Investigating Renewable Energy Potentials in Jordan

Leen Hayek

Professor Judith B. Cardell, Research Advisor

ABSTRACT

Jordan is a developing country with an increasing electric demand and very limited fuel resources. As a result, the majority of Jordan's electric generation is fueled by imported fossil fuels, which greatly stresses the country's economy. While Jordan is incredibly resource poor when it comes to fossil fuels, it does have a vast untapped solar energy potential. Jordan's promising renewable energy potential, the negative environmental impact of fossil fuels currently driving Jordan's electric generation process, as well as the unstable nature of fossil fuel prices are the motivators behind this research. This research project will investigate renewable energy technology potentials in Jordan, with focus on solar and wind energy, as they are the most abundant.

During the course of this research project, wind and solar availability data are collected for various regions in Jordan. The regions with the highest wind and solar availability are selected as possible generation zones to be considered for modeling. Similarly, data about Jordan's current load demand and installed electric grid generation capacity is researched. The obtained data – both load demand data, and wind and solar availability data- are modeled using HOMER [1] computer software in order to investigate the multiple ways the selected renewable energy technologies can be incorporated into the existing electric grid. The details of the installed Jordanian electric grid are discussed in terms of generation capacity, fuel sources and transmission lines. The most feasible models will be further investigated in terms of reliability and economic feasibility. Lastly, the social and economic impacts of incorporating renewable technologies into the grid will be investigated in terms of predicted economic growth; jobs created by the addition of the technologies, and increased electrification in rural areas, among others.

TABLE OF CONTENTS

I. INTRODUCTION

1.1 Motivation

Jordan is a rapidly developing country located in the heart of the Middle East. Unlike many of its neighboring countries, Jordan is lacking in natural resources, specifically fossil fuels that are traditionally used for electricity generation. Due to increasing urban development and electric demand, Jordan faces many challenges with regards to meeting its electric demand and allocating the financial resources necessary to do so. This project is motivated by the need to develop alternative electric power resources to support Jordan's development, focusing on solar and wind power alternatives.

1.2 Background

Jordan's current energy generation process is highly dependent on fossil fuels. As of 2014, Jordan's oil reserves were estimated at around 1 million barrels, while its natural gas reserves where estimated at around 200 thousand billion cubic feet [2]. The relatively low fossil fuel resources force the country to import most of the fuel needed for electric generation; 88% of Jordan's electricity generation is supported by imported fossil fuels, while local fossil fuel production only supports 2% of the country's demand. The import of fossil fuels proves a strenuous economic toll on Jordan, as it accounts for nearly 40% of the country's budget [2]. Furthermore, due to the constantly changing political situation in the Middle East, Jordan's energy security is repeatedly threatened as it imports significant amounts of oil from Iraq and natural gas from Egypt through the Arab Gas Pipeline (AGP) running through Sinai and Syria. In recent years, the political instability of Syria and Sinai has led to a dramatic decrease in Jordan's natural gas import from 89 billion cubic feet to 17 billion cubic feet and effectively causing

Jordan to increase its oil demand. The shift in fuel resources for energy production in 2011 as a result of the political instability in Syria has cost the kingdom around 5 billion USD in losses as the power plants were adjusted to burn heavy fuels [3]. The shift in Jordan's fuel consumption is highlighted by figure 1 below. Jordan's dependence on imported fossil fuels for electric demand poses a great risk to the country's energy security, especially considering the political nature of its bordering countries.

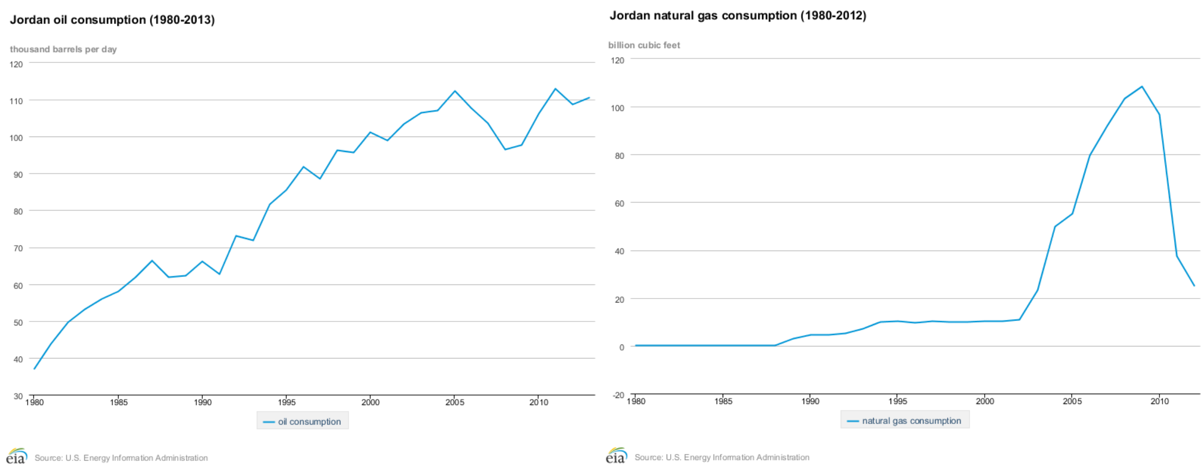


Figure 1: changes in Jordan's oil consumption (left) verses its natural gas consumption (right) from 1980 to 2012 [2].

