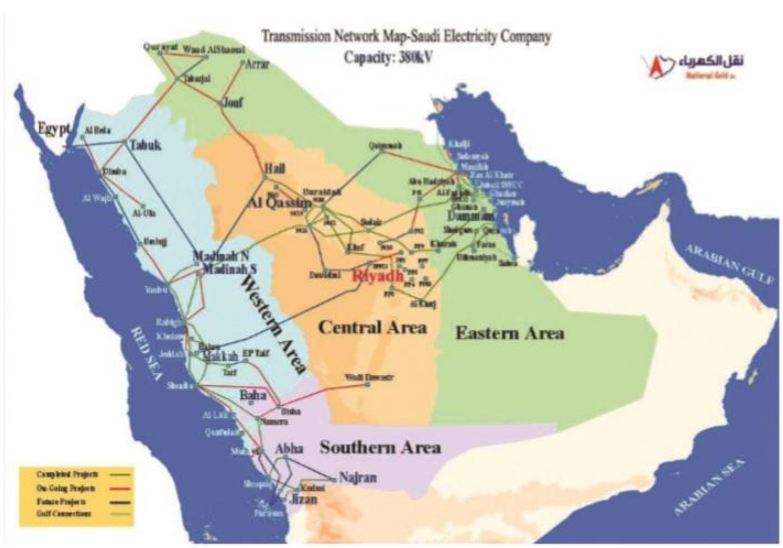
The presence of dust storms and other air-born particles is also an issue for an extended part of the year. While the dust itself does not affect the demand curve by a large margin, it might interfere with any PV solar power generation capacities.

Chapter 2: The Electrical Grid in Saudi Arabia

Electrical Market Structure:

The electrical power system in the country is mostly owned and operated by the Saudi Electricity Company (SEC) and its various subsidiaries. As of 2014, the Saudi government owns a majority share of SEC (74%) [SEC Annual Report 2014], and therefore has influence on how the company operates. This however is not without its merits, since the company benefits from low interest loans and grants given directly to the company, which helps drive the overall cost of capital and operation down. Since the Saudi government also owns Saudi Aramco (the oil producing company in Saudi), it sells fuel to SEC at discounted prices, which also helps with lowering the overall costs for SEC. This however makes investigating the operating costs of SEC a very messy affair, since both capital and fuel are subsidized at various levels, and these levels are subject to changed year-by-year depending on the economic situation of the country.

The Grid Structure and Electrical Regions



[Figure 4: Transmission Network Map, SEC Electrical Data 2000-2014]

The electrical grid in Saudi Arabia is divided into 4 main areas; Central, Eastern, Western, and Southern. The Central region, which covers Riyadh, Al Qassim, and Hail is the largest in terms of population numbers and electrical demand. It serves approximately 8.5 million people [2010 Census] and represents 30% of all electrical energy sold in Saudi Arabia.

This paper will focus exclusively on the Central electrical region. This is due to the fact that it is the largest and most dynamic, and the issues that the region is facing are the same that the other regions are facing, albeit on a larger scale.

Central Region Demand Structure:

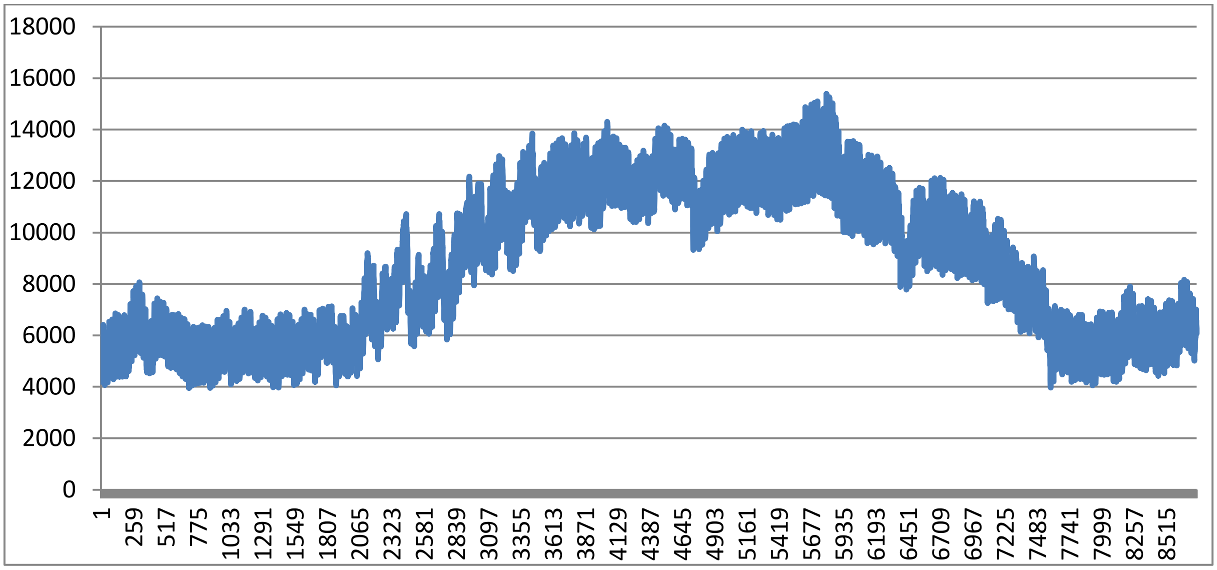
As with the rest of Saudi Arabia, the demand in the central region comes mainly from residential and commercial loads, with very little industrial or agricultural demand.

2015	Residential	Commercial	Industrial	Health & Educ.	Agricultural	Governmental	Desalination
Q1	40.9%	16.4%	26.2%	0.7%	2.0%	13.5%	0.4%
Q2	49.7%	15.4%	17.3%	0.9%	1.8%	13.6%	1.4%
Q3	56.4%	16.6%	11.5%	0.8%	1.8%	12.1%	0.7%
Q4	48.6%	18.0%	12.5%	0.7%	1.9%	16.8%	1.4%

[Table 1: Demand in Central Region by Type, SEC Internal Data 2016]

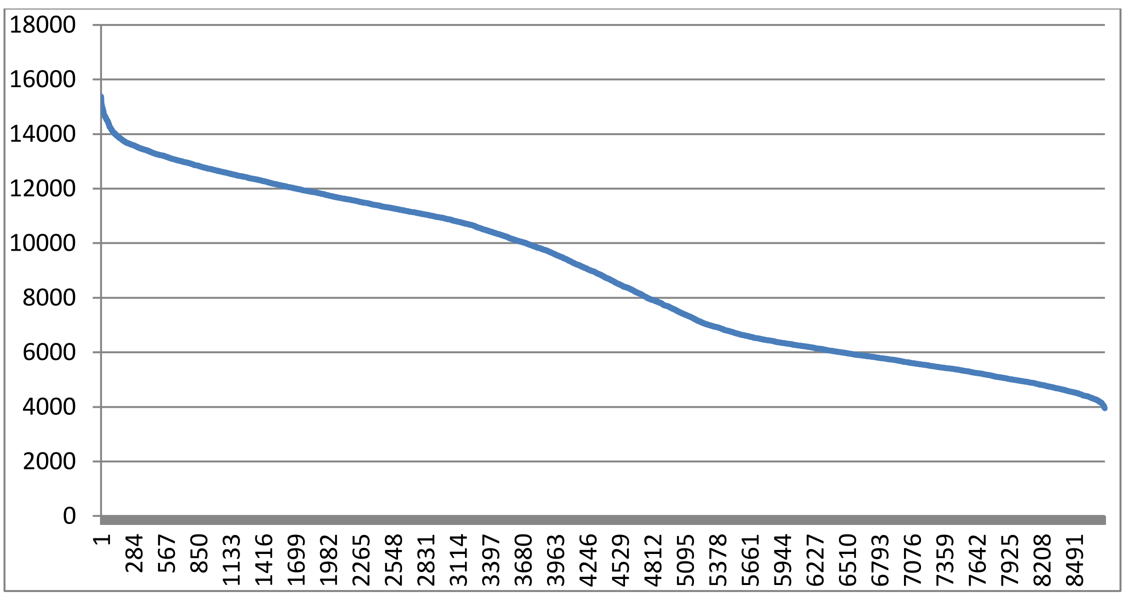
These residential and commercial loads have a large air-conditioning (A/C) demand component, due to the high temperatures of the summer months. The contribution of A/C to the demand reaches 70% of all connected loads [SEC Internal Data 2016]. This in turn leads to a

