AMERICAN UNIVERSITY OF BEIRUT

REQUIREMENTS AND SCENARIOS FOR HIGH SOLAR PENETRATION IN ELECTRICITY PRODUCTION IN SAUDI ARABIA

by
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AN ABSTRACT OF THE THESIS OF

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Title: Requirements and Scenarios for High Solar Penetration in Electricity Production in Saudi Arabia.

The newly adopted national plan "Saudi Arabia Vision 2030" aims to reduce the country's dependence on oil and generate 9.5 GW of power from renewable energy sources. Within this context, this thesis addresses the country's requirements for high solar penetration in electricity production through utilizing the duration and residual curve concepts as a simple method in determining the optimal energy mix in Kingdom in 2030. Different technologies of energy sources were incorporated and simulations of different renewable energy systems were carried out, covering several locations in the Kingdom. Calculations of electricity generation costs of different technologies were conducted for different deployment scenarios. Moreover, investment and opportunity costs due to the use of renewable energies were estimated; in addition to the policy changes needed for the suggested scenarios.

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ABBREVIATIONS

KA-CARE	King Abdullah City for Atomic and Renewable Energy
SEC	Saudi Electricity Company
ECRA	Electricity & Co-Generation Regulatory Authority
PV	Photovoltaics
CSP	Concentrated Solar Power
NREL	National Renewable Energy Laboratory)
SAM	SAM System Advisor model
CCGT	Combined Cycle Gas Turbine
GT	Gas Turbine
ST	Steam Turbine
GHI	Global Horizontal Irradiance
DNI	Direct Normal Irradiance
NETC	National Electricity Transmission Company
BOS	Balance of System
HFO	Heavy fuel oil
GDP	Gross domestic product
FIT	Feed-in tariff
LCOE	Levelised cost of electricity
O&M	Operations and Maintenance
LDC	Load duration curve
KACST	King Abdul-Aziz City for Science and Technology
SASIA	Saudi Arabia Solar Industries Association
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers

To My

Beloved Family

CHAPTER I

INTRODUCTION

Saudi Arabia has one of the world's largest proven reserves for crude oil and natural gas; the country has around 266 billion barrels of proven crude oil and 8.3 trillion cubic meter of natural gas reserves (1). With the oil sector accounting for 42 % of the country's GDP, it is evident that the Saudi economy is very much dependent on the oil industry, oil returns make up 87% of government revenues and it represents 90% of Saudi Arabia's export earnings (2). However, the oil market has recently experienced a downturn as prices have decreased from more than 100 US$ per barrel in 2014 to around 50 US$[1] (December 2016). Consequently, Saudi Arabia's budget deficit increased dramatically, and the Kingdom was forced to tap into the global bond market to fix its finances[2].

Coupled with the economic crisis, the country has been experiencing a surge in domestic energy demand. Electricity demand has been increasing within the Kingdom at a rate of 7.5% per year, while Peak demand for power during summer has increased by 93% from 2004 to 2013 (3). The Kingdom has been relying on oil and gas to cope with its demand for electricity and desalinated water, missing out on opportunities to exploit the huge potential of renewable energy which could largely contribute to electricity production. Recently, the Saudi government showed signs of its intention to change its domestic energy policies and focus on diversifying the country's energy mix

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[1] Crude oil prices; available from http://www.nasdaq.com/markets/crude-oil.aspx; Internet; accessed 20 January 2017.

[2] Financial Times, 9 November 2015; available from https://www.ft.com/content/d1be572a-86fd-11e5-90de-f44762bf9896; Internet; accessed 20 January 2017.

(1). In 2010, the King Abdullah City for Atomic and Renewable Energy (KA-CARE) [3] was created to expand the Kingdom's power generation capacity through introducing solar, wind, geothermal, waste and nuclear power. According to the KA-CARE plan, nearly 50% of total electricity production within the Kingdom should come from non-fossil fuel sources, 17.6 GW from nuclear and 41 GW will come from solar power (with 16 GW from PV and 25 GW CSP), 9 GW from wind energy; 3GW from waste-to-energy; and 1 GW from geothermal by 2030 (4)[4], little has been done until now in the execution of the plan. Recently, the Deputy Crown Prince Mohammed bin Salman bin Abdulaziz Al-Saud has launched an ambitious plan "Saudi Arabia's "Vision 2030[5] " . The plan aims to reduce the Saudi Arabia's dependence on oil while simultaneously improving its investment status through opening up opportunities for the private sector, particularly in the energy sector. More importantly, the Saudi 2030 vision aims to redesign the energy subsidy system and promote the localization of the renewable energy value chain within the Saudi economy, with an initial target of generating 9.5 GW of electricity from renewable sources. The plan also stipulates involving the private sector in research, development and manufacturing. Moreover, a new city dedicated to energy will be created, while legal and regulatory framework that allows the private sector to buy and invest in renewables will be reviewed as public private partnerships, and such activities will be encouraged Finally, according to the Saudi 2030 vision, the competitiveness of renewable energy shall be guaranteed through the gradual

[3] KA-CARE was created by a Royal Order on April 17, 2010.

[4] The date of the nuclear element of KA-CARE's plans has been shifted to 2040, see World Nuclear Association; available from http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/saudi-arabia.aspx; Internet; accessed 11 December 2016.

[5] The "Vision 2030" was approved by the cabinet on 16 April 2016.

liberalization of the fuel market (5).

Within the context of “Vision 2030” which highlights the Kingdom’s willingness to use more and more renewable energies into the energy mix and signals the increasing need for conducting feasibility studies to support the energy transition within the Kingdom, this research work presents a preliminary feasibility study of achieving high penetration of solar power in electricity generation in Saudi Arabia. Until now little has been done concerning the usage renewable energy in Kingdom, with a total installed capacity not exceeding 17 MW, knowing that 125 MW in the pipeline in coming years (6).

In comparison, Germany’s total installed capacity of solar power by 2014 was around 38.5 GW, where 1.4 million PV plants generated 35.2 TWh covering 6.9 % of Germany’s total demand. On sunny weekdays, PV was able to cover 35% of electricity demand. Moreover, the PV industry employed approximately 56,000 people in 2013 in Germany (7). Also, in the Arab world, Egypt is expecting to produce 20% of it needs from renewable sources with 12% coming from wind. In 2015, Egyptian president declared that Egypt will pursue its strategies in implementation of renewable projects which include 4.3 GW of generation capacity 1.3 GW of solar and 2.0 GW of wind using FIT (feed-in tariff)[6] schemes (6).

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[6] Feed-in tariff is a scheme of offering long-term contracts to renewable energy producers.

CHAPTER II

METHODOLOGY

Before studying the requirements and the investments needed for high solar penetration in Saudi Arabia. An extensive desktop research was conducted, covering the both the energy sector in general and electricity sector in detail. The data gathered included daily supply and demand patterns, weekly load pattern, demand increase rates, electricity demand by sector of activity, fuel and technology generation mix and tariff structure. The research also looked at the institutional mapping of the energy sector in the Kingdom identifying all the key players, different organization and institutions involved in production, transmission and sales, structures, regulating bodies if any, governing laws and polices within the energy sector. The research also looked at Saudi Arabia renewable energy plans (KA-CARE, Vision 2030) including their quantitative goals and technologies used and why they failed.

The second part of the desk research included a technological review of renewable technologies in the world, mainly solar power, including PV (photovoltaics) and CSP (Concentrated Solar Power). This part focused on usage, advancement of the technology in last ten years, current and future cost projections, and adaptability to climatic conditions in Saudi Arabia. Status of solar energy projects in different areas of the World were also investigated, with interest in countries, like the United States for its PV and CSP projects, Spain for its fast deployment of CSP technology, China for its high deployment of PV technology and PV manufacturing capacities.

Solar resources of the Kingdom were investigated, covering different locations, DNI (Direct Normal Irradiance) optimal for CSP technology and GHI (Global

Horizontal Irradiance) optimal for PV technologies (data from 27 locations in the Kingdom is available from the ASHRAE) (8), this data was used as input for conducting solar projects simulations.

Simulating generation output form renewables is a complex process due to the variability of the resource the and sensitivity to both location and time. However, the use of the System Advisor Model (SAM) developed by the NREL (National Renewable Energy Laboratory) makes this task possible and easy, SAM is designed to predict the performance and establish a business model of renewable energy systems. SAM does hourly calculations and predict the energy output of the system, which can be viewed on different tables and graphs on an hourly, monthly and yearly basis (9).

For this work, the simulations were carried on imaginary solar plants located in Saudi Arabia which are identical to currently operating plants around the World such as the Noor I and II, solar CSP plants located in Morocco (10) and the Cestas PV plant located in France, the largest European PV plant (11) . The simulation results included the energy output, capacity factor and generation costs, which were used for as an input for the different deployment scenarios, the results were plotted on the estimated load duration curve (which is a sorted version of electricity load for 2030). The use of the duration and residual curves concept generally give a better visualization to renewable energy integration in the electricity grid, it also provides a first estimate on the feasibility of deployment scenarios, Generation costs of different technologies were then calculated and compared, screening curves of the different generation technologies were plotted to estimate the optimal generating mix for serving the load.

Using different results and scenarios, the potential of coupling natural gas generation with renewables was all examined to cover all the electricity demand in the kingdom by 2030, as gas is available in large quantities in Saudi Arabia, and Finally, policy recommendations needed for an energy transformation in Saudi Arabia were given, achieving high penetration of solar energy to cope with fast-growing energy demand.

CHAPTER III

THE ENERGY SECTOR IN SAUDI ARABIA

A. Oil and Gas

Oil prices have great influence on the Saudi Arabia's budget. The oil price needed by the Kingdom to breakeven with its expenditure has increased during the last decade from 78 US$ a barrel in 2012 to 89 US$ in 2013 according to the IMF (International Monetary Fund) (1). With oil trading around 50 US$ [7]months earlier, the budget deficit of the Kingdom for 2015 was estimated at 13% of GDP and should reach the sum of $87 billion in 2016, This situation forced the Kingdom to use its huge accumulated foreign currency reserves (750 billion USD$) to help it withstand the fiscal impact of low oil prices (2).

Saudi Arabia produced an average of 11.6 million bbl./d of total petroleum liquids in 2013 of which 7.7 million bbl./d of crude oil were exported and the rest used locally (12). As for natural gas, production has reached around 102 billion cubic meters in 2013, growing at a rate of 6.8% during the last five years. 86 % of the gas is associated gas, which exists as a joint product with oil (zero production cost) (13), providing 43% of Saudi electricity while oil provides the rest (14), all the produced gas in Kingdom is consumed domestically and is not exported. (15)

Beside electricity production, Saudi Arabia consumes large amounts of energy on water desalination, 10% of the fuel consumption of the country is for water desalination (15), with a daily 6,218,018 m^3/day capacity of desalination plants in 2014 (3) providing around 50% of the country fresh water requirements (15).

[7] http://www.nasdaq.com/markets/crude-oil.aspx

B. The Saudi Electricity Sector

To meet the increasing demand for electricity, peak power generation capacity in the Kingdom is expected to reach 120 GW by 2032 (3). This increase in demand is driven by a number of factors. Firstly, since 1980, the Kingdom's population has increased by more than 180% (2). Population growth has been a major contributor to energy demand since the residential sector consumes around 50% of electricity production. Secondly, Saudi Arabia has a fast growing economy where large investments motivated by cheap energy prices are made within the energy intensive industries, which represent 9 % of GDP (1). Thirdly, a cheap energy market where electricity is sold at 0.09 US$/kWh [8], this has been one of the important economic factors behind rising energy consumption, the Kingdom is known to be one of the largest subsidizers in the world where 46 billion US$ are dedicated to the oil sector alone and 15 billion US$ to the electricity sector (1).

C. Electricity Load

In 2014, the Saudi Electric Company sold 281,155 GWh of electricity (3), 51% was consumed by the residential sector, 22% by the industry, 14% by the commercial sector and 11% by the government sector in 2011 (16). Between 2007 and 2014, peak load increased from 35 GW to 57 GW (3). Energy consumption varied across the country with the highest rates in the western and central regions.[9] This division of regions originated for the setup of four distinctive companies for each region in the early days of electrification of the Kingdom, in 2011 37 % of customers were from the

[8] https://www.se.com.sa/en-us/customers/Pages/TariffRates.aspx.

[9] Saudi Arabia is divided into four distinctive regions East, West, Central and South regions.

western region, 32% from the central region, 14 % from the southern region, finally 17 % form the eastern the electricity region which is characterized by the dominance of the industrial sector in this area (16).

Table 1. Electricity minimum and maximum peak power and electricity sold in KSA

Year	**Peak Max**	**Peak Min**	**Electricity Sold**
	GW	**GW**	**GWh**
2008	37.15	20.46	187,163
2009	39.90	21.36	199,499
2010	43.90	23.60	218,254
2011	43.97	25.04	225,509
2012	50.75	28.10	246,610
2013	53.23	28.89	262,685
2014	56.83	31.88	281,155
2030	120.00	60.00	560,000

Source: ECRA. (2014). *Annual statistical booklet for electricity and seawater disalination industries.* s.l. and author calculations.

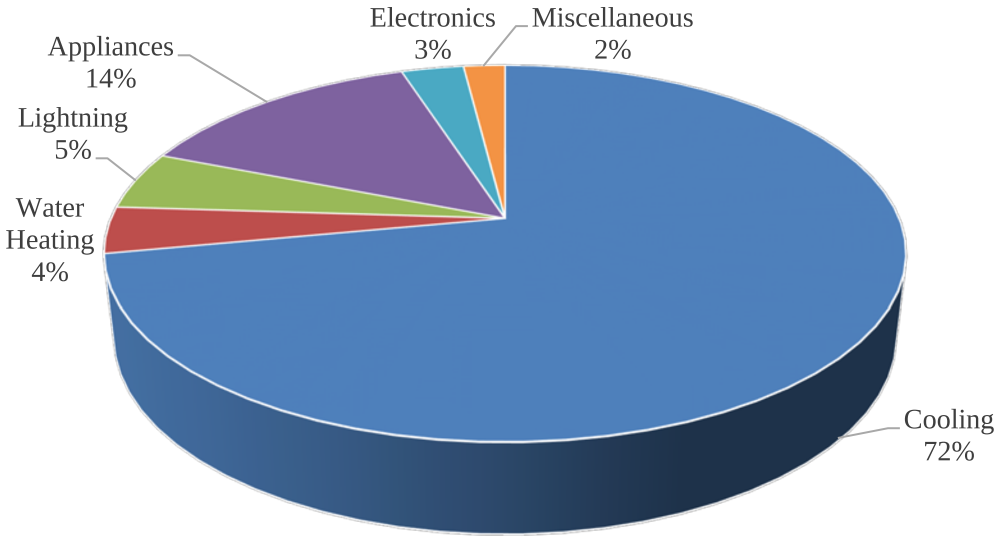

Fig. 1. Residential consumption by end use
Source: Faruqui, Ahmad, Hledik, Ryan, Wikler, Greg, Ghosh, Debyani, Prijyanonda, Joe and Dayal, Nilesh. (2012). “Bringing demand-side management to the Kingdom of Saudi Arabia”. S.l. *Electricity & Cogeneration Regulatory Authority*.

Within this context of high increase of consumption and the dominance of residential sector, the Kingdom has embarked in several initiatives and programmes to reduce its energy consumption over the next 20 years by initiating an energy efficiency plan and the creation of the Saudi Energy Efficiency Center (SEEC)[10], the entity is responsible for the development of energy efficiency initiatives and conservation policies targeting all sectors; one of the major accomplishment was the issuing energy efficiency labels for imported and locally manufactured air conditioners in beginning of 2014 (17).