The energy situation in Jordan is further exacerbated by the fact that electric demand is rapidly increasing. It is expected that the Kingdom's electric demand will increase from 2GW to 4GW by 2020, and then to 6GW by 2030 due to the increase in urban development in the Kingdom [3]. This means that without the diversification of the energy resources used in the Kingdom's electric generation process, the Kingdom will face an energy crisis in the near future. As a result, the Jordanian government plans to increase energy production from alternative energy resources from the current 18 MW to 1.8 GW by the year 2020 as shown in figure 2 below [2]. In addition, the Jordanian government plans to diversify the nation's energy reserves by constructing two 1GW nuclear power plants between 2015 and 2020.

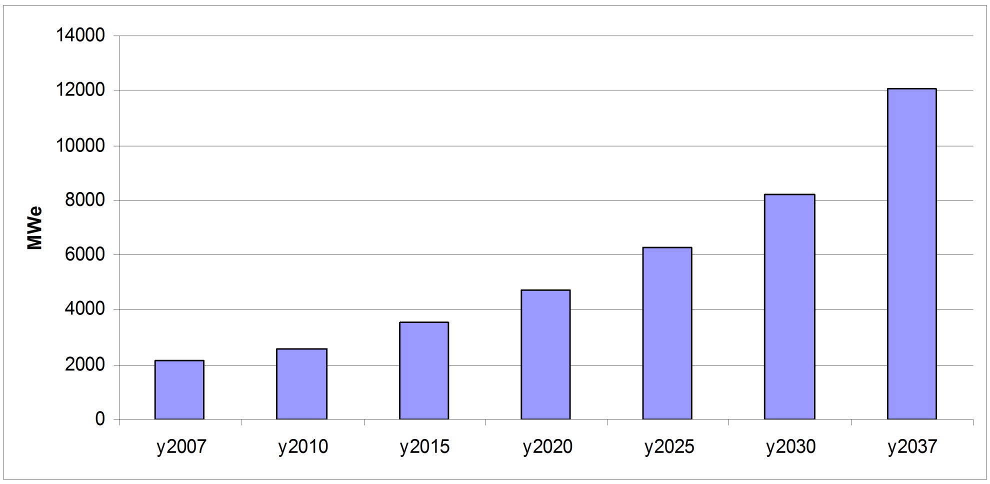


Figure 2: predicted increase of Jordanian electric load demand. [3]

The proposed nuclear power plants would be installed in Al Aqaba region in the South of Jordan, the Kingdom's only port city (figure 3) [4]. The power plants would rely on seawater from the Red Sea for cooling. Considering the fact that Al Aqaba is the Kingdom's only port city, and a large tourist attraction, installing nuclear power plants in the region is not only unsustainable for the aquatic life, but could also greatly affect the Kingdom's trade and tourism. While other sites were under investigation for the placement of the plants, they were deemed unreliable due to the lack of access to water for cooling.

Figure 3: map of Jordan displaying Al Aqaba, Irbid and the capital Amman and other major cities [5].

Studies have shown that Jordan's unharnessed solar energy resources are key to evading the eminent energy crisis in the most sustainable manner [8]. Due to the adverse environmental impacts and risk factors associated with installing nuclear power plants in Jordan, this research investigates the feasibility of meeting the majority of Jordan's electric load growth through renewable energy resources.

1.3 The Existing Electric Grid:

The current installed electric grid has a system capacity of 3168MW, with a 132kV and 400kV transmission network (figure 4). The transmission network interconnects with Syria through 230kV and 400kV tie lines and with Egypt through 400kV tie lines. The installed grid currently serves 99.9% of the Jordanian population [7].