demand profile that is very odd, with very high peak demand around noon in the summer months.



[Figure 5: Hour-by-hour demand for Central region in GW, 2015, SEC Internal Data 2016]

The load duration curve for the region illustrates this more clearly, with a very sharp peak for the top 100 hours of demand.



[Figure 6: Load Duration curve for central region, 2015, SEC Internal Data 2016]

Taking a closer look at the numbers, we find that the average demand is 9 GW, with a base (lowest) demand of 4 GW. The absolute peak demand is 15.3 GW.

Investigating the peak demand itself, we find that the spike is sharp, with very few hours contributing to the towering peak. The 100 hours of demand that are the highest actually contribute to 1.2 GW of electrical demand. We will call this demand 'the 100-hour peak', and it will be the subject of further analysis.

Future Demand Trends

If we use the '100-hour peak' as a benchmark for improvement, any solution will have to take into account the future growth of the demand. Based on SEC data, peak demand is growing at a rate of 7% per year [SEC Electrical Data 2000-2014]. Therefore, the '100-hour peak' will increase from 1.2 GW in 2015 to 4.64 GW in 2035 (20-year period).

Generation Methods:

Current power generation methods in the central region are exclusively fossil-fuel based, with little to no contribution from renewable, nuclear, or hydropower. The generation consists of: Combined Cycle Combustion Turbine (CCCT) power plants (usually running on natural gas), Simple Cycle Combustion Turbine (SCCT) power plants (usually running on crude oil), and Diesel power plants.

The CCCT units, using natural gas, act as the base demand generation method for the network. The diesel power plants act to stabilize the network and contribute to the peak demand. The job of satisfying mid-and-peak demand falls on the SCCT units, which run on crude oil.

The hot summers in the area combined with this setup results in a heavy usage of crude oil to meet the demand, as shown below:

	Diesel	Crude	Gas
Jan	12.9%	14.3%	72.8%
Feb	11.8%	17.2%	71.0%
Mar	11.2%	14.9%	73.9%
Apr	9.0%	25.5%	65.6%
May	10.0%	48.1%	41.9%
Jun	6.1%	57.4%	36.5%
Jul	6.9%	55.9%	37.2%
Aug	7.3%	58.8%	33.8%
Sep	7.1%	50.6%	42.3%
Oct	7.4%	41.8%	50.8%
Nov	11.3%	29.9%	58.8%
Dec	9.8%	27.2%	63.0%

[Table 2: Fuel Usage by Type, SEC Internal Data 2016]

This is considered a huge issue for the government of Saudi Arabia, since both the oil and the electricity are subsidized, large costs are incurred without any revenue to offset it. If this oil is exported instead of used, it would create a much larger profit margin.

Potential for Improvement

Upon further investigation, the main chunk of the cost of peak demand occurs in the form of initial costs and fuel costs. Initial costs include instillation of electric power generation capacity to meet the peak demand during mid-day of the summer months. Fuel cost is associated with crude oil prices.

This is the main focus of this paper: to quantify the peak demand capacity during the top 100 hours. Then, estimating the initial capital costs of these 100 hours. Then, to investigate how the current solutions fare in terms of reducing that cost, and what future technologies can be implemented to drive that cost down or have a cheaper solution than just conventional power sources.

Chapter 3: Regulation and Policies and their Effect on Peak Demand

The government of Saudi Arabia along with the SEC have been investigating several ways to reduce peak electrical demand (and demand in general) from the consumer side using various policies and regulations. Chief among those are the regulations dealing with A/C units, since their consumption accounts for 70% of the demand in the region [SEC Electrical Data 2000-2014].

Reduction of Electrical Loads through building insulation

The Saudi government on 2010 issued a royal decree on the application of thermal insulation as a mandatory rule for all new buildings whether residential or commercial, or any facilities and other constructions like government buildings in major cities of the Kingdom's regions.

This has translated into the SEC issuing its brochures in May 2015 outlining the various applications and benefits of the new policy for both the consumers and the nation. SEC published data estimates that a proper installation of thermal insulation would reduce A/C loads by 30-40% [SEC thermal insulation brochure 2015].

This reduction of A/C loads has not been achieved yet on a large scale, since the regulation applies to newly built buildings and ones under renovations, but does not apply to currently standing buildings in operation.

However, the effect of this policy is supposed to become more pronounced with time, since currently Saudi Arabia is experiencing a construction boom. SEC estimates that in 20 years (2035), most buildings would have thermal insulation installed which would make their A/C load

reduction of 30-40% a reality. This claim however requires further investigation, particularly, the 30-40% reduction.

Investigation SEC's claim by independent research

The nature of measurement of electrical load reduction through building insulation is a very complex problem. The laws of thermodynamics make the problems non-linear, with parameters like building size, shape, dimension, and orientation all playing a significant role in determining the thermal loading of the building which then dictates the electrical needs of the A/C to bring the temperature down.

A study is needed to assess the thermal response of a building that is specific to the Saudi Arabia region, since no extensive data was given in the SEC study that listed temperature variations or building size. A Study was found by M. Y Numan from the University of Dammam, Saudi Arabia that investigates the parameters on mosques building energy performance [Mosque Energy Performance, 2014].

The paper mainly deals with mosques, since they are numerous in Saudi Arabia and are highly standardized. Using the same type of insulation recommended by SEC, namely polystyrene insulation, this study was able to reliably assess a 15% reduction in total electrical load verses an un-insulated mosque of the same region, dimension and orientation [Mosque Energy Performance, 2014].

This agrees with the SEC data as well, since they predicted a total load reduction of 24% (30% reduction of A/C loads which account for 70% of the demand [SEC thermal insulation brochure 2015]). The slight difference in the results can be attributed to the building's shape, since mosques have higher ceilings and more open horizontal space, which makes thermal

insulation less effective. Therefore, for the proposes of this thesis, the 24% reduction is considered to be an accurate assessment in reduction of demand in Saudi Arabia.

Effect on peak demand

If we assume a reduction of 24% of the load due to building insulation, taking in mind that this assumption comes into full effect in 20 years (2035), this will reduce peak demand by a large margin. This thesis estimates that the peak demand in 2035 will drop from our previous estimation of 4.64 GW to 3.526 GW for the top 100 hours of demand. This will greatly help in reducing both capital costs (in terms of new generation capacity needed) and fuel costs (in terms of barrels of oil consumed).