Despite these measures and with the current pattern of consumption and no major decrease in demand it is expected that the maximum peak power will reach 120 GW with the minimum peak power at 60 GW in 2030. The calculated ratio between low and high peak load for the Kingdom is around 55% (from 2008 to 2014), it is considerably high compared to the United States, for example, where peak load ratio is between 27-33% (18), this high value can be attributed to night cooling and night consumption of the residential sector.

D. Peak and Hourly Load

In 2014, the maximum weakly peak load in the Kingdom was approximately 56.547 GW occurring during week 36 of 2014 (September 1-7, 2014), while the minimum peak load reached was 31.88 GW occurring during the first week of that same year (December 30 – January 5, 2014).

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[10] SEEC was created by the Council of Ministers in October 2010, based on a Royal Decree and currently operating under the umbrella of King Abdul Aziz City for Science and Technology (KACST)

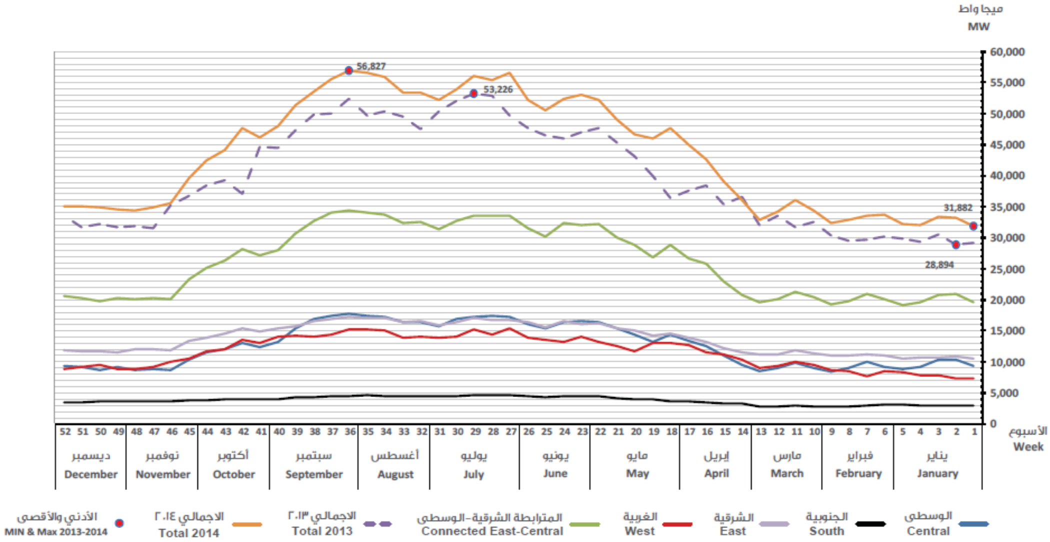

Fig. 2. Weekly Peak Load - National Grid Saudi Arabia
Source: ECRA. (2014). *Annual statistical booklet for electricity and seawater disalination industries.* s.l. and author calculations.

The summer occurrence of the peak load is typical to several countries including the Gulf countries where air conditioning is widely used in summer and electricity is barely needed for heating in winter, in contrast with other countries (Lebanon, other European countries) were the peak load occurs in winter due to the heating load requirements in winter.

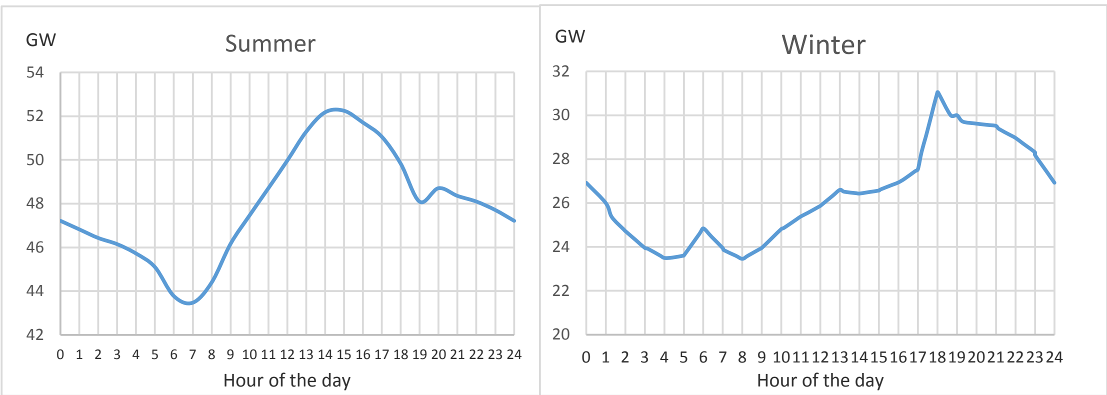

Fig. 3. Typical hourly load for summer on left, winter on the right
Source: ECRA. (2014). *Annual statistical booklet for electricity and seawater disalination industries.* s.l. and author calculations.

Concerning the typical hourly load the difference between highest and lowest load for summer was 8.77 GW, and difference for winter was 7.55 GW (3) , but looking in detail at the hourly load figures, we found the daily high peak load in summer occurs at 15:00, and is differed to 18:00 in winter, both not at the time when the maximum energy output form PV and CSP systems occur which correspond to 12:00 noon, showing the importance of storage for both PV and CSP, CSP with storage offer a great advantage in comparison with PV systems , energy is stored in the hours with reduced consumption and delivered back when peak energy is needed.

E. Generation Capacity and Technology

The Saudi power generation capacity is composed of conventional thermal plants fueled by a mix of crude oil, HFO (Heavy fuel oil), natural gas and other petro residuals (13). Technologically, electricity generation in the Kingdom is dominated by gas turbines, representing 60% of the total generation. Although less efficient (15-30% efficiency) than combined cycle or steam turbines; gas turbines offer a cheap alternative to cope with the increased energy demand and suitable in delivering peak power energy, with the advantage of running on different types of fuel (crude oil or associated gas). It can also operate without water for cooling which is a great advantage for Saudi Arabia.

Saudi Electric Company (SEC) controls 71% of generation capacity while 16 other companies are providing the remaining capacity. The reference generation cost of the SEC (Saudi Electric company) in 2010 was 0.10 US$/kWh. (13)

It is important to note that independent energy generation and water desalination companies as well as other industrial companies are sold fuel at a very low price. As shown below, the price of natural gas in Saudi Arabia was set around 0.75 US$/MMBtu in 2013, which was much lower than the average spot price set abroad

(12), such a very low price of oil influences the generation costs, see generation cost calculations in Appendix I and II.

Table 2. Generation companies in Saudi Arabia

Producer	**No. of Plants**	**Capacity MW**	**Percentage %**
Saudi Electric Company	46	54,717	71%
Saline Water Conversion Corporation	6	4,761	6%
Hajr for Electricity Production Company	1	3,415	4%
Jubail Water & Power Company	1	2,875	4%
Saudi Aramco	8	1,927	3%
Durmah Electric Company	1	1,756	2%
Marafiq	1	1,589	2%
Rabigh Electric Company	1	1,320	2%
Shuaibah Water & Electricity Company	1	1,191	2%
Tihama Power Generation Company	4	1,083	1%
Shaqaiq Water & Electricity Company	1	1,020	1%
Rabigh Arabian Water and Electricity	1	600	1%
Jubail Energy Company	1	250	Small
Saudi Cement Company	1	227	Small
Tuwairqi Energy Company	1	73.5	Small
Alaman Company	3	18	Small
Obeikan Paper Industries Company	1	16	Small
Total	**81**	**76,839**	**100%**

Source: ECRA. (2014). *Annual statistical booklet for electricity and seawater disalination industries.* s.l. and author calculations.

Table 3. Transfer prices for fuels paid by the power water, and petrochemicals sectors

Type of fuel	**Price in US$/MMBtu**
Methane and ethane	0.75 US$/MMBtu
Arab light	4.24 US$/bbl. (0.76 US$/ MMBtu)
Arab heavy	2.67 US$/bbl. (0.48 US$/ MMBtu)
Diesel	0.65 US$/MMBtu
HFO 360cst	0.36 US$/MMBtu

Source: Council of Ministers Resolution No. 55 and Electricity & Co-generation Regulatory Authority ECRA. (2014). *Annual statistical booklet for electricity and seawater disalination industries.* s.l. and author calculations

F. Electricity Regulatory Framework

Saudi Arabia's electricity sector is essentially managed by Saudi Electric Company SEC, a single vertically integrated electricity company, which owns most of the generation assets owned by its majority by the Saudi government. SEC also controls the National Electricity Transmission Company (NETC) which is responsible for transmission and distribution of electricity in Kingdom (1).

As part of restructuring efforts of the electricity sector in the Kingdom, the Electricity & Co-Generation Regulatory Authority (ECRA) was created in 2002, with the aim of regulating the electricity and water desalination sectors, ensuring reliability, affordability and quality of the service and providing the regulatory framework for the energy sector according to Saudi laws and best practices.

The aim of such measures in to improve efficiency of sector and creating energy an efficient energy market, adopting of new measures aimed to increasing efficiency and decreasing governmental spending within the sector (1).

The Saudi government's reform in the electricity sector was pushing for the full unbundling of the sector into three parts: generation, transmission and distribution, but only a partial vertical unbundling was carried out in Kingdom with the three sector activities (generation, transmission and distribution) still interconnected, the role of the regulator is still unclear and sector is dominated by high subsides distorting the generation costs, several independent generating companies were established but all using conventional generation technologies and are benefiting from the generous subsidy system.

The benefits of unbundling of electricity's public utilities is still controversial and has been successful in developed countries, mainly in Europe and has created an energy market where energy of renewables have a dominant role, but was less successful in less developed countries and in countries were energy demand is high and energy subsidies are dominant. (20).

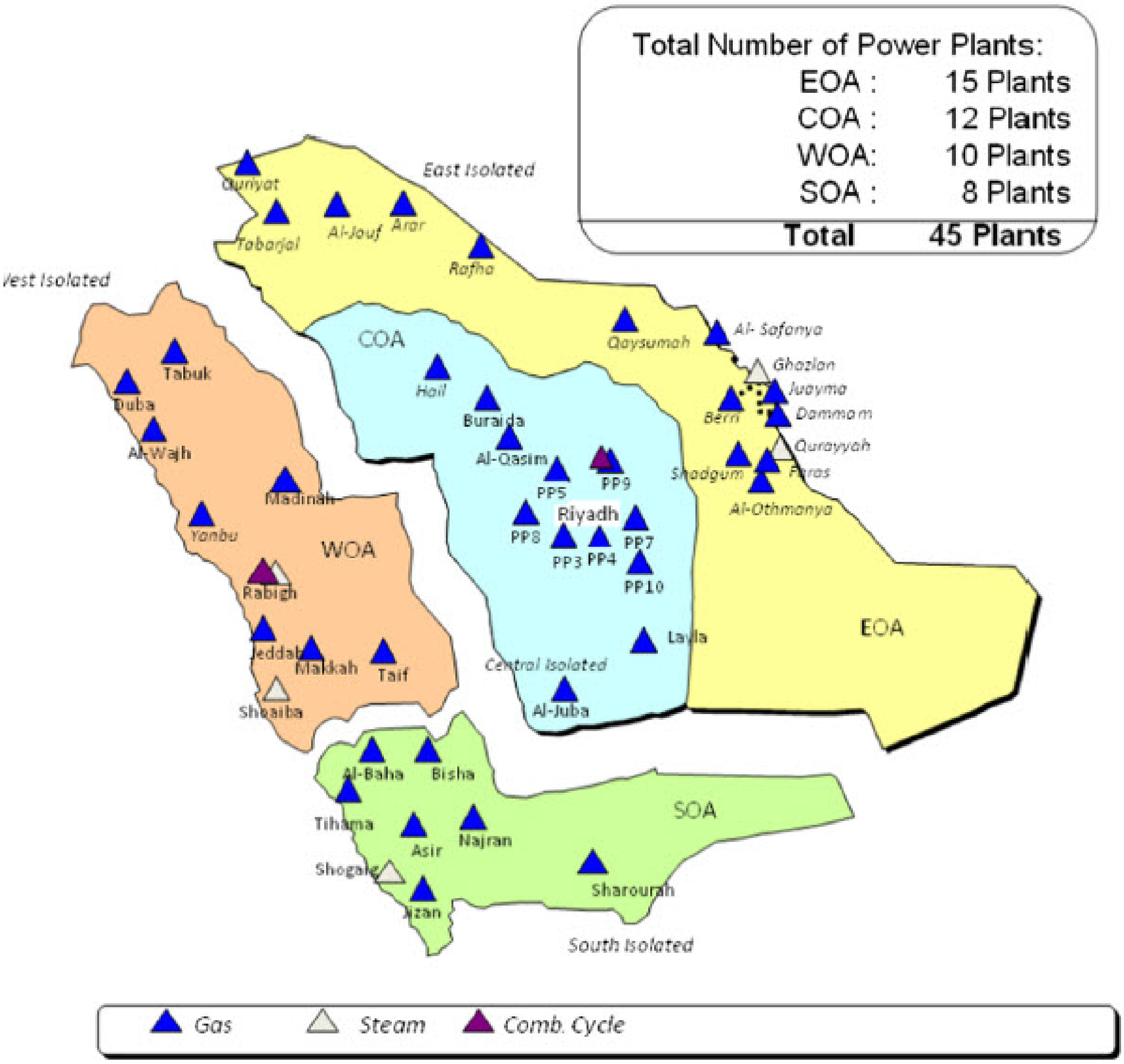

Fig. 4. Power plants in Saudi Arabia in 2011,
Source: ECRA. (2009/2010/2011). Annual statistical booklet for electricity and seawater desalination industries. s.l.

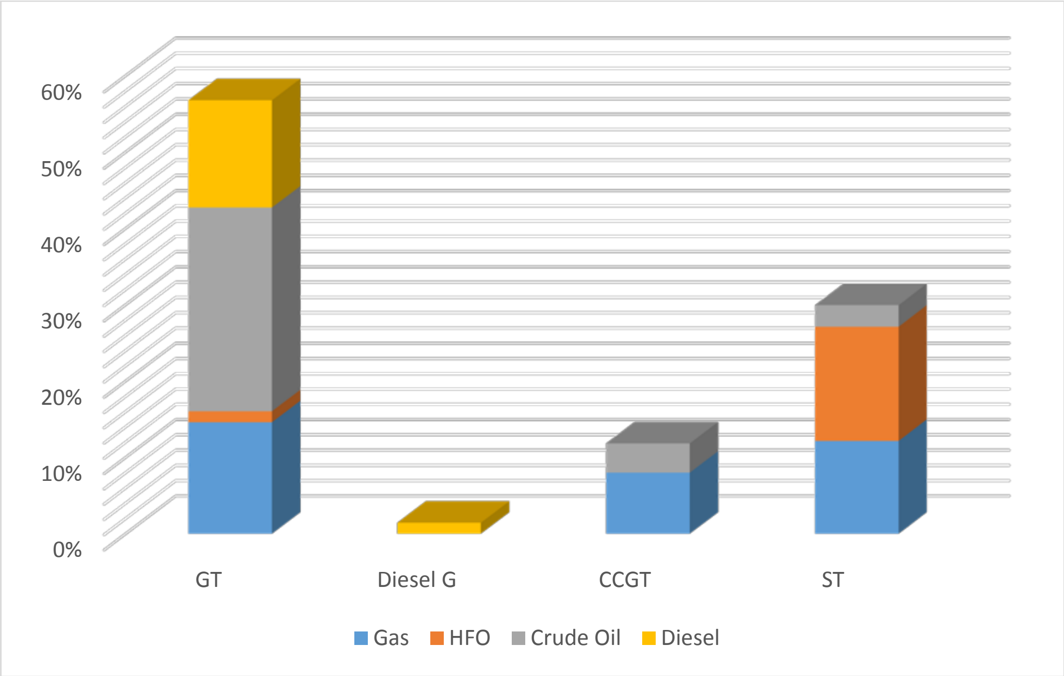

Fig. 5. Electricity generation in Saudi Arabia by type of fuel and generation technology *Source:* ECRA. (2014). *Annual statistical booklet for electricity and seawater disalination industries.* s.l. and author calculations

G. Solar Resources in Saudi Arabia

Saudi Arabia is located in the Arab peninsula between latitudes 17.5 and 31 degree north, 36.6 and 50 degree east, with a variation of altitude between 0 and 2680 meter above sea level. Two seasons are observed in Saudi Arabia, winter and summer and the vast areas of Kingdom experience high solar intensities and long hours of sunshine with an average annual solar radiation of 2200 kWh/m^2 (21).