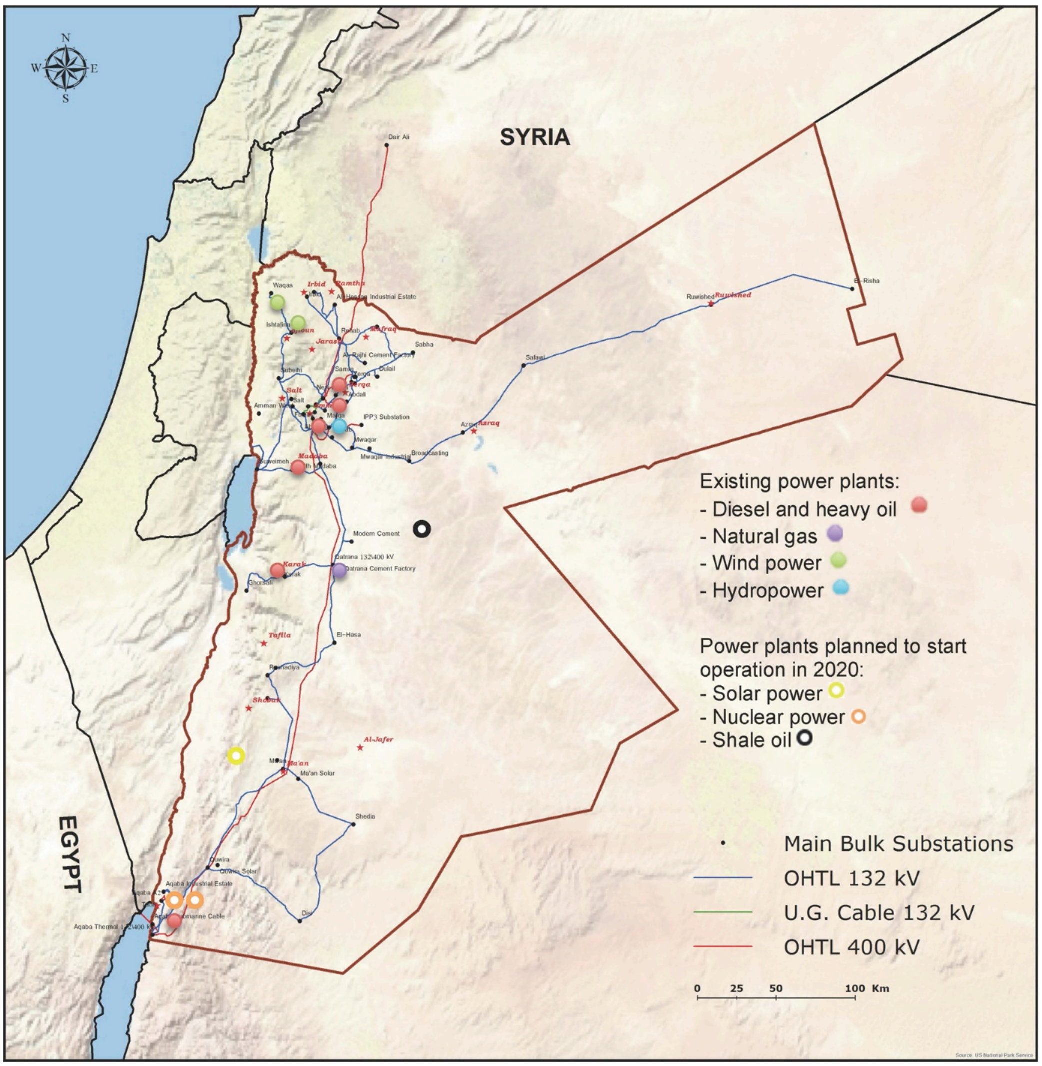


Figure 4: The transmission lines of the Jordanian grid [8], the figure was also updated to show installed power plants and those planned until 2020.

1.4 Generation Capacities:

The largest power station in Jordan is the Aqaba thermal power station, which generates 656MW. The power station relies on heavy oil and natural gas for fuel and seawater for cooling [8]. The rest of the power plants in Jordan and their generation capacity are detailed in table 1.

Table 1: power generation plants and their corresponding generation capacities.

Power Generation Facility	Generation Capacity	Fuel Source	Location
Aqaba Thermal Power Station [9]	656 MW	Natural gas Heavy fuel oil	Aqaba
Hussein Thermal Power Station [10]	198 MW	Heavy fuel oil Diesel oil	Az Zarqa
Risha Gas Power Station [11]	150 MW	Diesel oil Natural gas	Risha
Rehab Gas Turbine Power Station [12]	357 MW	Diesel oil Natural gas	Rehab
Marka Power Station [13]	80MW	Diesel oil	Marka
Amman South Power Station [14]	30MW	Diesel oil	Amman
Karak Power Station [15]	20MW	Diesel oil	Karak
Ibrahimyah Wind Power Station [16]	0.32MW	Wind power	Ibrahimyah
Hofa Wind Power Station [17]	1.125MW	Wind power	Hofa
Al Quatrana Power Plant [18]	373MW	Natural gas	Al Qatrana
King talal dam [18]	4 MW	Hydropower	Az Zarqa

The fuel source distribution of these power plants is displayed in the following figure.

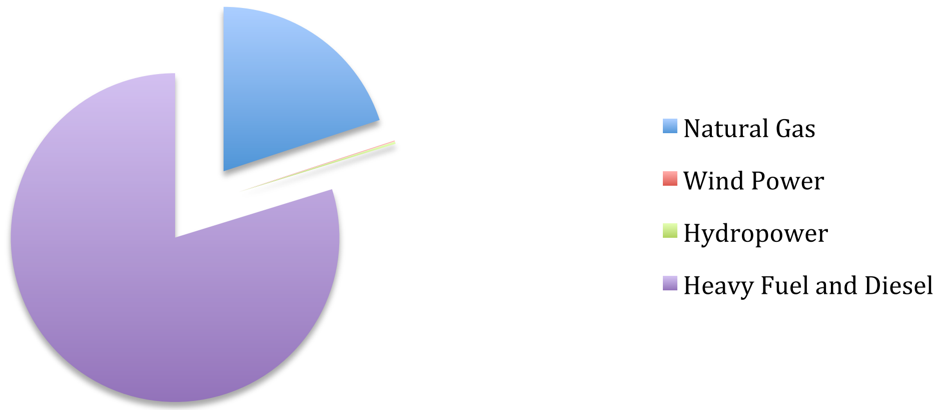


Figure 5: distribution of current power plant fuel sources in Jordan.

In addition to these existing power plants, several power plants are currently being planned or are under construction, these are displayed in table 2 below. As opposed to the existing power stations, the planned power stations will rely on local fuel sources such as uranium and oil shale and include a large solar energy project.

Table 2: planned power plants in Jordan, their generation capacities and expected year of commercial operation.

Power Generation Facility	**Generation Capacity**	**Fuel Source**	**Location**	**Expected Year of Commercial Operation**
Nuclear Power Plant [4]	1000MW	Uranium	Aqaba/Wadi Araba	2019/2020
Nuclear Power Plant [4]	1000MW	Uranium	Aqaba/Wadi Araba	2020/2021
Attarat Power Plant [19]	550MW	Oil shale	Attarat Um Ghurdan	2018
Ma’an CSP Plant [20]	100MW	Solar Power	Ma’an	2020

Figure 6: distribution of power plant fuel sources in Jordan for power plants stating operation in 2020.