Other potential policies for demand-shifting

Various load-shifting techniques has been proposed in Saudi Arabia to reduce peak demand. One proposed solution included Thermal Energy Storage (TES) of ice to supply A/C loads during peak time. However, such solutions usually require district cooling and other advanced methods of air conditioning that are only applicable in large-scale projects and buildings. Furthermore, these solutions do not translate well into traditional housing neighborhoods which use stand-alone A/C systems.

Such innovations will help reduce future peak demand, but they are currently impossible to predict, since they rely on different technologies and every project will have a varying degree of demand shifting or reduction.

Another area of interest is load-shifting on the consumer-side of non A/C loads (since the temperatures are high in the summer and A/C loads are considered non-shiftable by the average

consumer). Appliances such as washing machines and dryers can be disabled during peak time, to reduce the overall peak demand.

To accurately assess the amount of demand shifted due to these loads, data such as usage times, frequencies, and hour-by-hour electrical consumption of these devices are needed. However, currently no such data exists, making such calculations impossible.

If in the future such data becomes available, further studies can be done to accurately calculate how much demand such appliances contribute to the peak, and how much benefit can be gained by shifting them. If it is deemed worthwhile, a government policy can be drafted to provide a framework to facilitate the shifting.

However, if we are to do a rough estimation of what such a policy might look like, we can assume that 25% of peak demand (excluding A/C loads) is theoretically shiftable. This, will lead to a reduction of 7.5% of the total peak demand, which will equal to 264 MW in 2035. While such a reduction is not large, it is significant enough to warrant further research if a solution with a lower cost exists.

Chapter 4: Future Cost Estimation of Current Generation Methods

As discussed either in chapter 2, current generation methods relay solely on fossil fuels to satisfy the demand. Also, during the demand peak, a large chunk of the load is generated by the SCCTs running on crude oil, further adding to the overall cost.

Cost of Simple Cycle Combined Turbines

To estimate the cost of SCCTs needed to satisfy the peak demand for the central region in 2035, we would need a benchmark cost for every MW of capacity added to the network. This cost covers the capital cost (cost of equipment and installation). In this stage of the calculation, fuel costs and variable O&M costs will not be included, but will be added later at the discussion of crude prices. Also, transmission and distribution cost will be ignored entirely in this paper, this is due to the fact that these costs will remain relatively the same regardless of which method is eventually used to satisfy the peak demand, and therefore have no bearing on cost estimation between different generation methods.

There are different estimations of SCCT costs depending on the source of the data. Firstly, the SEC uses a simple benchmark of 3 million Saudi Riyal (800 thousand dollars US) per MW of installed peak capacity. While this number is extremely simplistic, it is a very good rough estimation of capital costs. Using this method, the 3.526 GW of demand needed in the top 100 hours in 2035 will cost an estimated $2.82 billion.

Another method of cost estimation is the one proposed by the National Renewable Energy Laboratory [NREL 2010], which gathers different papers on the subject and aggregates them together to get a more robust picture of the cost. They estimate a cost of $550,000/MW in capital costs for a SCCT operating as a peaker plant (<%10 CF). This cost however, does not

include any architectural or building costs associated with the plant itself. Therefore, we conclude that the SEC estimate to be true, where $800,000/MW covers the capital cost of a SCCT running on crude oil.

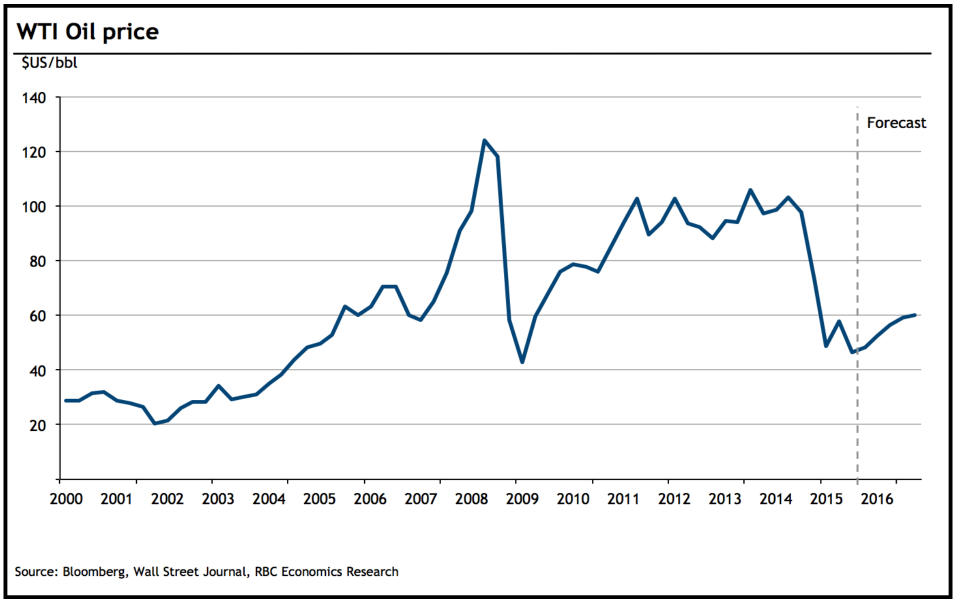
Crude Oil fuel costs

While the SCCTs running on oil produce more than 50% of the electrical demand during peak time, some of that demand is satisfied by gas plants and other generation methods. However, the SCCTs are continuously running even in off-peak times, covering about 10% of the demand. Based on current plans, any new capacity to satisfy peak demand will be covered by SCCTs running on crude oil.

To estimate how much new crude oil needs to be burnt every year to satisfy the increase in the peak, we need to estimate the total new energy that needs to be added to the system. If 3.526 GW of new capacity is needed to cover the top 100 hours of demand, this translates into 352.6 GWh/year of energy needed.

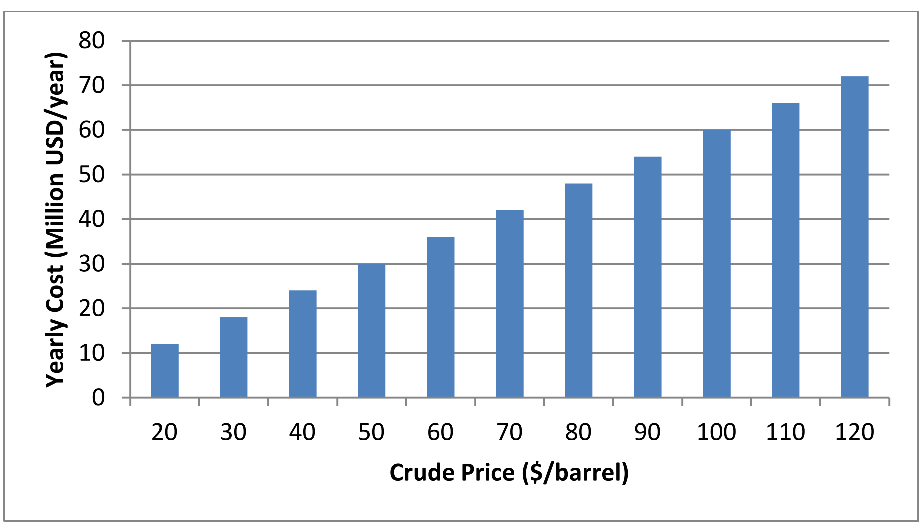
According to the EIA [EIA energy explained, 2016] each barrel of crude yields 5.729 Mbtu of thermal energy. This translates into 1,679 KWh of pure energy. However, SCCTs have a combined efficiency of around 35%, this translates to 587.65 KWh per barrel of crude. Flipped around, 1 KWh needs 0.001702 barrels of crude to be produced. To satisfy the increase in peak demand, an extra 600,125 barrels of crude oil need to be burned every year.