Until 2013, limited or outdated measures of the solar resource data were available for Saudi Arabia; solar data for different locations were estimated using satellite observations. This type data cannot be used for the design of solar large projects, which generally require accurate long-term ground based data, recently, the Kingdom equipped 30 metrological stations and conducted more accurate measurements including one-minute measurements of Global Horizontal Irradiance

(GHI), Diffuse Horizontal Irradiance (DHI), Direct Normal Irradiance (DNI) (22).

GHI daily measurements in the Kingdom ranged from 5,700 Wh/m^2 (average yearly totals of 2,080 kWh/m^2 yr.) to the highest 6,700 Wh/m^2 (average yearly totals of 2,445 kWh/m^2 yr.) with higher values measured in inland areas and lower values found on the cost, showing the possibility of using PV systems anywhere in the country, however, with decreased performance in areas subjected to high temperatures (over 30 degrees' Celsius annual average).

DNI daily values ranged from 5,510 Wh/m^2 (average yearly totals of 2,000 kW h/m^2 yr.) to 6,474 Wh/m^2 (average yearly totals of 2,400 kW h/m^2 yr.), showing the possibility of using CSP very effectively in the northern part of the country (23).

Solar data is available for 27 locations[11] in the Kingdom at ASHRAE weather data web site (8), this data is also available in different resolutions (hourly, daily, monthly) from Saudi renewable resource Atlas (22).

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11 Abha, Al-Ahsa, Al-Baha, Al-Jouf, Al-Madinah, Al-Qaisumah, Al-Taif, Al-Wejeh, Arar, Bisha, Dhahran, Gassim, Gizan, Guriat, Hail, Jeddah (King-Abdul), Khamis-Mushait, King-Khaled-Intl, Makkah, Najran, Rafha, Riyadh-Obs (OAP), Sharorah, Tabuk, Turaif, Wadi-Al-Dawasser, Yenbo.

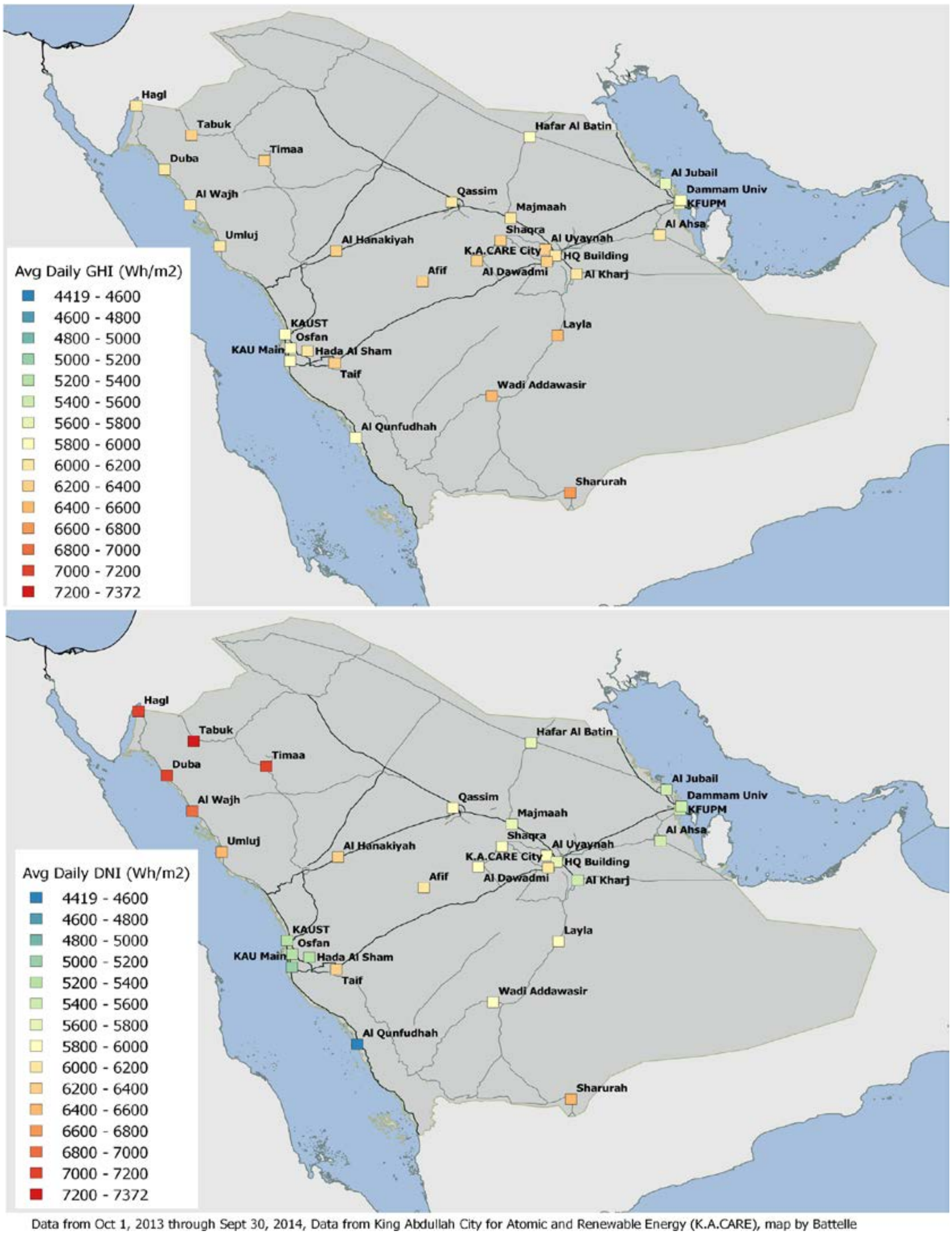

Fig. 6. Distribution of average daily GHI and DNI and values by station
Source: Zell, Erica, Gasim, Sami, Wilcox, Stephen, Katamoura, Suzan, Stoffel and Thomas. (2015). "Assessment of solar radiation resources in Saudi Arabia". *Solar Energy* 422-438, 119.

H. Motivations for Solar Power Deployment in Saudi Arabia

Saudi Arabia has many reasons for deploying and the use of renewable energy;

aside from meeting the increasing energy demand, integrating renewables within the Kingdom's current energy mix would be both economically and environmentally advantageous. Saudi Arabia has one of the highest potential of solar energy in the region where annual solar radiation is around 2,200 kWh/m^2; the total estimated potential energy that could be produced using concentrated solar power (CSP) is 124,560 TWh, which is by far greater than the country's annual energy demand (24).

Moreover, renewable energy industries, in the case of high penetration (20% to 30% penetration of renewables until 2030), could drive economic diversification of the country, create employment opportunities and alleviate unemployment which is around 11.4% of the total population (2). Moreover, introducing renewables into the Saudi market would further facilitate the implementation of climate change policies across the country, which would allow the government to address the fact that the country is among the top 15 of the world highest carbon dioxide emitters per capita (6).

I. Renewable Energy Framework and Deployment Scenarios

In order to benefit from the tremendous potential of renewable energy in Saudi Arabia, the King Abdullah City for Atomic and Renewable Energy (KA-CARE)[12] created in 2010 with the mission to be "the driving force for making atomic and renewable energy, an integral part of a national sustainable energy mix creating and leveraging the competitive advantages of relevant technologies for the social and economic development of the Kingdom of Saudi Arabia" (25).

KA-CARE produced an ambitious plan in 2012 recommending the introduction of renewable and nuclear energy gradually, by 2032, hydrocarbons will

[12] KA-CARE was created by a Royal Order on April 17, 2010.

remain a prime element in Saudi energy mix, but 50% of all electricity should generated will be from non-fossil fuels., using nuclear, solar, wind, waste-to-energy, and geothermal on the following basis: nuclear 17.6 GW; solar 41GW, of which 16 GW will be generated using photovoltaic cells and of 25 GW by concentrated solar power, wind 9 GW; waste-to-energy 3GW; and geothermal 1 GW (4).

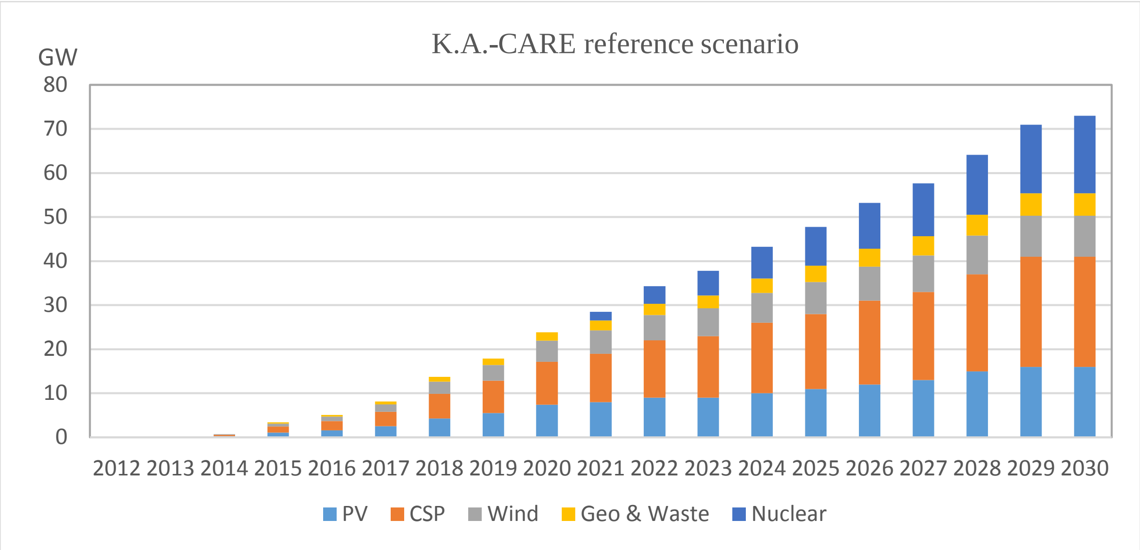

Fig. 7. KA-CARE Renewable scenario deployments of renewable/Nuclear
Source: Collins, Ross D., Gowharji, Waleed, Habib, Abdulelah, Alwajeeh, Rayed, Connors, Stephen R. and Alfaris, Anas. (2013). *Evaluating Scenario of capacity expansion given high seasonal variabilty of electricity demand : the case of saudi Arabia*. Cambridge, MA, USA. In Proceedings of the 31st International Conference of the System Dynamics Socity, 21-25.

To put this plan into execution KA-CARE published in 2013 a white paper giving some detail on the procurement process for renewable energy deployment outlining an introductory round of 500–800 MW projects, then a first round of 2,000 – 3,000 MW and a second round of 3,000 – 4,000 MW and so on to reach the plan’s targets (6), unfortunately little was done in the execution of the plan. Even some scholars argue that the KA-CARE’s plan was intended as scenario rather than an official target, new reports suggest that the plan has been pushed back by eight years with an objective 9.5 GW of renewables by 2022 and 54 GW (41 GW solar) it initial target to 2040 (15).

On the 25th of April 2016, the Deputy Crown Prince Mohammad bin Salman Al Saud launched “Vision 2030” plan with the aim to reduce the country’s dependence on oil while simultaneously improving the Kingdom’s investment status through opening opportunities for the private sector. This should be translated in the energy sector by a transformation in the energy sector within the country by increasing the capacity generated from renewable energy sources, redesign of the energy subsidy system, and the localization of the renewable energy value chain within the economy; through involving the private sector in research, development and manufacturing, an initial target of generating 9.5 GW of electricity from renewable sources set was through locally manufacturing parts of the required Moreover, a new city dedicated to energy will be created (5).

Within this context it, it is important to name the actors and institutions involved in field of renewable energy in the Kingdom, King Abdul-Aziz City for Science and Technology (KACST) is an independent scientific organization administratively reporting to the Prime Minister, KACST is involved in the development of renewable energy in Kingdom for long time both its also acts national science agency and national laboratories, the second important organization Saudi Arabia Solar Industries Association SASIA is a non-profit, non-governmental association promoting solar power in Saudi Arabia and across the Middle East. (25), within the new energy framework Saudi Aramco which is the national Saudi petroleum company (the largest oil exporter company) should play a major role in the transformation of energy sector as plans to change it to a global industrial company within the “Vision 2030” (5). Despite of number of institutions working the field of renewable energy, but their effort lacks of coordination with two organizations having the same task, for a fast-successful high penetration of renewable energy in Kingdom, better coordination is needed between the different institutions, clearer definitions of responsibilities and role between different actors insuring a better policy implementations in the field of renewable energy.

J. Current Renewable Projects In Saudi Arabia Status

The amount of electricity generated by solar projects in Saudi Arabia is almost insignificant compared to the existing potential. The Kingdom has several renewable projects, which are still small and capacity. Small scale PV projects were built in the Kingdom to provide power (cathode protection of petroleum pipelines) for the petroleum industry in remote areas starting from the sixties.

Table 4. Current renewable energy projects status as of 2014

Project	**Technology**	**Status**	**Size**	**Location**
SEC – Duba Integrated Solar Combined Cycle (ISCC) Power Plant Phase I	CSP	Under construction	50 MW	Duba
Saudi Aramco – KAPSARC	PV	Complete	3.5 MW	Riyadh
KAPSARC II	PV	Complete	1.8 MW	Riyadh
SEC – Farasan Island Solar Project	PV	Complete	500 kW	Farasan Island
KAUST	PV	Complete	2 MW	Thuwal
North Park	PV	Complete	10 MW	Dhahran
Tabuk KJC CPV	PV	Execution	1 MW	Tabuk

Source: Developing Renewable Energy Projects. (2015). *A guide to achieving success in the Middle East*. s.l., PwC, Eversheds.

Currently, the total installed capacity of renewable energy does not exceed 17 MW with projects of 125 MW in the pipeline, this number does not take into account the projects stipulated in KA-CARE plan round one which was put on hold. In comparison, the neighboring United Arab Emirates (which is 3% of the Kingdom's total area) with the same weather conditions has an installed capacity of 125 MW and 270 MW in the pipeline and a planned capacity of 2,248 MW by 2020 (6).

CHAPTER IV

TECHNOLOGY OVERVIEW

Before studying deployment both of photovoltaics and concentrated solar power in the Kingdom, it is important to start with a technological overview of both technologies, focusing on development of the technology, performance and cost.

There are several technologies, which can be used to generate electricity from the sun, he most widely used technologies are solar photovoltaics cells referred as PV and Concentrated Solar Power referred as CSP in, with 97% of generation coming PV and 3% by CSP at the end of 2013 (26):

A. Photovoltaics

Solar Photovoltaics is the most widely used solar technology directly converting sunlight into electricity (26), there are different PV technologies commercially available mainly those based on crystalline silicon cells (representing approximately 85% of the global market), thin-film cells, including amorphous silicon (a-Si) and cadmium telluride (Cd Te). Several new technologies are being developed and commercially tested. (27), no single technology has an advantage on all the three characteristics, first higher power conversion efficiency, second low materials usage and thirdly low manufacturing complexity and cost (26).