II. SITE SELECTION

2.1 Renewable Energy Potentials:

Jordan is located in the solar belt of the world, thus it has the potential to generate at least 1000Gwh annually [20]. In a recent report by the International Renewable Energy Agency [21], the cost of electricity generated by concentrated solar power (CSP) could be as low as $0.14/kWh if the storage period is less than six hours. Compare this to a cost of $0.13/kWh for a conventional natural gas burning combustion turbine, $0.20/kWh for offshore wind turbines and around $0.1/kWh for advanced nuclear [23]. The low cost of solar power generation paired with Jordan's solar potential makes Jordan's reliance on renewable energy feasible. Jordan's solar potential is displayed in figure 7.

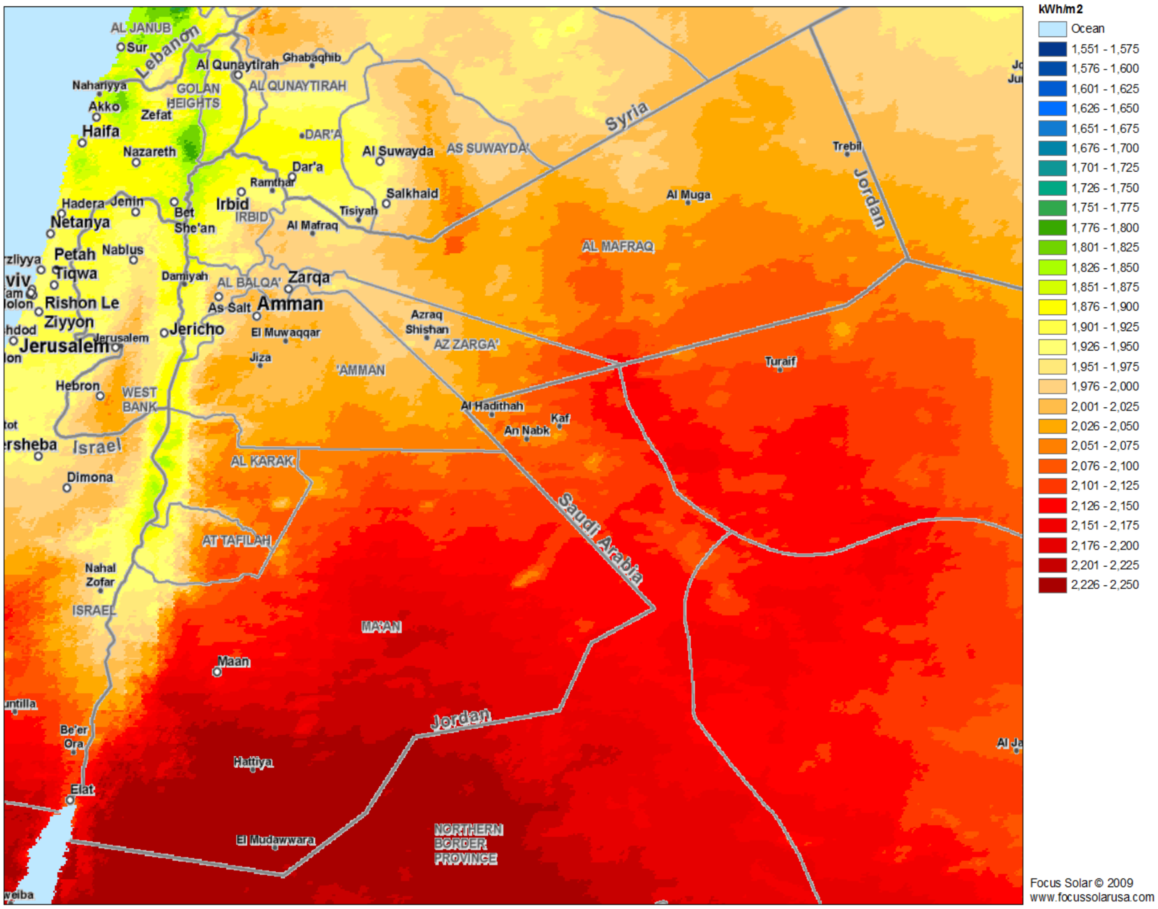


Figure 7: map of Jordan showing solar radiation (kWh/m^2)[7].

The solar potential in Jordan is capable of meeting 100% of the electric demand – provided there is an efficient storage solution- due to many favorable factors; low humidity, moderate temperatures, and the high availability of flat land mass. The solar availability data obtained will be modeled using HOMER in order to investigate the feasibility of installing solar farms.

Similarly, Jordan also has good wind potentials as demonstrated by the small wind farms currently installed. The wind map of Jordan is shown in figure 8.

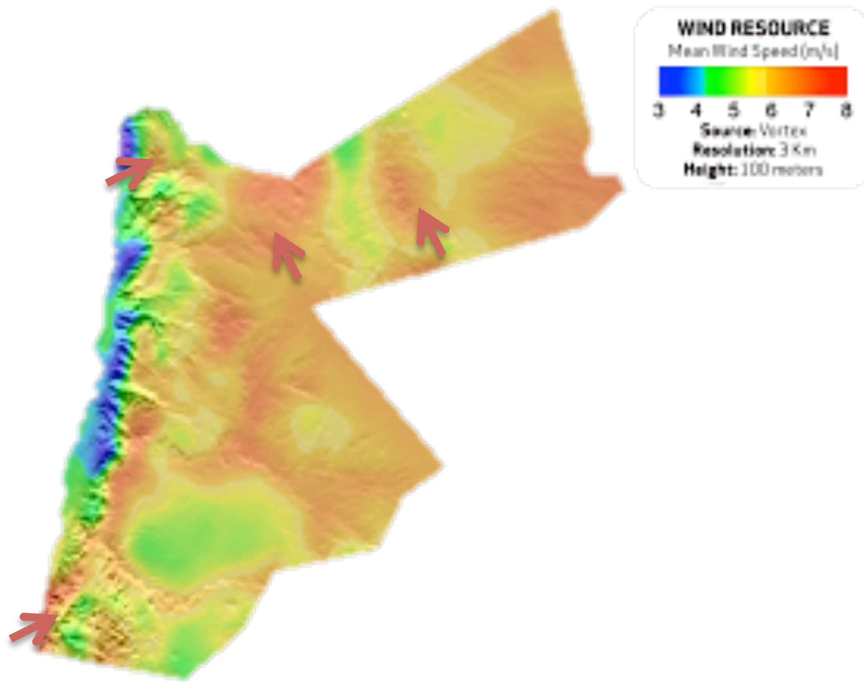


Figure 8: wind availability map of Jordan [21]