This price of this crude oil is volatile and is effected heavily by international politics and global trade. In the last 5 years, the price of crude has ranged from 30$ to 120$ per barrel. At the time of writing this paper, the price of crude has been in the 40-60$ a barrel range.



[Figure 7: Global Crude Oil Prices, Bloomberg, 2016]

To estimate the cost of oil needed to satisfy the growth in peak demand, a number of different prices of crude was used to get the total fuel cost per year:



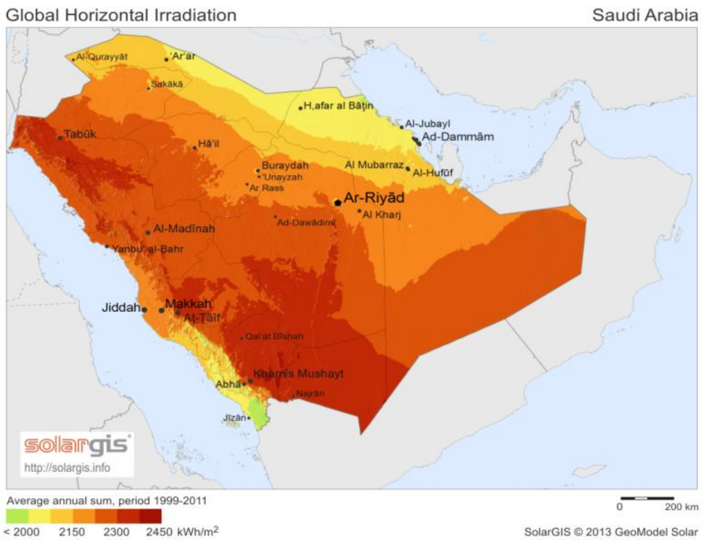
[Figure 8: Cost of Fuel for SCCTs vs. Crude Price]

As we can see, the numbers differ radically depending on the oil price. Fuel cost estimates range from $12 million/year at $20/barrel to $72 million/year at $120/barrel.

Chapter 5: Solar Potential to Meet Peak Demand

The Solar Resource in Saudi Arabia

Saudi Arabia is a very sunny country, with sunshine happening year-round. There are little to no clouds in the area, which makes it an excellent region for solar power applications.



[Figure 9: Solar Irradiation in Saudi Arabia, SolarGIS, 2013]

The region, however is very dry and hot, which is an issues for technologies that are temperature-dependant such as photovoltaic (PV) cells. There is also large amounts of dust in the air and sandstorms are a frequent occurrence.

There are some small-scale solar power generation sites already operating in Saudi Arabia, but they are mostly pilot projects and research-oriented, and they on the order of single MWs of generation. Many future projects are currently in planning and partial construction, however the political climate and crude oil prices are effecting their completion date, making timelines of future solar generation capacities uncertain.

There are however, a few projects in the region that use solar on a utility scale and are currently up and running. Chief among which is the Shams project in the UAE.

Shams Solar Power Station and Its Costs

The United Arab Emirate is a close neighbor of Saudi Arabia, and shares the same climate and culture. In 2013, the Shams Solar Power Station project became operational, providing 100 MW of installed capacity [Shams 1, 2013].

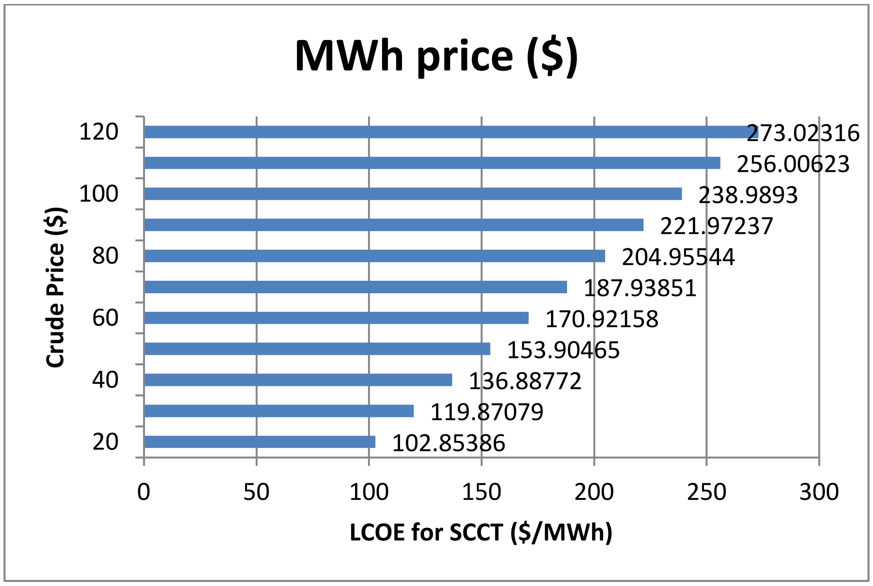
The Shams project is a concentrated solar power (CSP) generation plant, which uses parabolic trough mirrors to concentrate sunlight to heat a transfer fluid which in turn is used to boil steam and generate electricity. The Shams project has a solar field aperture area of 0.625 square km. CSP technologies have many advantages over PV; most importantly resistance to high ambient temperatures and easier dust management, which is ideal for the region.

The Shams project had $600 million in construction and capital costs, which when compared to its capacity of 100 MW would yield a capital cost of $6 million/MW. This is considerably higher than the SCCTs capital cost of $800 thousand/MW, but the advantage of CSP is that there are no associated fuel costs at all. Price reductions are happening in the CSP field, but it is still far from capital cost parity with SCCTs, where a reduction of 86% is needed, which is unlikely in the near future. However, once fuel costs are added to the calculation, a completely different picture emerges.

CSP Vs. Crude Price breakeven

If we envision a Shams-like CSP project to meet the increase in peak demand (namely, 3.526 GW) in Saudi Arabia, we need to do further calculations on the associated costs.

First, in terms of the SCCTs currently in operation, no internal SEC data was found to determine the levelized cost of energy (LCOE) per KWh. The NREL data determined a $68.82/MWh combined capital and O&M costs (LCOE without fuel costs).



[Figure 10: LCOE for SCCTs vs. Crude Price]

As an example, at an oil price of $60 a barrel, the LCOE for SCCT (which uses crude oil) is $170/MWh. In terms of CSP, the NREL data shows that there are multiple estimations of future prices based on the reduction of prices expected by 2035. These numbers range from 150 to $250/MWh. For the proposes of this paper, a mid-price range estimate of $200/MWh was assumed as the LCOE for CSP plants in 2035.

Comparing these numbers with the graph above, we see that to reach a breakeven price for CSP ($200/MWh) the price of crude oil would have to be more than $80/barrel. Any oil price higher than that would produce a net savings by the CSP, and any lower will mean that the CSP plant investment will take longer than expected to recover the capital.

CSP Vs. Crude Return on Investment

Another way to look at this issue is to take the LCOE out of the equation, which contains by definition plant lifetime and capacity factor, and just focus on the raw financial data to estimate the time for return on investment (ROI).