A photovoltaic module is made of several PV cells, which are wired together and encapsulated (protection from weather conditions) to form a PV module. A typical PV project would include tens to thousands of modules connected in arrays, generating DC (Direct Current), then converted to AC (Alternative Current) using an inverter to be used then with other ordinary electric equipment's (26).

B. Solar Photovoltaics Cost and Performance

The price PV cells and performance have improved greatly over the past several decades mainly due research and development, innovation, improved manufacturing techniques, and learning-curve improvements related the global PV markets growth and maturity.

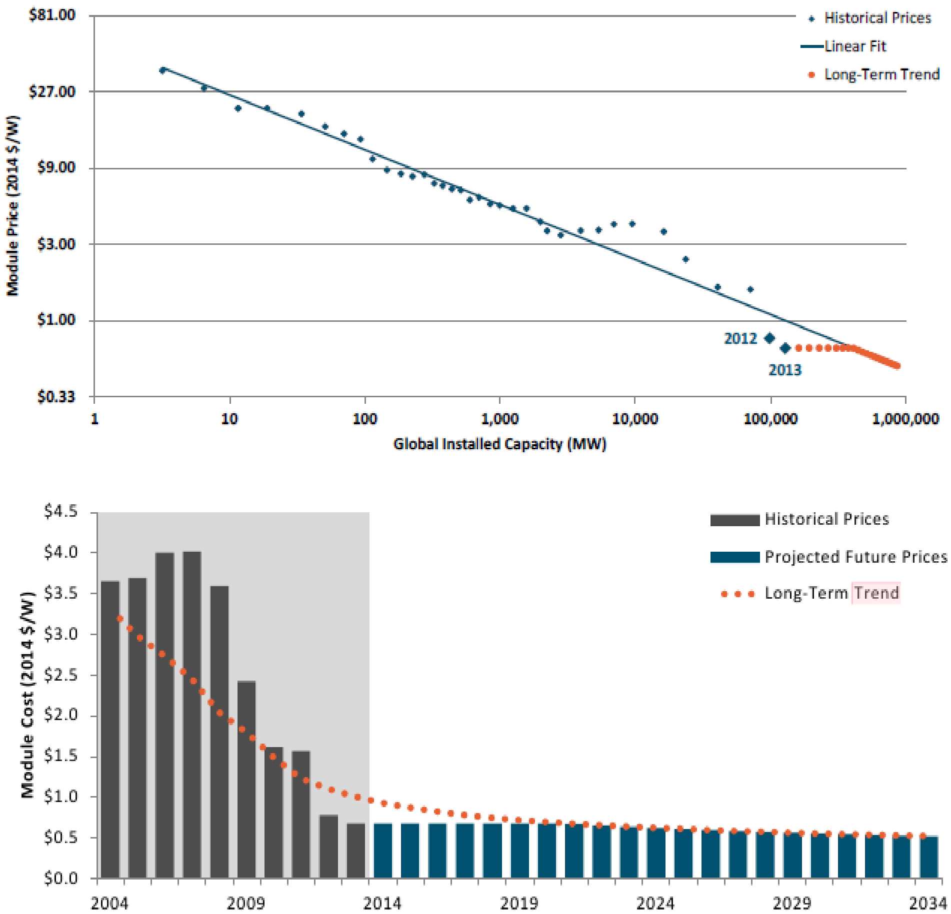

Fig. 8. Historic and projected solar PV module prices based on observed learning curve
Source: NREL. (2012). "Renewable Electricity Futures Study". Volume 2. Renewable Electricity Generation and Storage Technologies. S.l. and Olson, Arne, Schlag, Nick, Patel, Kush and Wok, Gabe K. (2014). Capital Cost Review of Power Generation Technologies. Prepared for the Western Electric Coordinating Council, Energy and Environmental Economics, Inc.

Since the early 1980s, PV module prices have decreased by more than 90%, selling price of modules has declined by approximately 20% for every doubling of cumulative installed capacity, with prices deviation from 2004-2008, based on a temporary imbalance between global supply and demand (higher demand), with prices below the learning curve because of disruption in the demand and supply in 2013 as the European Union imposed anti-dumping and anti-subsidy duties on imports of solar cells and solar panels from China)[13] (28).

PV prices has reached historically low prices despite that it shall continue to decrease at a slower rate by achieving improvements to existing technologies, and by developing new technologies with a potential for significant price breakthrough, cost reduction will come from increasing module efficiencies, manufacturing throughput increase, reduction of wafer thickness (crystalline silicon) or the thickness of the cells, along with other improvements (selective emitters). Other technologies including thin-film PV technologies have similar cost-reduction potentials (26).

C. Balance-of-Systems Costs for Solar Photovoltaics

PV projects costs are divided into module costs: direct cost of photovoltaic modules, non-module "hard" costs: costs of inverter, racking, electrical equipment, etc... and "soft costs": labor, permitting fees, etc., hard and soft are also referred as Balance-of-systems (BOS).

BOS costs are generally higher than module costs and are approximately in the range of 1-4 US$/W depending on system size, location, and project margins. BOS cost can be reduced by lowering the both the "hard costs", and "soft costs" (29), in the case

[13] http://trade.ec.europa.eu/doclib/press/index.cfm?id=1461.

of Saudi Arabia both costs should be higher for the first implemented projects as large part of the equipment will be imported, this should decrease significantly as more and more localization of the solar equipment value chain occurs, with some of the equipment manufactured locally like inverters, trackers, mounting hardware, etc.,

In the other hand, soft costs should be also lower than of other regions of the world as empty large areas of land is available in the Kingdom, favorable government renewable energy policies should help also in the decrease of permitting fees, finally design fees could be lower as number of projects increase and the market matures in the Kingdom.

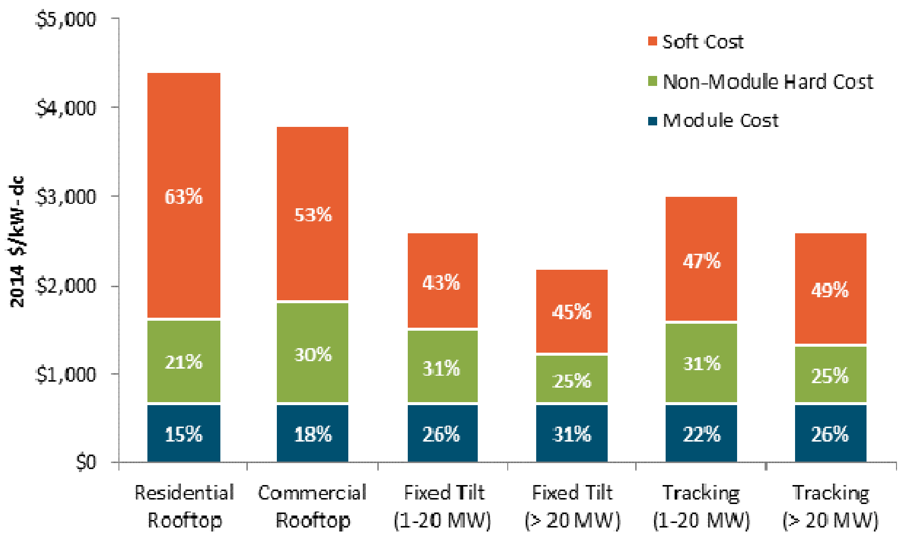

Fig. 9. Estimated breakdown of module and non-module “soft” and “hard” costs by solar PV segment
Source: Olson, Arne, Schlag, Nick, Patel, Kush and Wok, Gabe K. (2014). Capital Cost Review of Power Generation Technologies. Prepared for the Western Electric Coordinating Council, Energy and Environmental Economics, Inc.

Different capital costs for PV systems were recommended with 3,080 US$/kW (for monocrystalline ordinary cell, 1.4 inverter loading and Non tracking) and 25

US$/kW-yr. for Operations & Maintenance (29) another older source recommends a capital cost of 3,300 US$/kW with same specification and 48 US$/kW-yr. O&M. (27) newer projects tend to use lower prices for example the Dewa project in Dubai rated 260 MW project priced at 328 million US$ giving a capital cost of 1,225 US$/kW (thin film technology), the plant is expected to produce electricity at world record of 5.85 US cent/kWh, It is difficult to give an accurate pricing for PV projects as any price given will depend heavily on the project site and the technology used (10), a capital cost between 2,000 -3,000 US$/ kW should be within an acceptable range.

D. Market Trends in PV Power Plants

In 1999, the cumulative capacity of PV installed worldwide was less than 500 MW, from that time the market has grown rapidly, mainly in the second half of 2000, in 2012, the PV installed capacity worldwide reached 100 GW and 140 GW at the end 2013.

In 2000, the major PV markets were Europe to shift starting in 2011 to China and USA and other countries in the Asian regions, at the end of 2013 with the expansion of the Chinese market, the cumulative PV installed in China reached 19.7 GW, of which 16.3 GW was large scale projects and the rest for small scale (rooftop installations), annual PV installation in 2013 reached 13 GW (28).

PV power plants of several hundred of megawatts of capacity are in the commercial stage and feasible, with capacity record are broken every year, currently the number operating plants with a capacity of 100 MW exceeds 20 plants around the world, USA Topaz plant in California, which started operation in November 2014 has a size of 500 MW, in the UAE, a 260 MW plant should be completed shortly, it consists the second phase of the 1GW capacity at Mohammed bin Rashid Al Maktoum Solar

Park showing a growing interest in PV technology in the region (10).

Concerning the supply side, there was a significant increase in production, PV manufacturing companies worldwide, many companies could fulfil the increase in demand especially for new markets like the Chinese market, many companies has demonstrated the ability to expand from initial commercial manufacturing to become a major global player within five years (27).

Table 5. Manufacturing capacity for several solar PV companies (27)

Year	FirstSolar[b] (MW)	Suntech[c] (MW)	Yingli Green Energy Holding Company[d] (MW)	Trina Solar[e] (MW)	LDK Solar[f] (MW)
2005	25	150	50	—	—
2006	100	300	100	28	215
2007	308	540	200	150	420
2008	716	1,000	400	350	1,460
2009	1,228	1,100	600	600	1,800
2010	1,502	1,800	1,000	1,200	3,000
2011e[g]	2,308	2,400	1,700	1,900	4,000

[a] Manufacturing capacity represents the amount of PV capacity that could be manufactured in one year, and is generally higher than historical production.
[b] (FirstSolar 2011b)
[c] (Suntech Power 2011)
[d] (Yingli Green Energy Holding Company 2011)
[e] (Trina Solar 2011)
[f] (LDK Solar 2011); manufacturing capacity refers to poly-silicon wafers, not cells or modules.
[g] Expected

Source: NREL. (2012). "Renewable Electricity Futures Study". Volume 2. Renewable Electricity Generation and Storage Technologies. S.l.

E. Temperature Impact and Water Usage for PV System

Photovoltaics performance is affected negatively with increase of temperature and the built up of dust on the modules, as Saudi Arabia is located in an arid area and subjected to desert weather conditions, the impact of temperature, dust accumulation is of great importance in the design and installation of solar projects.

Except form the province of Asir on the south-western coast, Saudi Arabia has a desert climate with extreme heat during the day and sudden drop in temperature at night and very low annual rainfall, in the Riyadh region in the central province, very high temperatures are frequent and the temperature can easily reach 50º C in the summer with no humidity, even reaching 54° C with an average summer temperature of 45° C, generally heat becomes intense shortly after sunrise and lasts until sunset, followed by cool nights, in winter, the temperature is generally higher than 0° C with nearly no humidity, heat in spring and fall is moderate with average temperatures of 29° C, the coastal areas of the Kingdom are subjected to high temperature too but with high humidity ratios, eastern province is subjected to high temperature, with frequent sandstorms.

As temperature rises, PV cells semiconductors of the solar cells are subjected to band gap reduction thus reducing its voltage and lowering the output power, referred by the temperature co-efficient of PV modules (19), other factors affecting negatively the solar cells and modules beside high temperature is the large temperature differences between day and night, and the exposure to ultraviolet radiation, these two factors increase the degradation rates of solar cells and modules thus affecting the negatively the performance and reliability of solar installations.

Table 6. Shows different commercial efficiencies of different technologies and power temperature coefficients

Technology	**Commercial efficiency %**	**Theoretical efficiency %**	**Power temperature coefficient**
Mono crystalline	18.0	25	-0.38%°/C
Multi crystalline	14.5	25	-0.45%°/C
Thin film (CIGS)	12.2	30	-0.31%°/C
Thin film (CdTe)	12.8	30	-0.25%°/C

Source: CSP Today. (2014). *CSP Prosepects in Saudia Arabia* . s.l. MENASOL; available from http://www.csptoday.com/menasol; Internet; accessed February 20, 2017

Experiments carried in Saudi Arabia showed a drop between 30-45% in solar energy efficiency observed for a solar system not cleaned over three months, and a measured decrease of 60% in solar energy efficiency due to dust storms (30), unfortunately until now no international standardized method was developed for evaluating the durability and performance of PV modules under desert conditions.

Table 7. Comparing method of cleaning by water, examples in China

Methods	**Cleaning Equipment**	**Water Consumption (ton/10MW/times)**	**Cleaning speed**	**Cleaning result**	**Cleaning cost**
Wash +Wipe	Water pipe installation or water, transportation vehicles	100	Fast	Excellent	High
Spray + wipe	Water and spray pipe installation	50-60	Fast	Excellent	High
Special wash vehicle and machine	Cleaning equipment and water supply vehicles, water and equipment maintenance	30-40	Fast	Excellent	High
3 persons+Water	Very little equipment	10	Slow	Good	Low

Source: IEA - PVPS. 2015. "Energy from the Desert Very Large scale PV Pants for shifting to Renewable Energy Value". S.l. IEA - PVPS T8-01.

To solve the soiling problem (dust accumulation) cleaning is advised when the cleaning costs are is less than the income collected from the difference in the energy output due to cleaning, the cleaning process is influenced by the cost of labor and water therefore the choice is very much dependent of the local conditions, many technologies and solutions are in the development phase including special coating of panels (preventing dust accumulation), dry-type cleaning/dusting robots for PV panels, air blowing techniques, and electrostatic discharge screens, all these technologies are moving towards shifting from 'wet' to 'dry' cleaning, from 'restoration' to 'prevention' of panels' loss of efficiency (28). Table 7 shows water and labor requirements for large scale PV plants, this extra costs are generally underestimated when designing solar renewable systems but the extra cost affects the feasibility of the project on the long term.

F. Concentrating Solar Power

Beside PV, the other technology used to produce electricity from the sun is CSP technology, classified as indirect solar technology, as its use mirrors or lenses to focus sunlight onto a solar receiver, a thermal fluid is used to transfer the thermal energy in a closed-cycle to the heat engine which drive the electrical generator. The presence of a thermal fluid provides the possibility of adding energy storage tank and/or a natural gas backup boiler, which can provide electricity in absence of the sun thus improving the capacity factor[14] of the system. CSP systems with storage are in operation in Spain (Andasol 1 and 2) with more than 7 hours of storage. (26).

CSP systems can use one of the four different technologies approaches, parabolic trough concentrators that use a linear receiver with 1-axis tracking to collect concentrated sunlight, solar power towers system that use flat mirrors (heliostats) arrays with 2-axis tracking the sun into a fixed central receiver, linear Fresnel systems that use a fixed linear receiver and an array of heliostats with 1-axis tracking system, and finally dish concentrators using a dish with 2-axis tracking system.