As shown by the maps, locations with the highest wind speeds are Al Aqaba, Al Mafraq, Irbid and Al Azraq. These four locations exhibit average wind speeds ranging from 6m/s to 8m/s, measured at a height of 100m. All these locations are relatively rural and would be ideal locations for wind farms since availability of space is not a constraint. Generic wind speed data was initially acquired for Aqaba and an initial HOMER analysis was conducted, the initial wind data processing in displayed in appendix B, while the HOMER analysis result are displayed in appendix C. New wind data was obtained from the National Energy Research Centre (NERC) at the Royal Scientific Society (RSS) in Jordan. The acquired data for these locations and the data will be analyzed using HOMER to investigate the feasibility of grid-tied wind farms in these locations.

2.2 Aqaba

Aqaba is located around 330km south of the capital city Amman as shown in figure 1 [29]. Aqaba is Jordan's only coastal city and is an area that undergoes vast amounts of trade annually. The city receives high solar radiation and experiences moderately fast winds. The city is surrounded by largely undeveloped desert land while the city's urban spaces undergo large economic development. Thus, Aqaba is an ideal site for both wind and solar farms and was selected as such for this project.

2.3 Irbid

Irbid is located around 70km north of Amman and while the city is a highly urbanized area, it is surrounded by large amounts of agricultural and unutilized land. Irbid is one of the country's largest cities, the third after the capital Amman and Az Zarqa. Irbid experiences some of the highest wind speeds in the Kingdom; between 6m/s and 8m/s on average. Irbid's high population density, its proximity to the capital city, as well as its high wind availability and accessible land make it an excellent candidate for wind farm projects in the Kingdom.

III. HOMER ANALYSIS

3.1 Load Data

The HOMER analysis includes daily load data only from the capital city Amman at this point. The data were obtained from the daily load curve of the city for the month of May in 2010 [23] rather than time series data (figure 10). The month of May was selected since it contains the city's peak load. This data is being used temporarily until daily load data can be obtained from the Jordanian National Electric Power Company. Load data were requested from the company to include the entire country. While this model only incorporates Amman's electric demand, it will still give significant results since Amman's electric load is the largest in the country.