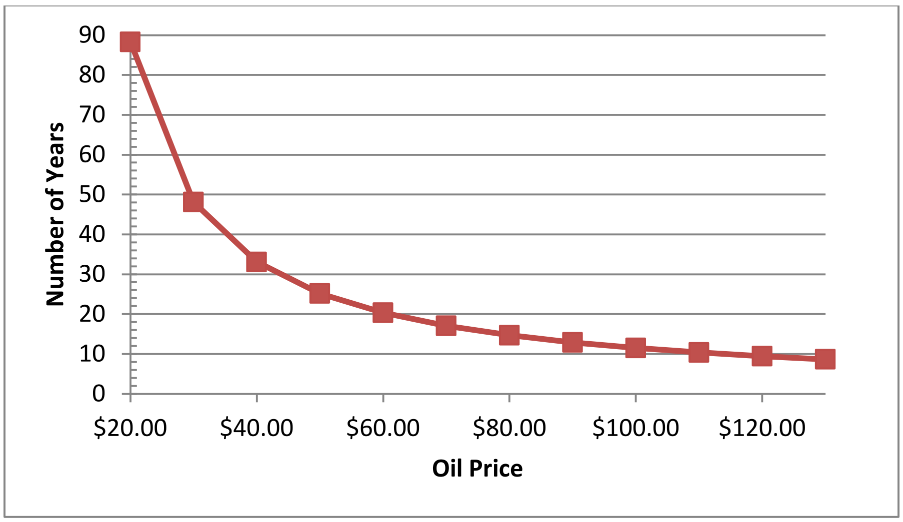
First, starting with the capital cost, a plant of size 3.526 GW will have different capital cost if it's a SCCT plant of CSP. Based on the calculations from the previous section, SCCT will cost $2.821 billion, and CSP will cost 21.156$ billion, producing a net capital cost difference of $18.335 billion.

In terms of O&M, the NREL [NREL, 2010] estimates O&M for SCCT is $10.5/KW/year, for the total demand of 3.526 GW, this becomes $37.023 Million/year. O&M for CPS is $50/KW/year, for the total demand, this is $176.3 Million/year. So, CPS plants cost $139.277 Million/year more than SCCT.

In terms of capacity factor, crude oil calculations for SCCTs are more difficult to estimate. While this research focus on the top 100 hours (1.14% CF), in reality, the SCCTs plants are in operation for more than that. While in the peak time they provide up to 50% of the total demand, some of the units still keep operating even on off-peak times, producing up to 10% of the total demand [SEC internal Data, 2015].

So, to calculate the amount of oil displaced by the CSP, we rely on estimations of capacity factors of CSP plants only. This research takes the uses the average assumption of 33% capacity factor for CSP plants. This means that the CSP plant will provide 10,193 GWh each year. Using our previous calculation of KWh to barrels of crude, this translates into 17.348 Million barrels/year of oil.

Now, since we have all the relevant data, we can calculate the return on investment. Using the $18.335 billion net capital cost as our initial investment, we calculate the amount of years needed to pay that money back based on fuel cost savings. The fuel cost savings also depend on oil price. Below is a chart demonstrating oil price vs. numbers of years needed to recuperate the capital cost of a CSP plant:



[Figure 11: Time for Return on Investment for CSP vs. Crude Price]

As is seen from the chart, at $20 a barrel, CPS will save $346.968 Million/year in fuel costs, taking away O&M difference, this becomes $207.691 Million/year. To get back the $18.335 Billion in capital costs, that would take 88.376 years. The picture looks more promising with higher oil prices, with 20-year ROI on $60 a barrel and 10-year ROI on $100 a barrel.

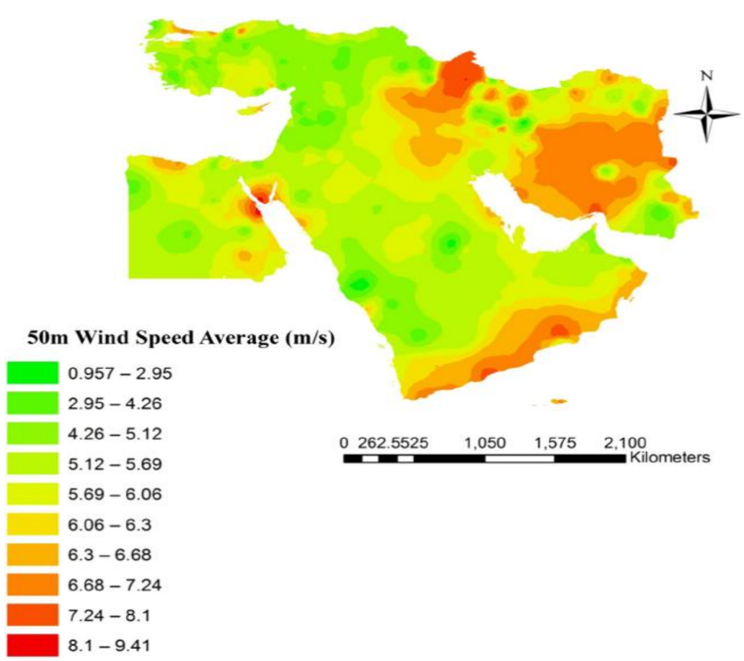
The plant lifetime was not taken into account in this model. However, considering that most CSP plants have an average lifetime of 45 years, any price of oil above $35 a barrel would mean that the plant would be able to pay back its initial investment over the lifetime of the plant.

Chapter 6: Wind Potential to Meet Peak Demand

The Wind Resource in Saudi Arabia

Saudi Arabia as a geographical area does not have a large wind resource within its borders. While some sites for wind energy generation potential do exist, they are not in the central region which this research focuses on. In Riyadh particularly, annual average wind speeds at 100m are in the range of 4.0 to 4.5 m/s [Renewable Resource Atlas, 2016]. These speeds are at the range of the cut-in speeds of large wind turbines, which makes the prospect of a wind energy site in Riyadh very bleak.

However, this does not mean a wind energy site outside of the central region cannot be used and its energy transmitted back. To pick the best sites for wind generating plant that is in transmission distance from Riyadh, we take a look into the annual average wind speeds of the whole region:



[Figure 12: Wind Speeds over the Middle East, Renewable and Sustainable Energy Reviews, 2015]

Within the borders of Saudi Arabia, the areas of the gulf of Aqaba and the city of Yanbo on the shores of the red sea in the northwestern seem like a good option with high average wind speeds. Looking for a more extensive source of data, we find a paper done by Dr. S. Rehman at KFUPM discussing wind energy in Yanbo, which lists the average wind speed there at 4.63 m/s at 50m height [Wind Energy for Yanbo, 2003]. The research also examines different utility-scale wind turbines and their practical wind output at the site, with one tested 2.3 MW turbine producing 5949 MWh of energy, which translates into 29% capacity factor.

Yanbo Case Study

Therefore, it is safe to assume that any future utility-scale wind energy generation plant in Yanbo would produce around 30% capacity factor, which are numbers very comparable to CSP plant capacity factors (33%).

In terms of the cost of such a plant, no real-world examples of utility-scale wind energy plant exist in the region to model the cost upon. However, the NREL data [NREL, 2010] lists the capital cost of onshore wind at $1.75 to $2.5 Million/MW. For this research, a capital price of $2 million/MW was assumed, producing a total capital cost of $7.052 billion for a wind plant of size 3.526 GW.