Parabolic trough collectors were put into commercial use in 1984 and currently account for 96% of the global CSP deployment (27), CSP differs from PV systems (non-concentrating) that it only uses direct solar radiation, which makes it less effective

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[14] Capacity Factor of a power plant is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity.

in intermittent cloud cover or hazy skies, second, CSP is very sensitive to scale which means that systems need to be large (tens of megawatts or larger) to be economically feasible in terms of maximizing efficiency and minimizing costs; in contrast of PV systems that can be installed anywhere at scales ranging from a few kilowatts to hundreds of megawatts, a third challenge for CSP deployment is the large land and water requirements needed for large-scale CSP plants, as its operation is identical to conventional generation systems, (steam generator, turbine and condenser), dry cooling can be used in areas with scares water resources increasing the cost of CSP project greatly. (26)

The effect of temperature on the decrease of CSP systems efficiency is nearly similar to PV systems but less significant, but the reason behind it is completely different. The efficiency of solar field of a CSP system mainly depends on the thermal losses to the ambient air from the thermal fluid circulating in the absorber tubes and the piping, any increase in temperature should lower these losses and improve the efficiency of the solar field, but this rise will affect negatively the efficiency of the power block, as the increase in temperature will increase the condensate temperature thus lowering power block efficiency, the effect of reduction in the power block efficiency is much more than the overall increase solar field efficiency. Calculations under constant relative humidity conditions shows that average reduction in power block efficiency with increase in temperature is 0.01 %/°C. (19)

CSP plants use large areas to concentrate the sun, based on past projects and studies, 3 hectares are needed per megawatt of CSP capacity (3 km^2 for 300 MW plant), this should not be a problem in Saudi Arabia as the country has large unexploited lands which can be used for the installation of CSP projects (26).

CSP different technologies are impacted differently by dust and soiling, parabolic troughs are more affected by soiling than the heliostats used in solar tower and the slightly curved mirrors used in linear Fresnel technology, CSP plants are affected negatively by dust-storms, as dust particles absorb or scatter direct part of solar radiation reducing the direct normal irradiance reaching the CSP mirrors meaning a reduction in performance. (19)

Different capital costs of CSP trough system were recommended in a number of publications ranging from 5,000 US$/kW (Trough/ Tower, without storage, and 6,000 US$ for Trough/ Tower, with storage and 60 US$/kW-yr. O&M costs for dry cooling the capital cost is multiplied by 1.4 (31), other publications recommend of 8000 US$/kW with 6 hours storage (29), these values vary and are very much dependent on the technology used, site (land, connection to grid, labor).

CSP is not a mature technology yet, with substantial opportunities for technology advances that would result in the reduction of the capital costs considerably, thus reducing energy costs, these developments include, first, the use of heat transfer fluids operating at higher temperatures thus improving efficiency of system (reducing collector area and storage volumes), second, better system design including (optimal mirror sizing, advanced receiver coatings, low cost foundations and support structures), and third, better storage systems using higher temperature and phase change materials. Cost reduction potential estimates are in the range of 15% in the short-term (five years) and 30% in the long term (20 years), USA and Spain are leading in CSP technologies.

CHAPTER V

SIMULATION

Before plotting the generation output of renewables on the consumption curve of Saudi Arabia, it is imperative to simulate the output of both PV and CSP systems for givens locations in the Kingdom on an hourly basis using a renewable energy simulation software, in our case SAM was the choice.

A. The System Advisor Model (SAM)

Simulating the generation output of renewables is a complex process due to variable nature of the resource and sensitivity to both location and time. However, using System Advisor Model (SAM) software, developed by the U.S National Renewable Energy Laboratory (NREL), facilitate this task, since SAM is one of the best available free software. SAM is designed to predict the performance and establish a business model of renewable energy systems, the results can be viewed on different tables and graphs on an hourly, monthly and yearly basis.

Table 8. Locations in Saudi Arabia with available weather data

	City	**North°**	**West°**	**Altitude m**	**Zone**
1	Abha	18.23	42.65	2,093	South
2	Al Baha	20.30	41.65	1,652	South
3	Al-Madinah	24.55	39.70	636	Western
4	Arar	30.90	41.13	549	Eastern
5	Dhahran	26.28	50.17	17	Eastern
6	Hail	27.43	41.68	1,002	Central
7	Jeddah(King-Abdul)	21.70	39.18	17	Western
8	Makkah	21.43	39.78	240	Western
9	Riyadh-Obs(Oap)	24.70	46.73	620	Central
10	Tabuk	28.38	36.60	768	Western

SAM does hourly calculations and predicts the energy output of the system and can be applied to different technologies and locations (with the appropriate weather data), photovoltaics systems (non-tracking, tracking and concentrating) with battery storage, CSP including (parabolic trough, tower using molten salt and direct steam, linear Fresnel and dish Stirling engine (9).

Within the context of this work, SAM was used to simulate imaginary solar plants (PV and CSP) located in different regions of Saudi Arabia, using available weather data; SAM can interpret different file weather data, in the case of Saudi Arabia, (10 locations were chosen from the 27 available) covering all the Kingdom regions (representing the four electrical regions of country) (8). The imaginary solar plants are identical to currently operating plants around the world, the Cestas PV plant located in France (11) and Noor I and II, a solar CSP plants located in Morocco (10).

The Cestas solar farm, is 300 MW PV plant on a 250-hectare site (2.5 km^2) near to the French city of Bordeaux south of France, developed by Neoen[15] for a cost of 382 million US$, it was connected to the grid on November 2015, selling its energy for 11.1 US cents /kWh for 20 years (32).

Noor 1 plant is parabolic trough CSP plant located in Ouarzazate, south of Morocco, with a capacity 160 MW built by ACWA[16] power at cost 1.2 billion US$ selling its energy at price of 18.9 US cents/kWh, started production December 1, 2015 (33).

The simulated PV plant used standard PV modules, with DC to AC ratio of

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15 Neoen is an independent French renewable energy producer created in 2008.

16 ACWA is Saudi Company specialized in Energy projects.

1.4[17], fixed open track installation, and losses accounting 16.71% (5% soiling). Simulation results for the PV plant (for the ten Saudi locations) show a little difference in energy output between the chosen sites of the Kingdom, Abha shows better results than other areas: with better solar resources and a lower daily mean temperature because of the altitude 2093 m above sea level, also, little difference in the energy output between summer and winter is observed, capacity factor for the PV plants vary from 15% (low value) for Makkah and 18.9% for Abha confirming the negative effect of temperature and weather conditions on the PV system.

For the CSP, a 160 MW imaginary generic system (tower or trough) with 6 hours' storage was chosen, simulation results show that the performance of CSP system is better than the PV system with higher capacity factors ranging from 26.4% to 37.3% for CSP system without storage, Capacity factor values are increased by adding six hours of storage to reach 47.5% for the worst location and 63.5% in the best case; showing clearly that CSP systems are superior over PV, in terms of providing higher capacity factor especially when using storage, thus the ability of providing energy for a larger portion of 24 hours, below tables show the energy output of both PV and CSP systems for the ten Saudi locations (Abha, Al Baha, Al-Madinah, Arar, Dhahran, Hail, Jeddah, Makkah, Riyadh and Tabuk).

[17] DC to AC ratio also known array to inverter ratio which ranges between 1.1 - 1.4 increasing it improves solar economics.

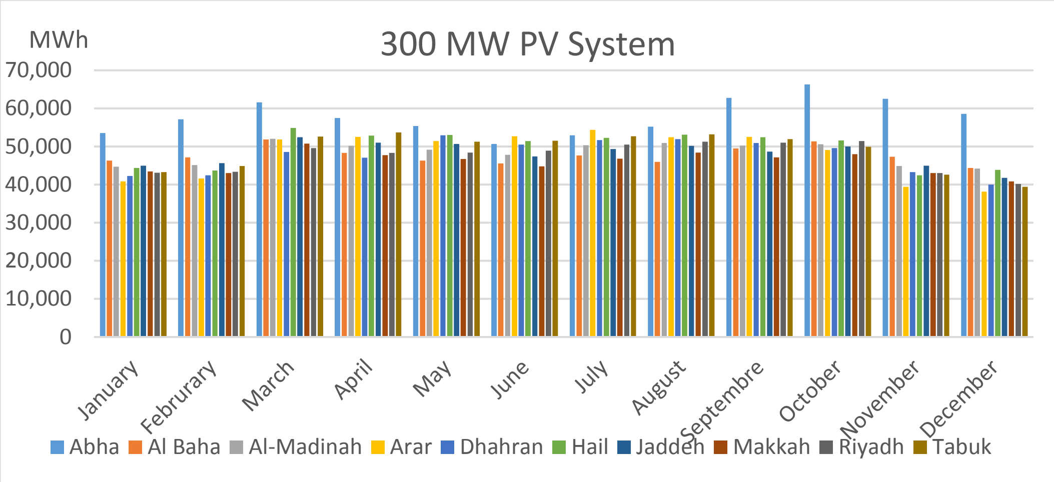

Fig. 10. Simulation results of PV system and monthly output for different locations in the Kingdom, SAM Simulation

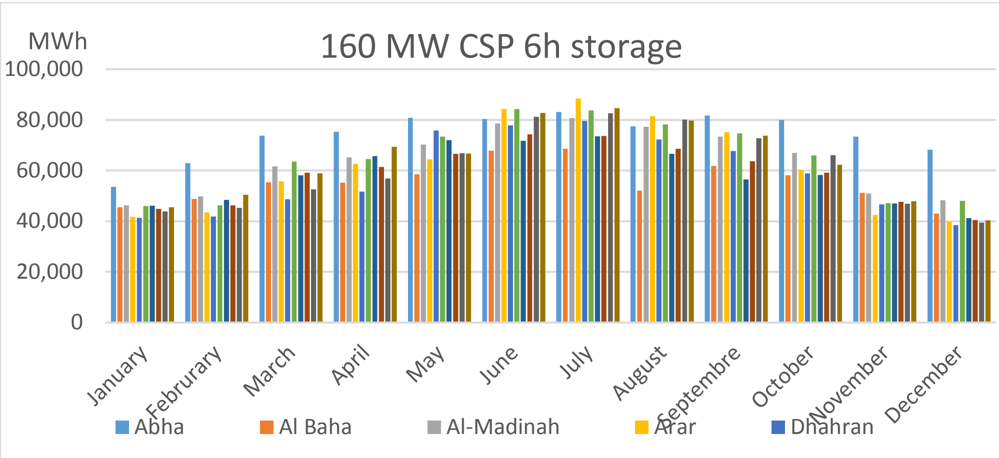

Fig. 11. Simulation results of 160 MW CSP plant and monthly output for different locations in the Kingdom, SAM Simulation

To calculate the levelised cost of electricity (LCOE), the Riyadh region was taken as reference (mean energy output among the ten regions), for the financial calculations, a capital cost of 2,500 US$/kW was used for 300 MW PV plant, no tracking and 2,800 US$/kW for one-axis tracking; a fixed operating cost of 25 US$/kW-yr., and an interest rate of 4%, this capital cost should represent an average price until 2030 (29).

Table 9. Simulation results for 300 MW PV plant located in Riyadh region using SAM

	Non-tracking	One axis tracking
Annual energy produced MWh	568,951	656,871
Capacity factor %	15.5	17.9
LCOE US cent /kWh	9.23	7.98

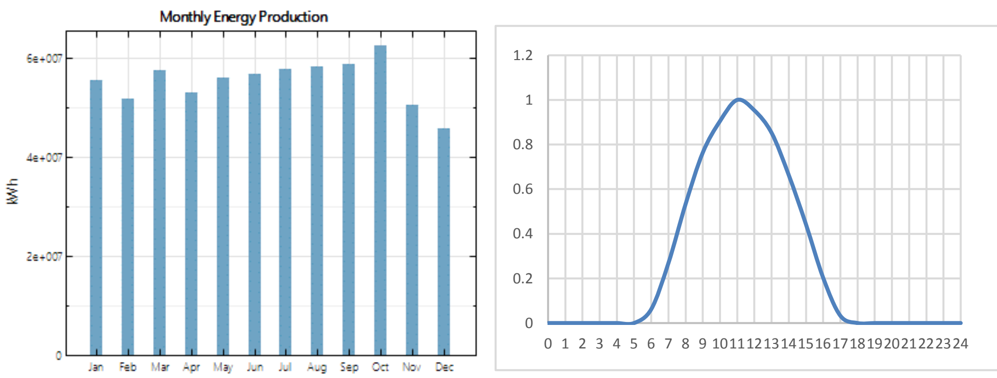

Fig. 12. Monthly (left) and daily (right) energy output from 300 MW PV plant, SAM simulation

Table 10. Simulation results for 160 MW CSP 6 hours' storage plant located in Riyadh using SAM

	CSP no storage	CSP 6 hours' storage
Annual energy produced MWh	516,053	734,356
Capacity factor %	36.8	52.4
LCOE US cent /kWh	12.69	12.28

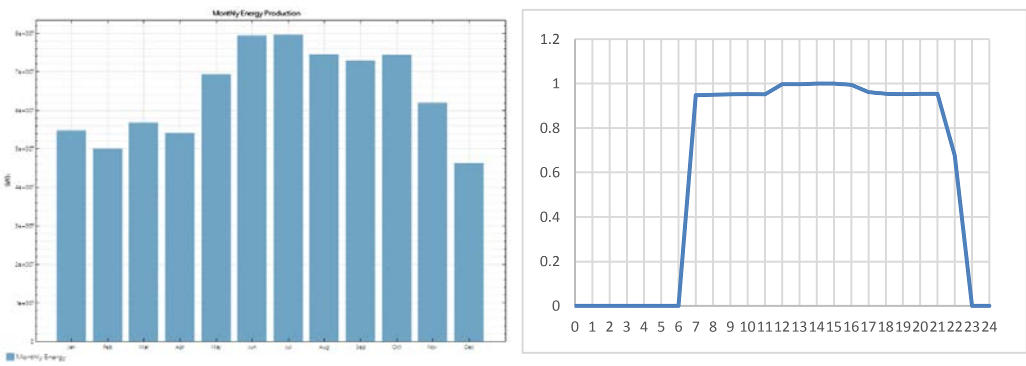

Fig. 13. Monthly (left) and daily (right) output from 160 CSP plant 6-hour storage, SAM simulation

For CSP systems simulation, the capital cost of 5,500 US$/kW for no storage for a plant of capacity of 160 MW was used and 8,000 US$/kW for 6 hours' storage, a fixed operating cost of $60/kW-yr. and an interest rate of 4%. (29)

Simulated LCOE values for the PV system ranged from (9.23 US cent for non-tracking, 7.98 US cent for one axe tracking) which is less than the selling price of Cetas plant at 11.1 US cents /kWh, but higher of the selling price of the solar plant in UAE at 5.83US cents /kWh, according to Lazard levelised cost of energy analysis in 2015 the LCOE for PV system ranges between 5.8 -7.0 US cents /kWh solar for PV Crystalline utility scale, 5.0 – 6.0 US cents /kWh, these values do not account for differences in heat coefficients, balance-of-system costs or other potential factors which may differ across solar technologies (34).

For the CSP systems, the LCOE values range from 12.69 US cents /kWh for CSP with no storage and 12.28 US cents /kWh for CSP, which also less than the selling price electricity of Noor I plant in Morocco, which is 18.9 US cents /kWh, according to Lazard levelised cost of energy analysis the LCOE for levelised cost of energy for CSP system with storage range between 11.9 -18.1 US cents /kWh, Low end represents concentrating solar tower with 18-hour storage capability and high end represents concentrating solar tower with 10-hour storage capability (34).

B. Load Duration and Residual cuvre

To study the effect of the renewables on the Saudi electricity system the load duration and the residual curve concepts are used, taking the simulation results as an input for building the residual curve from the load duration curve.

It is known that electricity demand (defined as load) is not stable and fluctuates across the day and year but never drops to zero as there is always a minimum load known as the baseload, this baseload is usually covered by baseload power plants, like steam power plants, Nuclear energy plants and more recently CCGT (Combined Cycle Gas Turbine) characterized by high capital costs and low variable costs (fuel costs).