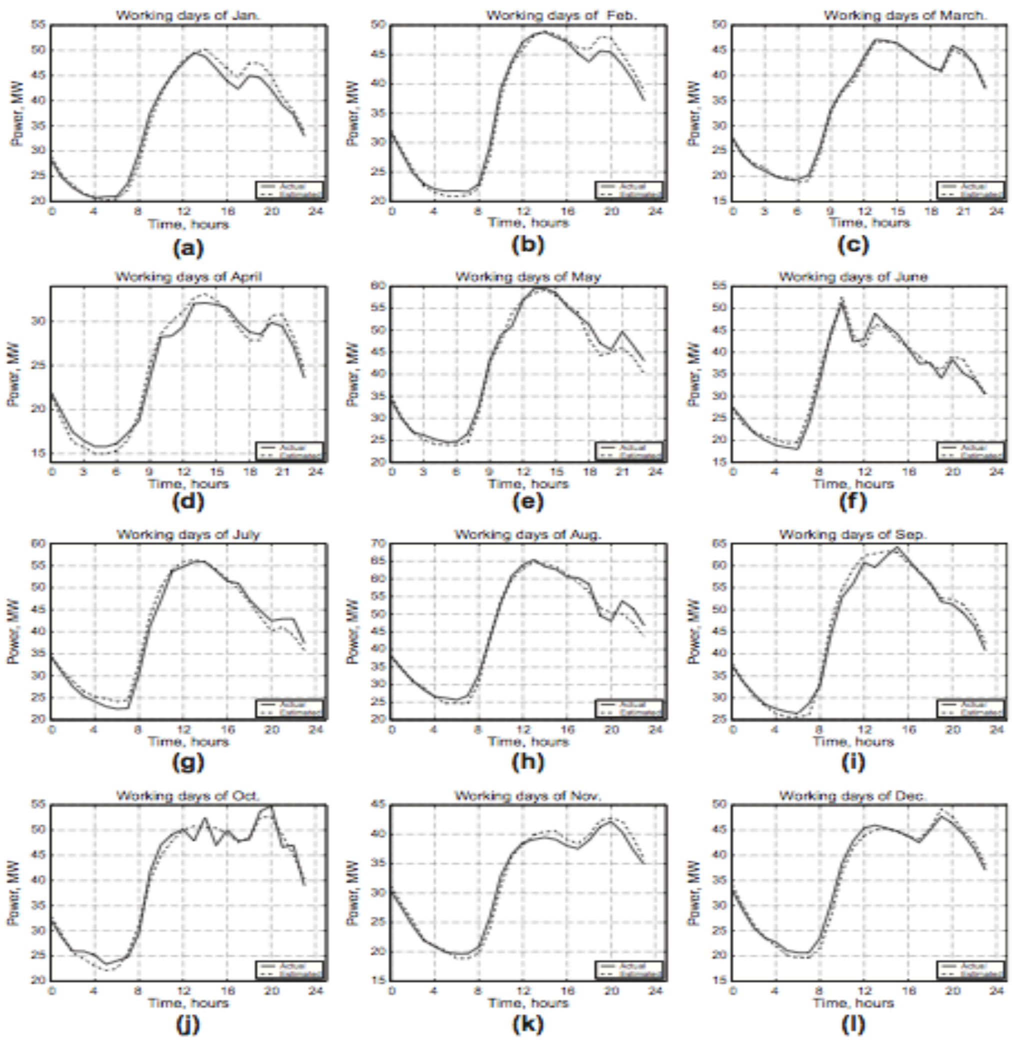


Figure 10: daily load curves for Amman in 2010 [23].

3.2 Wind Resource Data:

Two areas selected as the location for the proposed wind farms; the city of Al Aqaba and the city of Irbid. Monthly wind speeds were obtained new wind data was obtained from the National Energy Research Centre (NERC) at the Royal Scientific Society (RSS) in Jordan. While monthly averages instead of hourly time series data is less accurate, no such data was currently available for any location on Jordan. The average monthly wind speeds for Al Aqaba and Irbid are displayed in the following figures.

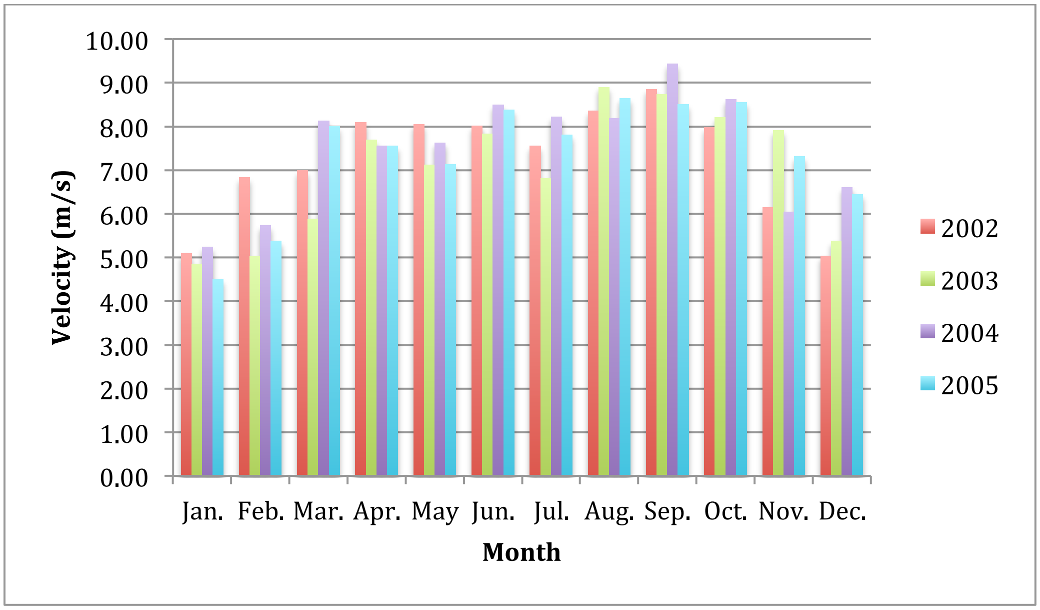


Figure 11: monthly average wind speeds for Al Aqaba recorded at 45m above ground level (m/s).

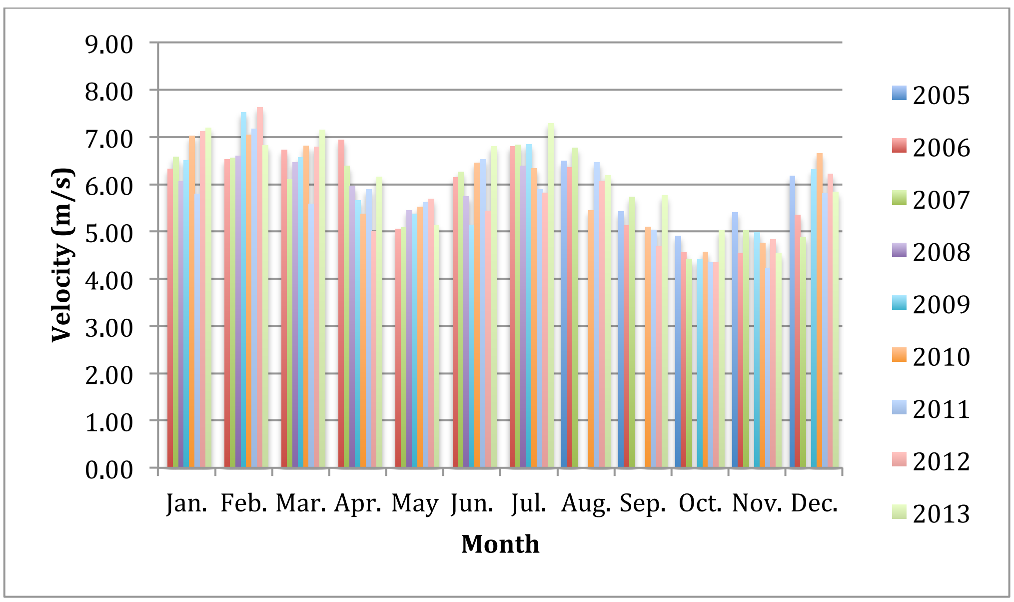


Figure 12: monthly average wind speeds for Irbid recorded at 10m above ground level (m/s).