In terms of overall LCOE of wind, the NREL data provides multiple estimates ranging from 60$ to 100$/MWh. For the purposes of this research, we will assume a $80/MWh LCOE for onshore wind.

When comparing that to the traditional SCCTs running on crude, the picture is very bright, with LCOE for SCCTs is $85/MWh at 10$ a barrel crude price (which makes it breakeven at that price). Such estimations are very optimistic however, since the capacity factor

calculation in the NREL data assumes 45-50% CF for wind, while in reality our site in Yanbo can only provide 33% CF as a generous estimate.

Another issue is availably of energy at peak. With CSP, 100% of the installed capacity is assumed to be generating at peak demand (around 3 pm May-September) since that is the time that the sun is the hottest, and therefore maximum generation happens (due to thermal conduction in CSP) and maximum demand happens (due to highest ambient temperature dictating A/C loads). With wind however, the issue is not as straightforward, since peak generation can happen at different times of day and does not follow the daily demand cycle. This will lead to the wind plant needing another solution to cover the peak demand, which will drive the overall cost of the scheme higher by an amount that is difficult to predict.

Wind Energy from Oman

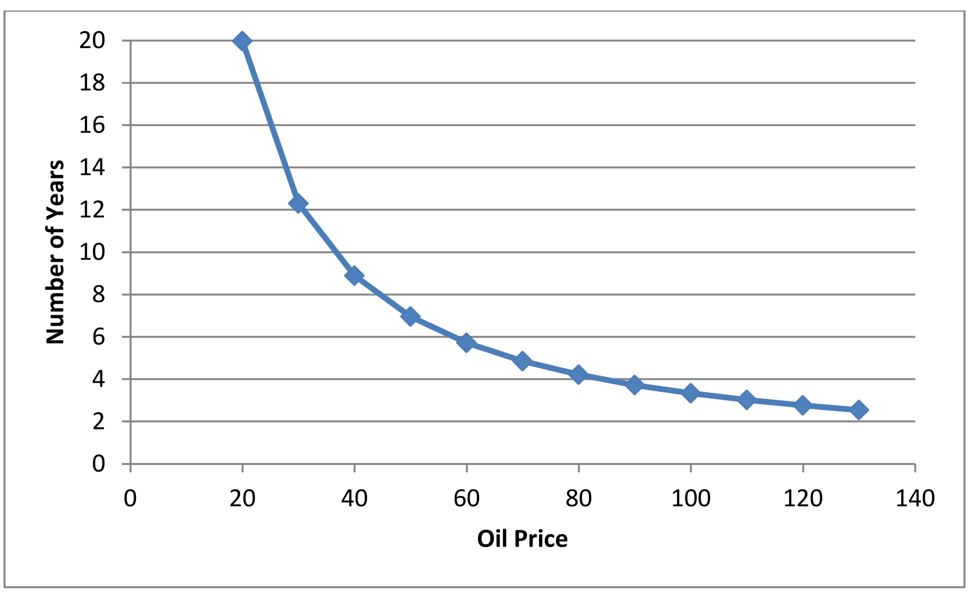
To overcome the problems of low capacity factor and generation-timing mismatch for wind energy, another site should be chosen with a higher overall average wind speed. Looking at figure 12, we can see that the area of the southern Arabian Peninsula (particularly western Oman) has a lot of high speed winds that are consistent year-round. Thumrait (near the city of Salalah) boasts an average of 6 m/s wind speed at 10m height [Wind Energy in Oman, 2010].

However, since Oman is a different nation than Saudi Arabia and has its own separate grid, a high voltage transmission line must be constructed to deliver the energy from Oman to the Central region. In terms of distance, Riyadh (Saudi Arabia) to Salalah (Oman) is 743 miles or 1200 km. This distance is straight (as the crow flies). To account for non-straight actual case, we add 10%, which turns out to be 820 miles or 1320 km.

In terms of the transmission line itself, the best suited type is overhead HVDC line. Data was found for 600 kV DC bipolar transmission line cost [Capital Cost of Transmission, 2014] of $1,614,000 per 1 mile. This totals to $1.323 billion for the whole 820-mile length. There will be other costs associated with the transmission line, such as substation costs and O&M, however these would be harder to estimate, since they depend on the specific route taken for the particular project.

In total, a wind energy plant in Oman would cost $8.375 billion in capital costs (this includes the cost of the 3.526 GW plant and the transmission line). We will assume the O&M costs of the plant to be 30$/KW/year [NREL 2010].

At 33% capacity factor, the plant would displace the same amount of oil as the CSP plant, namely, 17.348 Million barrels/year of oil. The net capital cost increase over SCCTs for Wind would be $5.555 billion, and the net O&M cost would be $68.757 million/year. Using the same method to calculate ROI vs crude oil price we get the following chart:



[Figure 13: Time for Return on Investment for Wind vs. Crude Price]

As seen from the chart, at $20 a barrel, the wind energy plant in Oman would take 20 years to recuperate the initial investment. At $100 a barrel, it would only take a little more than 3 years for the project to pay for itself.

These numbers however are highly theoretical and do not accurately represent the true cost of the project. O&M, political costs, transmission line issues, and other issues can significantly alter the overall result.