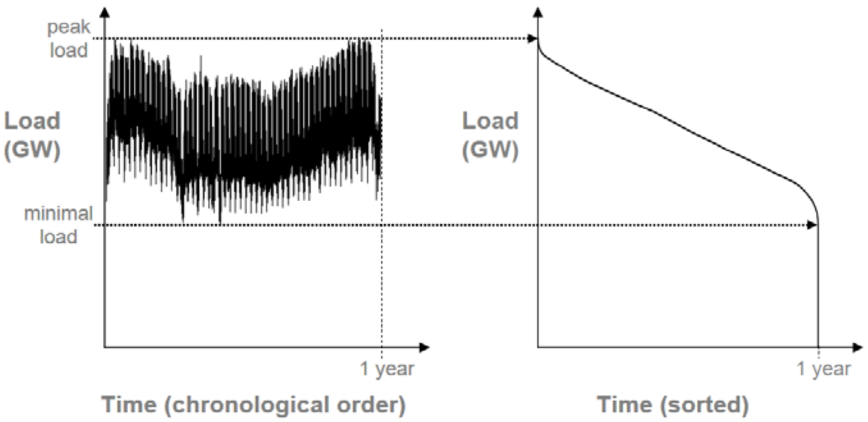

Fig. 14. Load duration curve (left) is derived from sorting load curve (right)
Source: Ueckerdt, Falko, Brecha, Robert J., Luderer, Gunnar, Sullivan, Patrick, Schmid, Eva Bauer, Nico and Böttger, Diana. (2011). "Variable Renewable Energy in modeling climate change mitigation scenarios". s.l. in Proceedings of the International Energy Workshop.

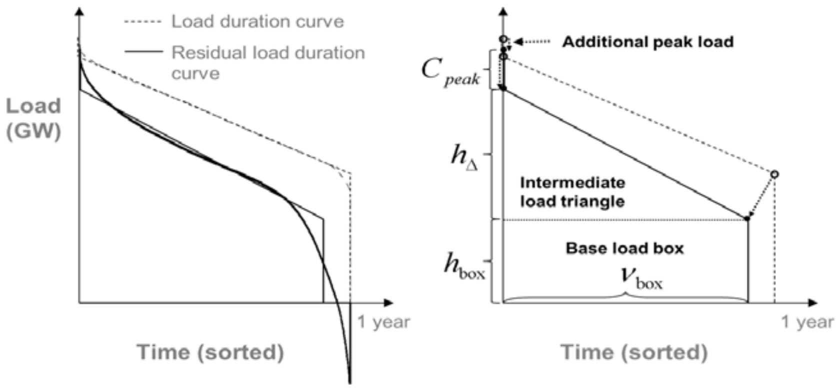

Fig. 15. The load is approximated by a box and a triangle (Base load and Intermediate load triangle) load (left). The transformation is controlled by the change of four parameters (νbox, hbox, hΔ and Cpeak).
Source: Ueckerdt, Falko, Brecha, Robert J., Luderer, Gunnar, Sullivan, Patrick, Schmid, Eva Bauer, Nico and Böttger, Diana. (2011). "Variable Renewable Energy in modeling climate change mitigation scenarios". s.l. in Proceedings of the International Energy Workshop.

On the other hand, the peak load which occurs for shorter periods than the baseload and which needs to be instantly and continuously covered by peak power plants, such as gas turbines, characterized by fast response to load change, and by low capital and high variable costs (18).

Unlike dispatchable[18] conventional generation plants, power generation from renewable sources such as wind and solar power vary continuously depending on weather conditions, renewables are considered variable sources of energy and are difficult to incorporate with the conventional energy generation systems, to visualize the interaction between the two types of generation, the load duration and residual curves are used.

A load-duration curve is a representation of the load that shows the number of hours of the year at which the load is equal to or above a given value, to build a load duration curve, the peak loads of the system in percentage or in GW are sorted in a decreasing order, which makes it easy to see when the load exceeds a certain level, a flat load duration indicates a better grid (a small intermediate tringle) where dispatchable generation is less needed.

From the yearly load, it is easy to derive the duration curve, which represents the cumulative amount of time during which demand exceeds a certain level, while the area under the curve represents total energy produced in kWh/yr., MWh/yr. or GWh/yr. (30).

$$LDC(t) = sort[Load(t)]$$

Adding renewables to the load curve poses some challenges in dealing with the variability, using a derived method from the duration curve it is possible to define a

[18] Dispatchable Generation is a source of electricity that can be started or dispatched

residual load-duration curve:

$$ResLDC(t)=sort[Load(t)-GenerationRES(t)]$$

This residual curve is obtained by sorting the load duration curve minus the energy output of the renewable sources (in other word the renewable source is considered a negative generators), with the area between the two curves representing the energy produced from the renewables. The resulting curve (residual) below represents the new duration curve which should be covered by all the other types of generation (35).

As the penetration of renewables increases within an electrical grid, the variable nature output will become a more important feature of power systems and will have impact on the amount of capacity to be covered because of this variability (35).

C. Numerical Results

To study the different penetration scenarios of solar energy on Saudi electricity system, the hourly load variations of 2009 were used to represent the 2030 load variation (24) taking into account the high peak load value is 120 GW, and the minimum peak load is 60 GW, assuming also no change in the consumption patterns due to the implementation of an energy efficiency programmes, which may result in high gains in the cooling efficiency, or a change consumer behavior changing the load patterns.

By sorting the 2030 hourly load variation in the descending order the corresponding load curve of 2030 is obtained, this curve can be simplified to a trapezoidal area representing a load of 788,400 GWh, this area can be divided into two distinctive areas, a rectangle representing base load 525,600 GWh and a tringle above the rectangle representing the intermediate load 262,800 GWh.

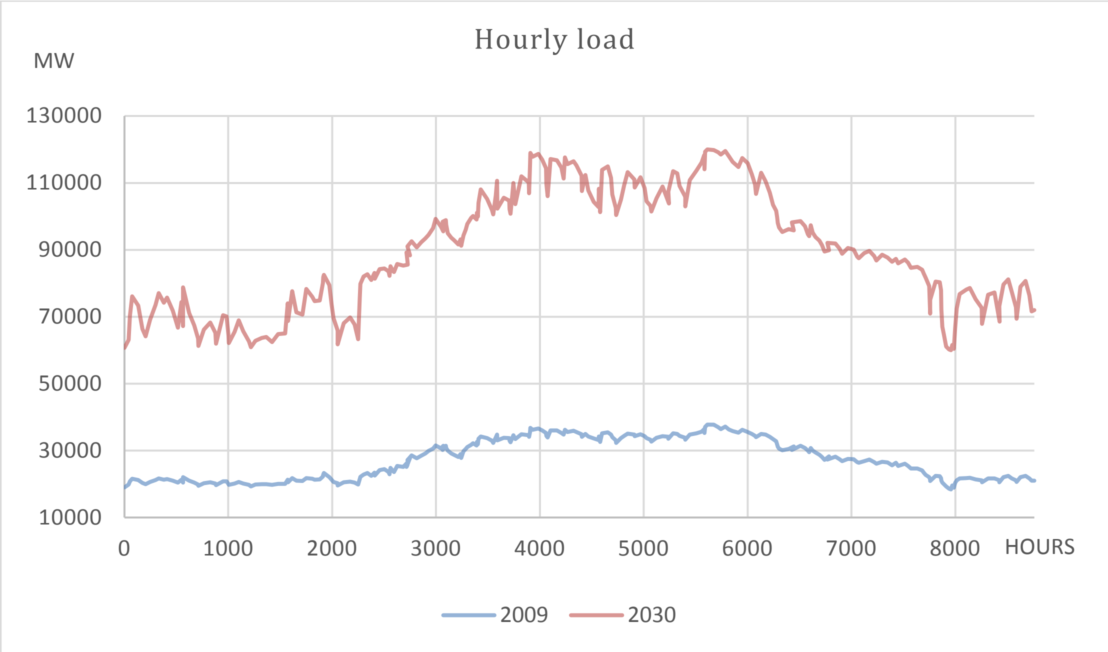

Fig. 16. Hourly load 2030 derived from hourly load of 2009
Source: Farnoosh, Arash, Frederic Lantz, and Jacques Percebois. "Electricity generation analyses in an oil-exporting country: Transition to non-fossil fuel based power units in Saudi Arabia." *Energy* 69 (2014): 299-308 and author calculations.

The residual duration curve for 2030 (due to use of renewables) will be the duration curve minus the sorted energy generated from the renewable sources simulated on an hourly basis.

Based on the simulation results, three scenarios were studied, the first consists the deployment of 9.5 GW of PV power (according to vision 2030) which represents 7% of peak load, the difference between the load curve and residual curve is minimal, with a minor effect on the baseload, with 18,685 GWh of electricity generated from renewables representing only 2% of total needed electricity energy, representing a saving 68,049 barrels of oil daily (using actual heating rate for the calculation), this low output can be attributed to the low capacity factor of the PV system.

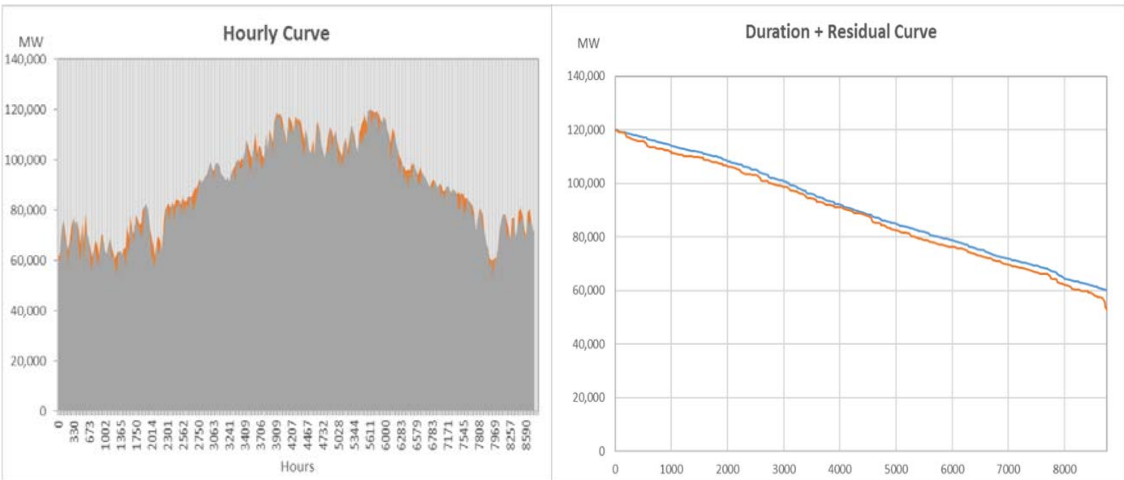

Fig. 17. Duration and residual curve for 9.5 GW PV “Saudi Vision 2030”
Source: author calculations.

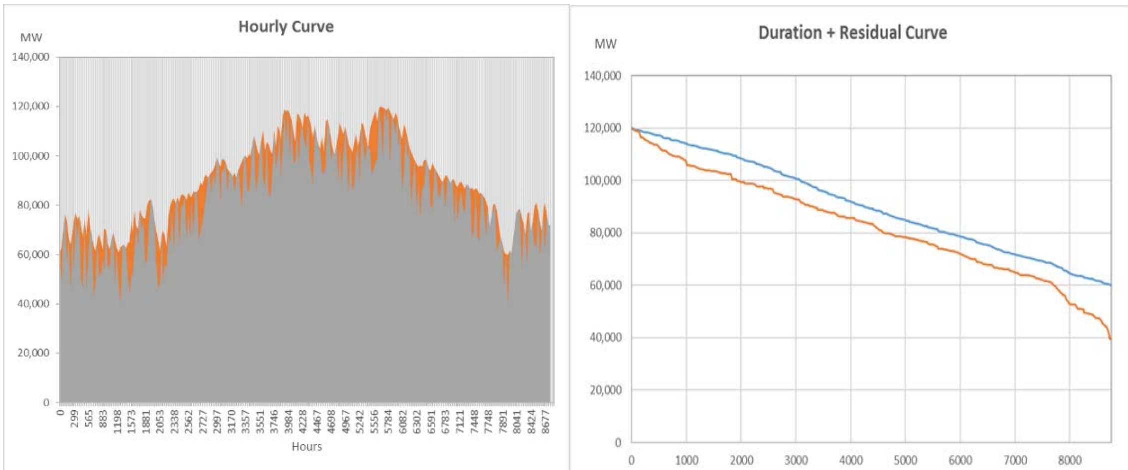

Fig. 18. Duration and residual curve for a modified plan 26 GW of solar renewables (16 PV and 10 GW CSP with 6 hours’ storage
Source: author calculations.

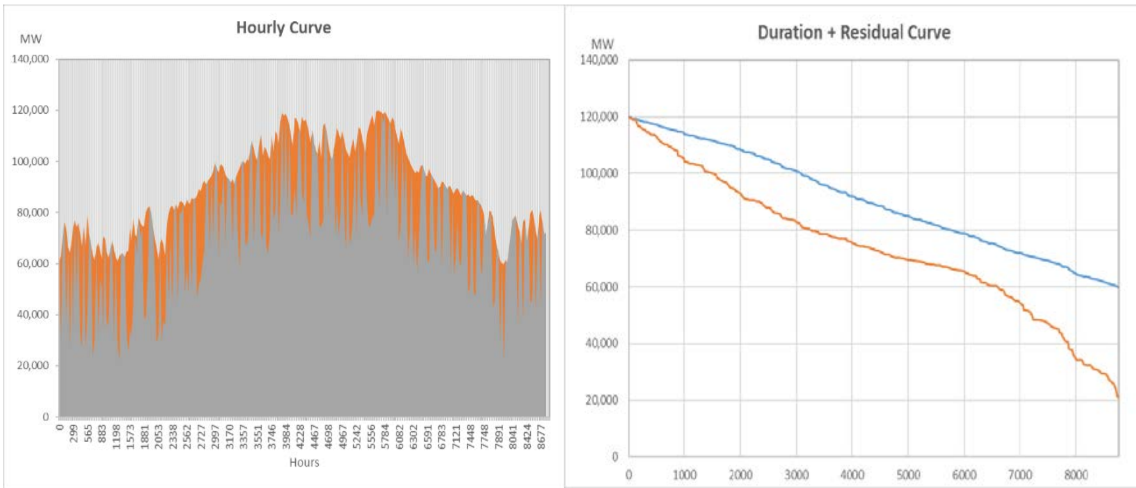

Fig. 19. Duration and residual curve for 41 GW (16 GW PV and 25 GW CSP) KA-CARE plan ”*Source*: author calculations.

Another deployment scenario which offers a compromise between the very ambitious KA-CARE deployment plan and “Saudi Vision 2030” modest targets, consists of the deployment of 16 GW of PV and 10 GW of CSP with 6 hours of storage. for this deployment, the difference between the load curve and residual curve is bigger with a decrease of baseload to value of 350,400 GWh, with a quantity 75,692 GWh of electricity generated from the renewables sources representing nearly 9% of electricity needs in 2030 ,and a saving of 275,661 barrels of oil daily, with a yearly gain of 5 billion US$ for an oil price at a price 50 US$/ barrel.

The third scenario is the implementation of the solar part of the KA-CARE plan, which consists of the deployment of 41 GW (16 GW PV and 25 GW CSP) for this deployment, the difference between the load curve and residual curve is the biggest, with a decrease of baseload to 175,200 GWh, and a quantity of 141,934 GWh of electricity generated by renewables representing nearly 18% of electricity needs in 2030, and a saving of 516,906 barrels.