In order to account for the variability of the wind, the data will be modeled using a Weibull distribution. Modeling the wind data using the Weibull distribution informs us of the probability of a certain wind speed occurring at the given location. The modeling will be done using R software such that the scale factor “k”, will be calculated and input into HOMER.

3.3 Solar Resource Data

The location of the solar farm was also selected to be Al Aqaba due to its high average solar radiation. The average monthly solar radiation values for Al Aqaba were obtained from NASA records, these are plotted in figure 13.

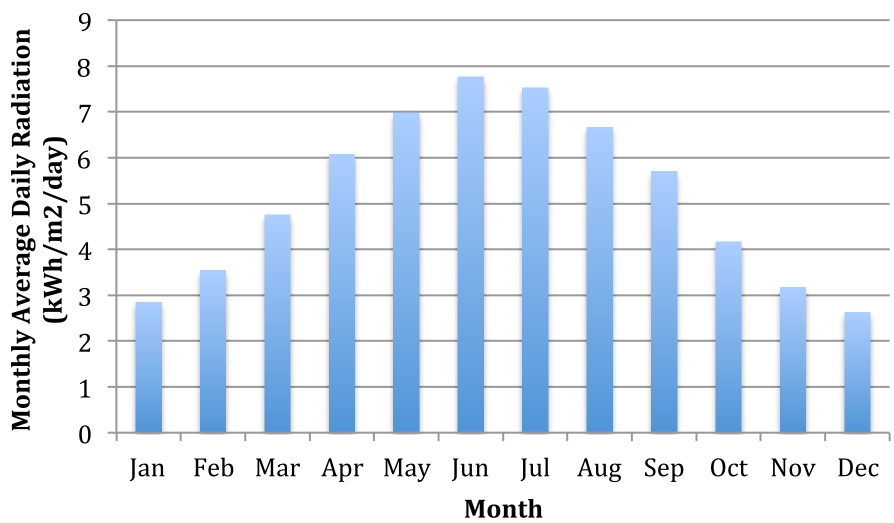


Figure 13: monthly average daily solar radiation for Al Aqaba (kWh/m²/day).

The monthly average radiation values were used to calculate monthly clearness index as well and the optimal tilt angle, which had a value of 25 degrees. Details of these calculations are displayed in appendix II. Clearness index values and the optimal tilt angle were used in HOMER in order to model the solar resources available.

Table 3: the table below displays the calculated clearness index values (K_T) for Al Aqaba.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
K_T	0.48	0.49	0.54	0.59	0.63	0.68	0.67	0.63	0.61	0.54	0.51	0.47

3.4 Fuel Costs

The fuel costs selected for this HOMER model are \$0.97/L [25] for diesel and \$11/m^3 for natural gas [26]. While the diesel costs were specific to Jordan, it is an average of the price between 2010 and 2014. On the other hand, the natural gas price obtained is specific to the United States because no accurate values of the Jordanian price were found. When modeling the system again, both fuel costs should be specific to Jordan to obtain the most accurate reflection of the system costs.

3.5 Capital and Operations and Maintenance Costs

Capital costs for the existing power plants funded by the World Bank were obtained from the World Bank records. Otherwise, capital costs as well as operations and maintenance costs (O&M) were estimated using the assumptions displayed in table 4 below. All cost values were obtained from EIA records [27] with the exception of diesel, which was obtained from the KPMG report [28].

Table 4: cost assumptions for different generation methods.

Generation Method	Capital Cost ($/kW)	Fixed O&M ($/kW-yr)	Variable O&M ($/MWh)
Natural Gas (Conventional CT)	973	7.34	15.45
Diesel	984.77	10.16	31.52
Offshore Wind	6,230	74.00	00
Photovoltaic	3,873	24.56	00

IV. RESULTS AND SENSITIVITY ANALYSES

4.1 Solar Heavy Base Cases (10%, 20%, 30% renewables)
4.2 Wind and Solar (10%, 20%, 30% renewables, with equal generation from both wind and solar)
4.3 Optimizing Reliability
4.4 Optimizing Low Emissions
4.5 Optimizing Cost

V. CONCLUSION

5.1 Conclusion and Reflection

Modeling the system using HOMER showed that Jordan's renewable energy resources could be key in solving its eminent energy crisis as the optimization results showed a system with a low cost of electricity, low emissions and high reliability for the capital city Amman. The financial implications of adopting renewable energy technology are something to consider, especially since the economic component is crucial in the case of a developing country like Jordan. While renewables require a much higher capital cost, they require very little operations and maintenance cost, are more sustainable, will bring new technology and know-how to the country and create jobs. As are result, conducting a life cycle analysis for the different technologies for Jordan's case is something I am interested in pursuing if time is available.

I will be finalizing my HOMER modeling of the system from this point on for the base cases discussed. Since new data was obtained, this will allow me to conduct more accurate analyses. In addition to wind data, problems with obtaining daily load demand were also encountered. As a result, for this model average hourly daily data for one month were input into HOMER and HOMER estimated the rest of the year's electric demand accordingly.

VI. REFERENCES

[1] HOMER. Computer software. HOMER Energy. Vers. Legacy. N.p.. Web.

[1] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." *U.S. Energy Information Administration (EIA)*. EIA, Web. <http://www.eia.gov/countries/country-data.cfm?fips=jo>.

[2] "Electricity Demand Expected to Triple by 2030 - Minister." *Jordan Times*. Web. <http://jordantimes.com/electricity-demand-expected-to-triple-by-2030----minister>.