Chapter 7: Other Renewable Technologies

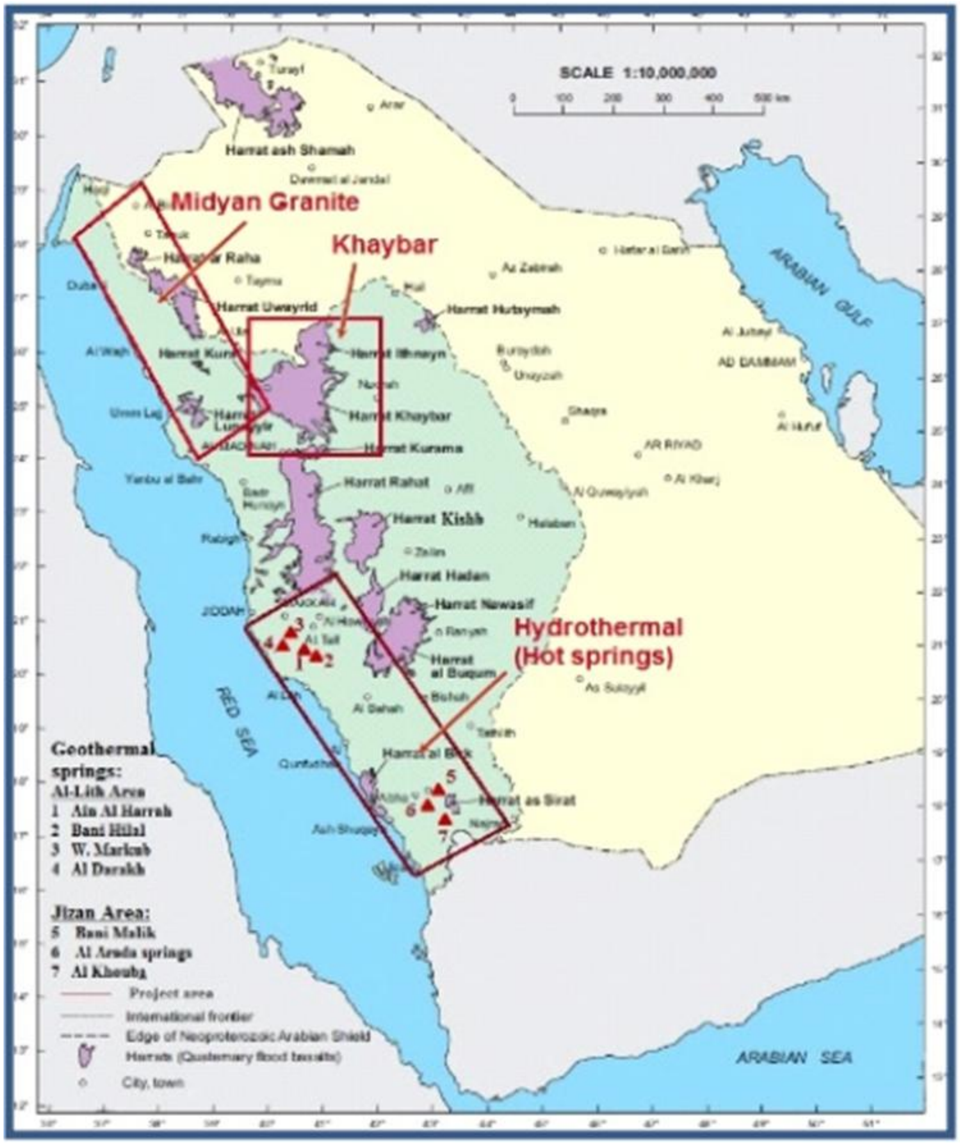
The Geothermal Resource in Saudi Arabia

Another generation method to meet peak demand in Saudi Arabia would be geothermal electric power generation. Globally, geothermal technology is still in its infancy, with large installations located in the global north and especially Scandinavian nations, but with limited application elsewhere.

Surveying the region, there are no operational geothermal power plants (or ones under construction) in Saudi Arabia or the neighboring countries in the middle east. Currently, 3 'academic' geothermal plants by King Saud University (KSU) [Geothermal Resources in Saudi Arabia, 2015] these are all on the medium enthalpy/hydrothermal spectrum and are in the southwest region of Saudi Arabia. However, these research facilities are very much in their infancy. Research in the area is still underdeveloped. Much more geological analysis of the area is needed.

Nevertheless, we shall take a quick look into the geothermal resource in Saudi Arabia. There are 3 types of geothermal resource sites based on enthalpy: Low, Medium, and High Enthalpy sites.

Low enthalpy sources are mainly deep seated aquifers accessible only by deep oil wells in the eastern region. They have a limited capacity for development. Medium enthalpy sources are hot springs and wells (hydrothermal) found mostly in the southwest region. These have the best capacity for development. High enthalpy sources are volcanic eruptions creating large solidified lava field called 'Harrat'. These have some capacity for development but the technology is not yet matured to utilize it.

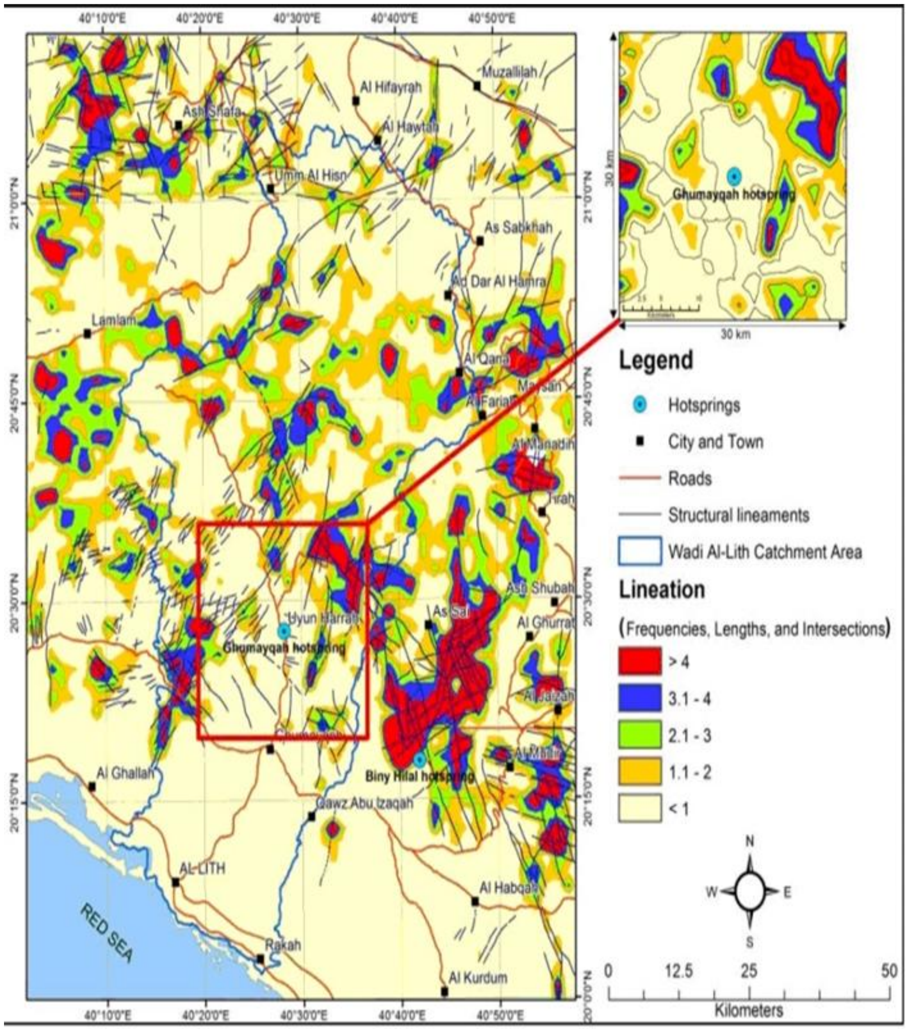


[Figure 14: Geothermal Resources in Saudi Arabia, Proceedings World Geothermal Congress 2015]

When evaluating the medium enthalpy sources (hot springs in the southwest), the main issue that KSU researchers have discovered is that the geothermal resource is dispersed. Wells of 1MW electric capacity are abundant, but not sufficient for the scale of 100s of MWs.

Based on KSU study, Al-Khouba system was taken as an example; even though it has not been drilled, but has exploration data available. They came up with an estimate of $2.95 Million

per 1 MW. This number includes plant construction, drilling, and electrical generation equipment (total capital cost per MW).



[Figure 15: Geothermal Sites in the Southwest, Proceedings World Geothermal Congress 2015]

But, how do these numbers compare (in terms of capital cost estimates)? With \$2.95 M/ MW (geothermal), \$1.24 M/ MW (oil based SCCT), and \$6 M/ MW (CSP Solar) show that geothermal is highly attractive and competitive, but it’s a very rough estimate. Much more R&D is needed before actual utility-scale generation cost estimation is reached.

It is safe to assume that even with a big push towards geothermal, it will take many years until a basis for actual construction of a plant takes place. Not a lot of money is spent by the government to develop it; only $2 M was spent in 2010-15, on a team of 8 persons in KSU. Private industry is doing little research as well, with only a team of 3 persons by ACWA power.

Energy Storage Systems (ESS)

Another Way to solve peak demand is to completely store the energy needed for peak demand from off-peak times. This method will solve peak demand, but will not reduce oil consumption, since the same amount of oil will be burnt, the only savings will the capital cost of the peaker power plants.