Integrating renewable energies to the electricity grid offer many benefits and challenges: starting with the reduction generation capacities (as renewables lower the load duration curve) obliging many dispatchable power generation plant to ramp up[19] and be downed, but in the other hands introducing renewable energies tend to increase the need of flexible generation capacities (36) (Saudi Arabia relies 60% of electricity generating capacity on Gas turbine plants making it less difficult to integrate renewable energies). Another challenge is that only a small part renewable energy output can be considered reliable enough to be used in peak-demand situations, thus requiring an increase of dispatchable capacity reserves (36) (peak load/capacity ratio was around 92.14% Saudi Arabia in 2013). Finally, the overproduction of the renewable energy sources in the case of high penetration cannot be used directly and should be stored or transmitted, this effect is minimized by a proper deployment of renewables geographically, regional inter connections and storage solutions. In our case, over production in renewable sources for Saudi Arabia is observed over 25 % of penetration, unfortunately, Saudi Arabia cannot rely on pumped storage power storage used in many countries to cope with sudden peak increases or to store over production; but instead any over produced electricity can be used for producing water using RO technologies which then stored for future demand (technical aspects and feasibility should be investigated).

In the terms of numbers, for a zero-renewable penetration and with the simplification of the load curve into rectangle representing the baseload and tringle representing intermediate load, the baseload value will be 525,600 GWh and the intermediate load 262,800 GWh. For a 10% penetration of renewables, the baseload is decreased to 350,440 GWh and the intermediate load is increased to 350,440 GWh,

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[19] Ramp rate, expressed in megawatts per minute, is the time that a generator need to change its output

when penetration reaches 25% only the intermediate load is left with value 550,600 GWh, increasing the penetration to 50% the intermediate load becomes of 390,000 GWh and is only needed for 6500 hour and a over produced energy of 67,800 GWh need to be stored.

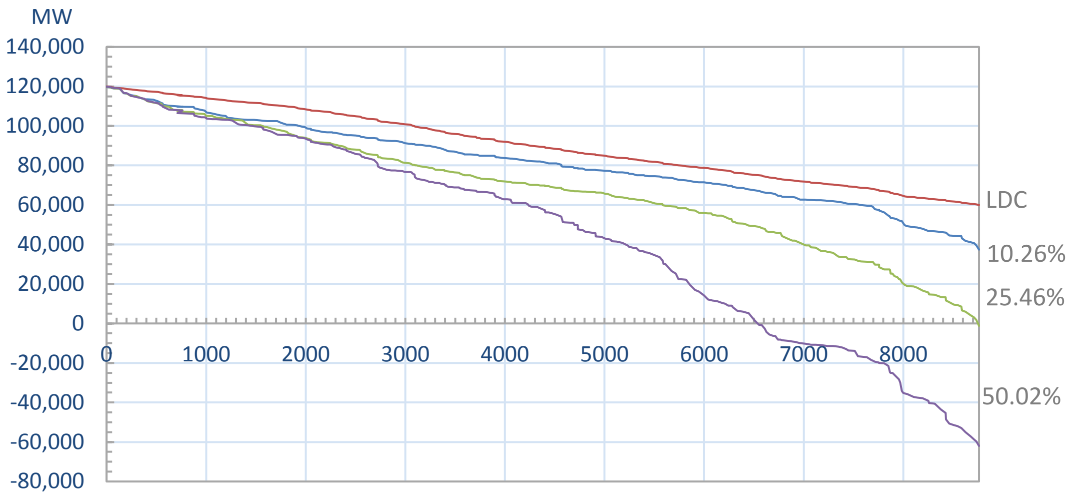

Fig. 20. Residual and duration curve for different penetration percentages with (PV:CSP ratio 2:1) *Source*: author calculations.

D. Cost of Generation Screening Curves with Merit-Order Dispatch

Screening curves are generally associated to load duration and residual curve, used to estimate the optimal generating mix for serving a load at the lowest-cost, screening curves are a very useful tool used for capacity-expansion planning, and determining the costs of generation of different technologies, this simplified approach does not take in consideration the starting cost, ramping constraints and other system consideration like transmission losses (37).

Screening curves also provide the possibility in examining cost curves of all power technologies plants from “peaking” generation plants (low capital cost, high variable cost) offering the cheapest choice when used at low capacity factor generally consisting of Gas turbine, “intermediate ” generation plants (medium capital cost, medium variable cost) offering the cheapest choice when used at medium capacity factor and, and finally “baseload” generation (high capital cost, low variable cost,) offering is cheapest choice when used at high capacity factor generally covered by steam turbines, and more recently by combined cycle power plants (38).

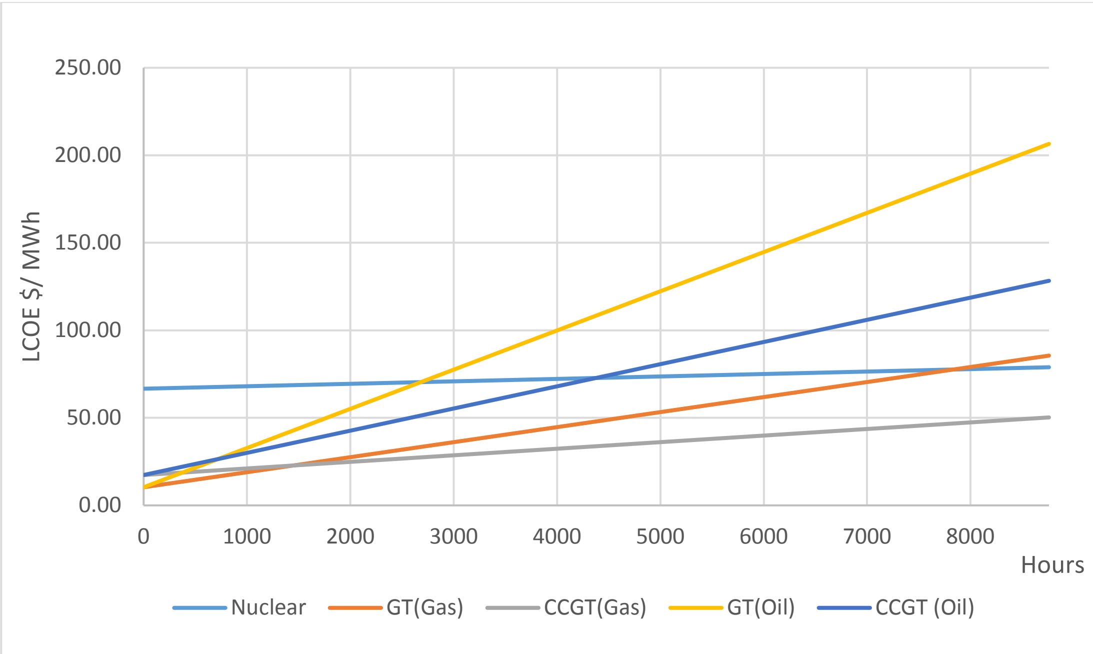

Fig. 21. Screening curve for generation cost of different technologies in $/MWh using 2014 fuel prices
Source: Author calculations.

With the difficulty to predict the price of oil in 2030, calculations were made taking in 2014 average prices of different petroleum products, using different capital cost of generation, operation and maintenance costs and heat rate of different generation technologies, these results are shown in Appendices I and II.

In 2014, the prices of oil and gas were relatively high compared to 2016 prices, with average price of a barrel of oil averaging 96.24 US$ (39). However, this prices do not reflect the real price paid by the Saudi operators and SEC to the government for subsidized fuel, resulting in very low generating prices making any new generation technology not able to compete; even with the reliance Saudi Arabia on Gas turbines for most of its generation which is considered not very economical for baseload coverage,

The decision to use gas turbines for generation is probably motivated by the abundance of energy (petrol and gas) in contrast of scarcity of the water resources in the Kingdom. It also shows that both gas fired CCGT and heavy oil steam turbines (despite heavy environmental burden) offer the best baseload options.

Table 11. Cost of generation in Saudi Arabia of different technologies using subsidized prices

Fuel/Technology	**Gas-light oil / GT**	**Gas- light oil/ CCGT**	**Heavy Oil/ ST**	**Diesel/ Diesel**
Fixed Cost (US$/MWh)	10.37	17.35	14.77	66.98
Var.Cost(US$/MWh)	37.69	8.70	8.23	21.50
LCOE (US cent/kWh)	4.81	2.60	2.30	8.85
LCOE (US$/MWh)	48.1	26.	23.0	88.5

Source: Author calculations.

All the new investments in the power sector in the Kingdom should be directed towards the use more efficient fuels (gas) and technologies, freeing more oil for export and compensating for the higher costs needed to introduce renewable energy to the market. Saudi Arabia should gradually switch to gas fired power plants, building more efficient combined cycle plants to replace its aging steam plants.

Table 12. Number of years needed to deplete Saudi Gas reserves using different technologies

	GT	CCGT	Actual[20]
No Renewables (years)	37	55	52
9.5 GW PV	38	57	53
16 GW PV 10 GW CSP 6H storage	41	61	57

On the other hand, the Kingdom has large quantities of gas reserves mainly in the form of associated gas (by-product obtained from oil extraction), but the country lacks the infrastructure needed for exporting natural gas, more gas usage in electricity generation will allow more oil to be freed for export. If renewables and solar energy are integrated into Saudi Arabia's energy mix, then, the lifetime of the Kingdom's natural gas reserves could be extended by 10 to 15 years depending on the technology used.

E. Investment Needs

To complete the study, investments needs until 2030 was calculated using the different deployment scenarios, starting with KA-CARE (16 GW PV, 25 GW CSP and 17.6 GW of nuclear power), the following capital cost of different technologies were used for the calculations 2,500 US$/ kW for PV, 6800 US$/kW for CSP with 6 hours' storage (less than value taken for LCOE calculation, assuming a significant reduction in CSP capital cost until 2030) (29) and 5,530 US$/ kW for Nuclear energy (40).

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20 Actual Saudi generation mix is composed 57% Gas turbine, 1% Diesel, 12% Combined cycle, 30% steam turbine author calculations

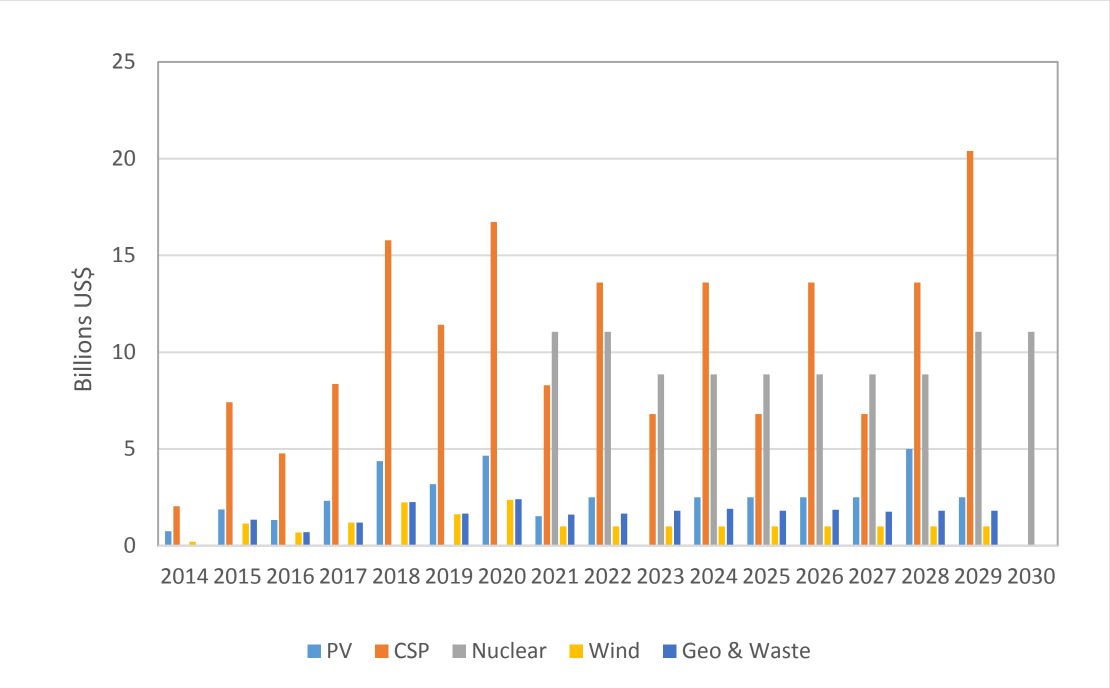

Fig. 22. Investment in Billion US$ needed to implement the original KA-CARE plan (16 GW PV, 25 CSP and 17.6 GW Nuclear) *Source*: author calculations

If the KA-CARE plan was implemented, the total investments for this scenario is expected to reach about 360 billion US$ by the end 2030, which is a considerable amount in the current financial situation of the Kingdom, CSP investments represents the biggest part, as the capital cost of CSP is the highest compared with other technologies, despite being more expensive, solar CSP offers many advantages, one of them that it is less sensitive to climatic conditions than PV technology (19), it has also the ability to incorporate energy storage and fuel back-up which transform CSP power generation from an intermittent to dispatchable source, the 50 MW CSP project in Duba, in Saudi Arabia, is an example of such initiative (600 MW Combined cycle plant coupled with backup system 50 MW CSP).

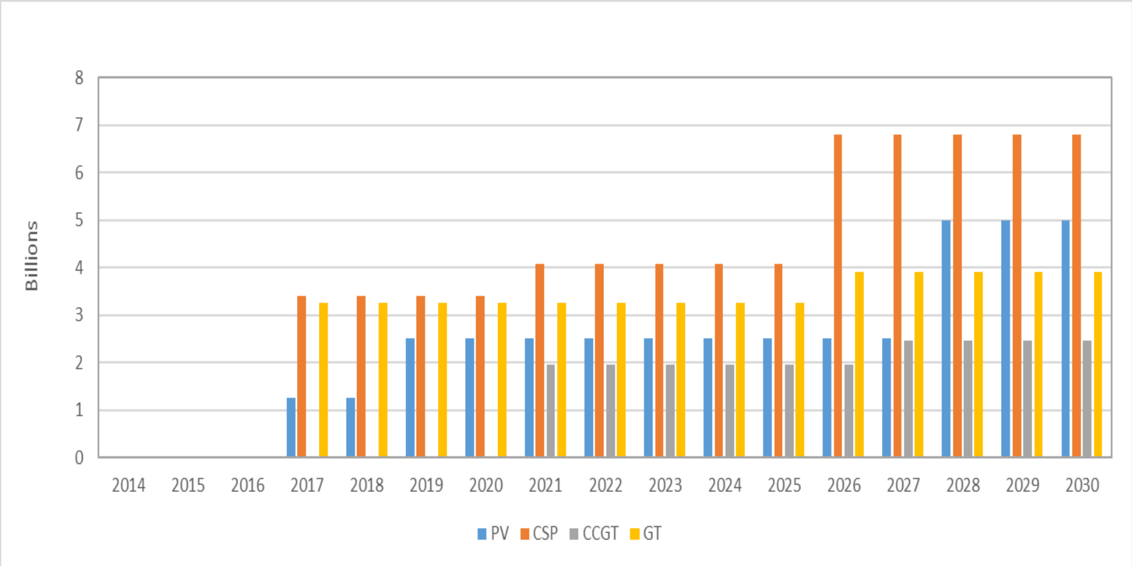

Fig. 23. Investment in Billion US$ needed to implement the modified plan (16 GW PV, 10 CSP and 17.6 GW CGGT and 30 GW GT *Source*: author calculations

A cheaper and more feasible scenario consists of replacing nuclear reactors in the original KA-CARE plan with CCGT power plants, besides being cheaper, the construction time for CCGT plants is shorter in time (60 months for 1000 MW reactor compared to 41 months for 580 MW CCGT power plant with Nuclear power reactors generally exceed their construction period (27), a capacity 30 GW of Gas turbine will be needed to cover the intermittency of the renewable resources (16 GW PV and 10 GW CSP are equivalent to 9.6 GW of full disputable source according to simulation calculations), The total investments needed for this scenarios amount to 150 billion US$, which represent nearly the half what was needed by the original KA-CARE plan.

Deployment of renewable energy in Saudi Arabia should be accompanied by localization of the value chain, for PV systems, the localization of BOS (Balance of the system) activities can be the first step; this could include manufacturing support structures, trackers, mounting hardware, electric protection devices, wiring, monitoring equipment and installation (27), as a second setup in the localization, a solar cell manufacturing facility can be built in the country, the capital required to build a 1 GW/yr.

PV manufacturing facility cost ranges between 1 and 2 billion US$ per plant (27), with a start a 500 MW capacity and increasing the plant capacity by 500 MW yearly; the size of the plant will reach a capacity of 7 GW by 2030, a typical PV plant needs 2 persons/ MW in the construction stage, 7.5 person/ MW in the operation stage and 0.5 person/ MW for maintenance, by the end of the project 57,000 persons should be directly employed.

In 2012, the PV industry in the World created 3-7 direct jobs and 10-20 indirect jobs per MW produced. With a capacity 7 GW capacity in 2030 around 21,000-50,000 direct jobs and 70,000-140,000 indirect jobs should be created.

Localization of the CSP technology will be more difficult than PV and should take more time, as it is a more complex industry, but in contrast, it shares a lot of parts with the conventional generation technologies (boiler, turbine, condenser), as Saudi Arabia is increasingly looking for the localization of new industries, CSP technology could be one of these industries (28).

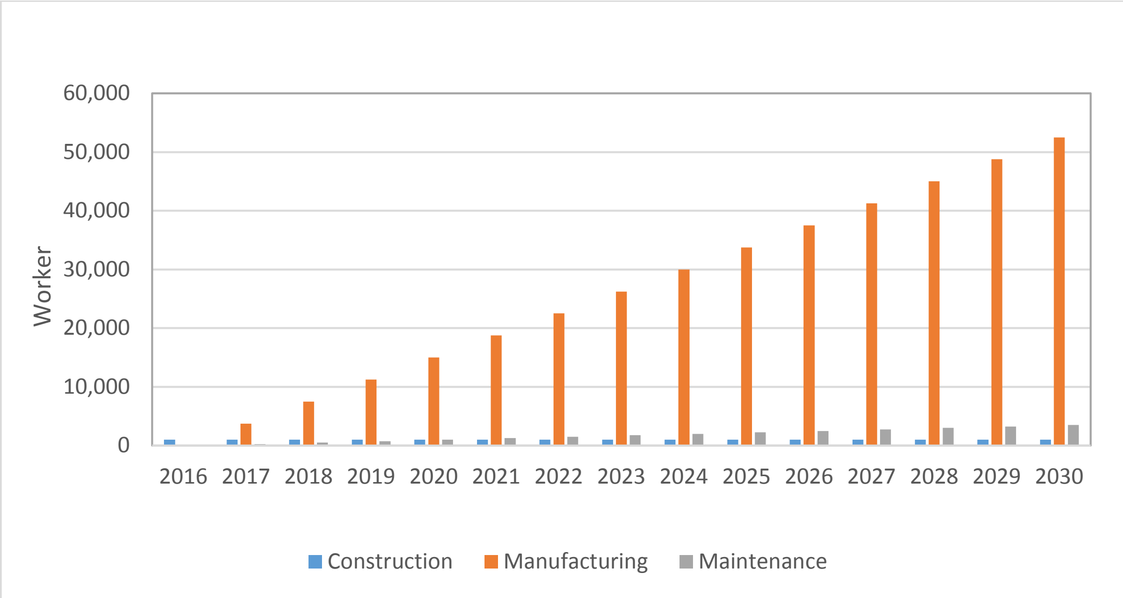

Fig. 24. Number of persons employed in PV manufacturing plant starting with 500 MW plant with a yearly increase of 500 MW/yr. reaching 7 GW of manufacturing capacity by 2030 *Source*: author calculations

CHAPTER VI

ENERGY TRANSFORMATION FRAMEWORK

Following the discussion of the benefits of adding renewable energies in Saudi Arabia's electricity grid, beside the economic factors discussed earlier, it is important also to discuss the policies needed to promote renewable energies in the Kingdom. High penetration of renewable energy in the Kingdom will need an important transformation of the energy sector, which resembles to the introduction of a new technology in any country or market.

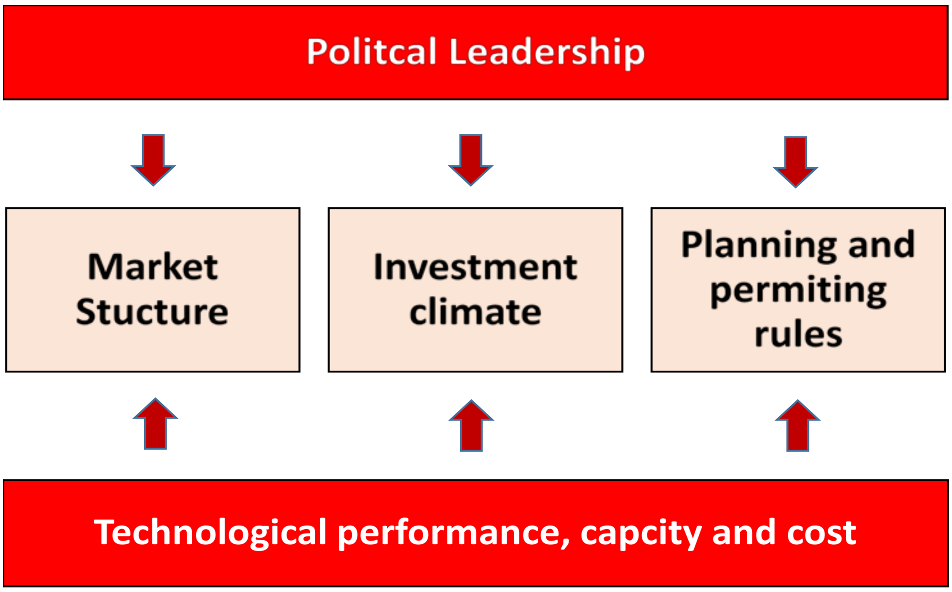

Fig. 25. Elements of the power system transformation, moving towards 100% renewable electricity in Europe & North Africa by 2050, *Source:* Achieving your solar potential, PwC Services and Citations, PWC 2011

History shows that for a new technology to move from a niche to a mainstream depends on events and elements happening at three levels, at the top level is political leadership which is needed to support the new technology implementation, the second is related to the type of the technology introduced and if it has the capacity to perform the job at the desired cost, on the middle level three main issues are to be addressed including the market structure, the investment climate within which project developers obtain financing and finally the permitting rules and regulations (41) .

Within this context, the recent restructuring in electricity sector in Saudi Arabia through the unbundling of Saudi Electricity company, creation of KA-CARE, “Saudi Vision 2030”, and other initiatives, shows an increasing political interest in the renewable energies by the Saudi leaders with a more sustainable approach to the energy sector, even that the energy sector is still strongly dominated the strong oil sector.

The under-development of renewable energies in Kingdom is due to a heavy oil-based economy, highly subsidized energy sector with very low fuel prices paid by the private sector generating companies, very low electricity prices which makes the Kingdom among the cheapest in the world, encouraging high consumption. despite some restructuring efforts within the Saudi electricity sector by gathering the companies in four regions under the authority the Saudi Electric Company, and establishing the National Electricity Transmission Company, there is still room for restructuring the sector to be more competitive and allow more room for introduction of renewable energy projects. Saudi Arabia was slower starting this energy transformation process compared to the neighboring UAE, a number renewable projects, creation of Masdar city.

Saudi Arabia is still in the process of establishing the regulatory framework to its energy sector and to support renewable energy producers from the private sector, for example, Germany high penetration of PV power were boosted by favorable tariffs for renewable generating companies and individuals. (7)

All the existing entities needed for leading the energy transition are still new or yet to be established or their role enforced, KA-CARE was established in 2010 with the aim of establishing an ambitious plan for renewable deployment unfortunately after seven years these plans never materialized, “Saudi Vision 2030”, should form a new commitment of the political leadership in initiating an energy transformation plan with a greater role of the private sector in implementing vision 2030 goals related to renewable energy. (5)

Until recently, renewable energies were never considered a serious competitor to conventional generation, consequently, very little research and development were carried in the Kingdom, further research on the effect of sand storms, soiling, aging and high temperature effects (mainly on PV systems) will be required, solar equipment standards specific Saudi Arabia developed.

The localization of renewable technologies should be viewed by Saudi policy makers as a top priority, Saudi Arabia can rely on a number of countries to develop its renewable energy sector such as China and Germany for PV (China is the world leader in solar photovoltaics manufacturing and installation with 13 GW of capacity installed 2013) (28), Denmark and India for wind power (the Indian wind energy sector has an installed capacity of 23,439 MW by March 2015 and is ranked in the 5th in the world) (42) and USA and Spain for CSP systems (Spain deployed 2.3 GW of CSP plants in less than five years, with an average of 300 MW financed every year between 2006 and 2012) (34); in the contrary other technologies like nuclear power which is complicated technology and is restricted and subjected to international nonproliferation treaties.

The Saudi private sector should be effectively involved in the energy transition efforts. ACWA power, a Saudi company is involved in important projects conventional energy inside the Kingdom and in renewable energies outside the Kingdom, and is leading a consortium which signed a power purchase agreement for the value of 900 Million US$, for the sale of the net electricity output of the Noor I CSP IPP (Independent power producer) with the capacity of 160 MW located approximately 200 km south of Marrakesh in Morocco (10).

It is important for Kingdom to continue to promote energy efficiency measures and programs, with aim of reducing high energy growth rates, and promote the usage of more efficient air conditioning systems, as the cost of saving a kWh is generally cheaper than producing the equivalent amount of energy, in other word, the cost of efficiency is a small fraction of energy production costs. The needed policies include the acceleration of technology development and demonstration, stimulating product demand via procurement policies, applying efficiency standards, encouraging utility demand-side management programs, (involvement by the utility to influence changes in customer's energy-using behavior sometimes using financial incentives) and in finding ways to create markets for energy savings. (43)

To help the integration of renewables, a better regional interconnection of the Saudi grid with the neighboring countries should be increased, as the interconnection of the grid provides means of sharing of capacity for both normal operating reserves and emergency conditions and developing market structure to allow for economic interchange of energy, on December 2001 the GCC Countries agreed to establish the GCC Interconnection Authority located in Dammam, Kingdom of Saudi Arabia, with the responsibility to overview the interlinking the power systems of the GCC countries and the introduction of a spot market for electricity pricing.

CHAPTER VII

CONCLUSION

The Saudi electricity sector is not sustainable, relying heavily on the abundant oil and gas resources of the country, with its current electricity demand growth rates, peak demand should double by 2030. Saudi Arabia can become a net importer of oil in the coming years if massive energy efficiency programmes are not introduced, massive use of renewable energies initiated, energy efficiency can reduce energy demand with limits as energy is massively consumed for cooling, in the contrast of abundant renewable energies sources. Many plans and targets have been set, including solar power. KA-CARE plan, which was probably too ambitious to be executed, the recently articulated “Saudi Vision 2030” is perhaps amore attainable target, a modified target was suggested if executed will provide 9% of the electricity needs of the Kingdom. All these scenarios were simulated using NREL SAM software and plotted on the load duration curve to obtain the residual curve, it was also found that reaching 25% of renewable penetration by 2030 will represent technical limit for the Saudi grid to handle without need of massive storage facilities. LCOE of renewable energies is not the main obstacle for the high penetration of renewable energies in Kingdom, despite a record low prices of photovoltaics system, but the huge subsidies offered to the energy producers, with fuel at 10% of the international prices generation costs are low beyond any competition from renewables. Simulations results of showed that PV systems were performing with a low capacity factor around 15% of in many locations of Kingdom, showing the impact and importance of the climatic conditions and location choice on the performance of PV systems.

It was found also that under the current energy framework; it will be difficult to implement high penetration plans of renewable energies in Kingdom, as heavy subsidies distort generation costs in favor of conventional generation system, affecting the feasibility of renewable energy projects which is an obstacle for the private sector in investing in the sector, Saudi companies are active in field of renewable energy outside the Kingdom in the UAE, Morocco but not in the Kingdom, different schemes such as Feed-in-Tariff should be envisaged with a strong political leadership.

Localization of renewable technologies should be priority as only 30% percent of the cost of PV system is related to module prices, the other costs include non-module known as hard costs including the costs of inverter, racking, electrical equipment, etc... and soft costs including labor, permitting fees, etc., referred as Balance-of-systems (BOS) this type of costs can be localized within the Kingdom, thus reducing costs any future system and helping the efforts in diversification of the Saudi economy, a PV solar cell plant could be built to cover the needs of the Kingdom and the region both for large PV application and other individual uses. Technological transfers and international partnerships can help the Kingdom in achieving its renewable energy ambitions.

Finally, it is important to note that only utility scale solar systems were covered in this research and that there is a great potential for individual roof mounted PV systems, which in many areas of the world are providing electricity to the national grid, wind energy also was not part of this research despite it very successful use in several countries for producing electricity and diversifying the energy mix.

APPENDIX I

COST OF GENERATION IN THE KSA OF DIFFERENT TECHNOLOGIES USING INTERNATIONAL FUEL PRICES IN 2014

Type	Nuclear	GT	CCGT	GT	CCGT
		Gas		Oil	
Unit Capital Cost ($/kW)	5,530	651	1,230	651	1,230
Fixed O&M ($/kW-y)	93.28	5.26	6.31	5.26	6.31
Variable O&M ($/MWh)	2.14	29.90	3.67	29.90	3.67
Heat Rate (BTU/kWh)		10390	6705	10390	6705
Capacity Factor	90%	90%	90%	90%	90%
Gas Used (MMBtu/MWh)					
Gas Cost (US$/MMBtu)		4.36	4.36	16.00	16.00
LEU Fuel Cost (US$/kg)	$3,211				
Fuel Consumption (kg/kWh)	3.15E-06				
Fueling Costs (US$/MWh)	10.11	45.30	29.23	166.24	107.28
Economic Life	60	20	30	20	30
Auxiliary Consumption	0%	0%	0%	0%	0%
Discount Rate	8%	10%	10%	10%	10%
CRF	0.081	0.117	0.106	0.117	0.106
Fixed Cost (US$/MWh)	68.50	10.37	17.35	10.37	17.35
Var. Cost (US$/MWh)	12.25	75.20	32.90	196.14	110.95
LCOE (US$/MWh)	80.76	85.57	50.25	206.51	128.30
LCOE (cent/kWh)	8.08	8.56	5.03	20.65	12.83

APPENDIX II

COST OF GENERATION IN THE KSA OF DIFFERENT TECHNOLOGIES USING SUBSIDIZED PRICES

Type	**GT**	**CCGT**	**ST**	**ST**	**Diesel**
	Gas /Oil light	**Gas/ Oil light**	**Oil Heavy**	**HFO**	**Diesel**
Unit Capital Cost ($/kW)	651	1,230	1,000	1,000	1350
Fixed O&M ($/kW-y)	5.26	6.31	6.31	6.31	15.00
Variable O&M (US$/MWh)	29.90	3.67	3.67	3.67	15.00
Heat Rate (BTU/kWh)	10390	6705	9500	9500	10000
Capacity Factor	90%	90%	90%	90%	40%
Fuel cost (US$/MMBtu)	0.75	0.75	0.48	0.36	0.65
Fueling Costs (US$/MWh)	7.79	$5.03	4.56	3.42	6.50
Economic Life	20	30	25	25	10

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