To size this storage system, we calculated that the peak demand is 3.526 GW (in 20 years) for the top 100 hours. This translates into 352.6 GWh of energy storage capacity to completely shift the peak.

The most common type of ESS for large applications is Pumped Hydroelectric. This is completely impossible in Saudi, since there are no running rivers or lakes that have water year-round (all the wadis dry up completely in the summer when the peak happens).

Compressed air is another form of ESS, but to store large amounts of energy, a is mine needed with non-porous hard rock (like granite). No such mines exist in KSA with the needed characteristics.

Another option is to used battery storage. The biggest battery ESS for cushioning peak load is in Hong Kong by the company BYD, it has 40 MWh of storage, using 60,000 LFP batteries. It took 3 months just to install the batteries [BYD, 2014].

Size of the plant needed for Riyadh would be 9,000 times as big, making this type of solution impossible, since it would take 2,250 years just to install the batteries. Therefore, a stand-alone ESS solution for peak demand in Saudi is completely unfeasible.

Chapter 8: Discussion of Relevant Issues

CO2 emissions

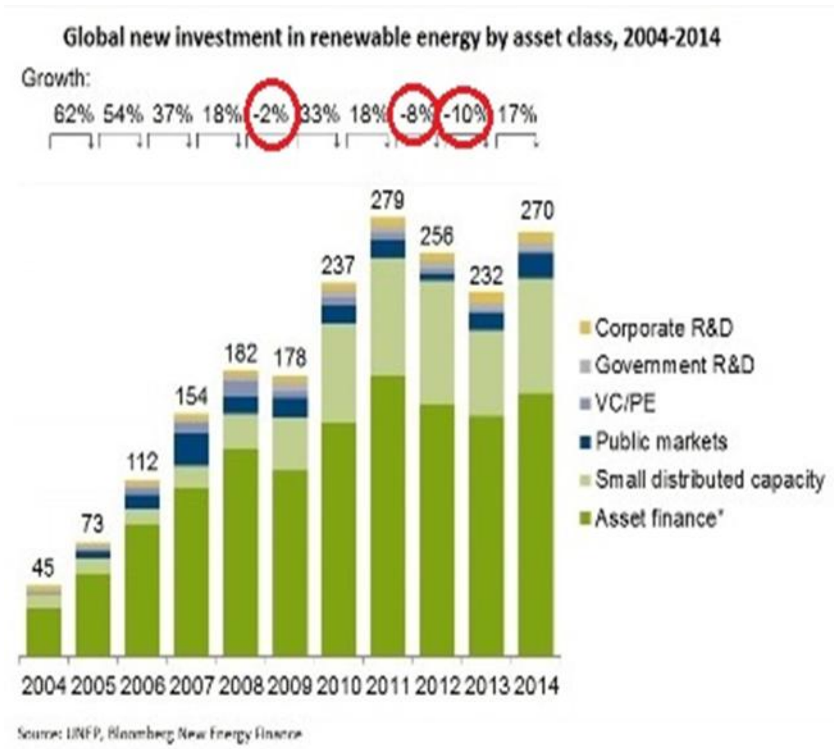
All the solutions discussed in this paper aim to completely satisfy peak demand, namely 3.526 GW. At 33% capacity factor (regardless of which renewable method used) translates into 17.348 Million barrels/year saved in oil.

Now, the task becomes to calculate CO2 emissions saved from not burning that oil, which entails calculating the amount of CO2 from a single barrel of oil. Multiple sources have different methods for calculating CO2 per barrel. This research uses the EPA method, which takes average heat content in a barrel, average carbon coefficient in a barrel, and 100% oxidation. This turns out to be 0.43 metric tons CO2/barrel. [EPA, 2015] At 17.348 Million barrels/year, that turns out to be 7.459 Million tons CO2/year.

Comparing that to the overall emissions in Saudi Arabia, per capita emissions is 17 tons CO2/ year, with central region population of 8.5 million. This results in the central region population emitting a total of 144.5 Million tons CO2/ year. Which means: This plan will reduce emissions by 5.16% every year.

Oil Prices and Renewables Investment

As a rule of thumb, the higher the price of oil, the more investment goes into renewable globally. This is due to energy companies wanting to cut costs and investors looking for a good profit. However, at lower oil prices, renewable investment seems to drop as well.



[Figure 16: Global Investment in Renewable Energy, Bloomberg New Energy Finance, 2015]

As is evident by the previous figure, there were renewable energy investment reductions in 2008 and 2013, these coincide with oil price drops in the same approximate time periods. Therefore, we expect to see such plans delayed if prices are low, and expedited if prices are high.

This same effect goes for Saudi Arabia as well. In 2012, when prices were high, Saudi announced 54 GW of renewable capacity by 2040. In 2014, when prices dropped, Saudi reduced that number to be 9.4 GW of new capacity. In 2017, as prices started to recover, they announced a new investment of $30-50 billion dollars by 2023. So, the implementation of this plan, or any other renewable proposal, is highly dependent upon the price of oil.

The Solar Industry in Saudi Arabia

Saudi Arabia is trying to create its own domestic renewable energy manufacturing industry. They have been focusing mostly on solar technology, with some interest into nuclear as well. Both PV and CSP technologies, but heavier focus on CSP due to favorable conditions (and the lack of large scale silicon/PV industry).

To reach this goal, Saudi Arabia created a few companies, the biggest of which is ACWA power. Headquartered in Saudi Arabia, maintains regional offices in Dubai, Istanbul, Cairo, Rabat, Johannesburg, Hanoi and Beijing. It invests in, develops, co-owns and operates a portfolio of 32 plants on three continents, with the capacity to generate 22.8GW of power and produce 2.5 million m3/day of desalinated water. They are involved in the ‘Shams’ CSP project done in the UAE. [AWCA Power, 2016]

Chapter 9: Conclusion

Recommendation of the Solar Solution

Even though Wind energy (Oman solution) might be cheaper, this research still recommends the solar CSP solution. This is due to many factors: no political hassle of an international deal, no long transmission line and problems associated with it, lack of Wind manufacturing industry in Saudi (everything for the project will be imported), and it boosts Saudi Solar industry and companies such as ACWA power allows Saudi to become the global leader in CSP (not many large CSP projects exist currently). Also, CSP technology is well understood and relatively simple, making it not technically demanding.

Taking into consideration that oil prices now are at $50 a barrel, CSP TROI tells us that it would take 25 years to pay it back. Most analysts suggest that oil prices will hover in the 60-70$ range in 2017-2020. So, the full capacity of 3.526 GW CSP plant should be built. However, any smaller capacity project would still help the current situation tremendously

Wind Considerations

This research recommends some type of small scale (50 MW) in the sites of Yanbo and Aqaba. This will give valuable data into capacity factor calculation and syncing with peak demand. It will also will inform on what type and how big a ESS solution will have to be to cover the peak.

Final Remarks

Policy changes are the most cost effective (economically) but they are the most fragile (politically). However, regardless of which method is used, a comprehensive solution is needed to solve the problem of peak demand in Saudi Arabia. This solution should take the form of solar, but wind or nuclear can meet the requirements with some modification.

The goal of this research is to present a basis of cost benefit analysis of electrical power generation in Saudi Arabia. It is our hope that this research will be used to create new a future concrete plans to improve the electrical network in the kingdom.

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