[3]"JORDAN 2011." IAEA, Web. <http://www-pub.iaea.org/MTCD/Publications/PDF/CNPP2011_CD/countryprofiles/Jordan/Jordan2011.htm>.

[4] Image obtained from google maps.

[5] "Jordan's Energy Future." *Booklet-Green Peace*. GreenPeace. Web. <http://www.greenpeace.org/arabic/PageFiles/481146/Jordan_Report2013.pdf>.

[6] "Solarkarten - Focussolar.de." *Solarkarten - Focussolar.de*. N.p., n.d. Web. 10 May 2015. <http://www.focussolar.de/Maps/RegionalMaps/MidEast/Jordan>.

[7] "Nationl Electric Power Company - NEPCO HomePage." *Nationl Electric Power Company - NEPCO HomePage*. Web. <http://www.nepco.com.jo/en/jordan_electric_system_en.aspx>.

[8] "Aqaba Thermal Power Station | Central Electricity Generating Company." *Aqaba Thermal Power Station | Central Electricity Generating Company*. N.p., n.d. Web. 10 Apr. 2015. <http://www.cegco.com.jo/?q=en%2Fnode%2F74>.

[9] "Hussein Thermal Power Station | Central Electricity Generating Company." *Hussein Thermal Power Station | Central Electricity Generating Company*. <http://www.cegco.com.jo/?q=en%2Fnode%2F75>.

[10] "Risha Gas Power Station | Central Electricity Generating Company." *Risha Gas Power Station | Central Electricity Generating Company*. <http://www.cegco.com.jo/?q=en%2Fnode%2F76>.

[11] "Rehab Gas Turbine Power Station | Central Electricity Generating Company." *Rehab Gas Turbine Power Station | Central Electricity Generating Company*. <http://www.cegco.com.jo/?q=en%2Fnode%2F77>.

[12] "Marka Power Station | Central Electricity Generating Company." *Marka Power Station | Central Electricity Generating Company*. Web. <http://www.cegco.com.jo/?q=en%2Fnode%2F78>.

[13] "Amman South Power Station | Central Electricity Generating Company." *Amman South Power Station | Central Electricity Generating Company*. <http://www.cegco.com.jo/?q=en%2Fnode%2F79>.

[14] "Karak Power Station | Central Electricity Generating Company." *Karak Power Station | Central Electricity Generating Company*. <http://www.cegco.com.jo/?q=en%2Fnode%2F80>.

[15] "Ibrahimyah Wind Power Station | Central Electricity Generating Company." *Ibrahimyah Wind Power Station | Central Electricity Generating Company*. <http://www.cegco.com.jo/?q=en%2Fnode%2F82>.

[16] "Hofa Wind Power Station | Central Electricity Generating Company." *Hofa Wind Power Station | Central Electricity Generating Company*. <http://www.cegco.com.jo/?q=en%2Fnode%2F83>.

[17] "Jordan News Agency (Petra) |King Inaugurates Qatranah Power Generation Plant." *Jordan News Agency (Petra) |King Inaugurates Qatranah Power Generation Plant*. <http://petra.gov.jo/Public_News/Nws_NewsDetails.aspx?Site_Id=1&lang=2&NewsID=60929>.

[18] "Jordan's Project:An Oil Shale Fired Power Plant with Capacity of 550 MW." *Enefit*. Web. <https://www.enefit.com/jordan>.

[19] "Solar Energy in Jordan." *EcoMENA*. Web. <http%3A%2F%2Fwww.ecomena.org%2Fsolar-energy-jordan%2F>.

[20] (Irena), International Renewable Energy Agency. *Renewable Energy Cost Analysis: Concentrating Solar Power*. Web.

[21] "Jordan Wind Map." · *Vortex*. <http://www.vortexfdc.com/jordan-wind-map/>.

[22] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." *U.S. Energy Information Administration (EIA)*. <http://www.eia.gov/forecasts/aeo/electricity_generation.cfm>.

[23] Daily load profile and monthly power peaks evaluation of the urban substation of the capital of Jordan Amman, Nabeel I. A. Tawalbeh, Electrical Engineering Department, University of Jordan, Amman, Jordan

[24] Alsaad, M.a. "Wind Energy Potential in Selected Areas in Jordan." *Energy Conversion and Management* 65 (2013): 704-08. Web.

[25] "Pump Price for Diesel Fuel (US$ per Liter)." *Pump Price for Diesel Fuel (US$ per Liter)*. <http://data.worldbank.org/indicator/EP.PMP.DESL.CD/countries>.

[26] "Pump Price for Diesel Fuel (US$ per Liter)." *Pump Price for Diesel Fuel (US$ per Liter)*. <http://data.worldbank.org/indicator/EP.PMP.DESL.CD/countries>.

[27] Wells, Peggy. EIA. Web. <http://www.eia.gov/forecasts/capitalcost/pdf/updated_capcost.pdf>.

[28] Finance, Corporate. *Cost of Capital Study 2013*. Web.

[29] "Practicalities." Aqaba. N.p, Web. <http://www.aqaba.jo/en/node/1410>.

VII. APPENDICES

7.1 Appendix A: Tilt Angle and Solar Radiation

In order to calculate the optimal angle, the total insolation at the horizontal must be calculated and then adjusted such that it is elevated to the plane of the array. As a result, the first set of calculations were done in order to find the monthly average daily insolation values for each month. In order to do so, the declination was calculated first using equation 1 below, where δ is the declination in degrees, and n is day's number in the year.

$$\delta = 23.45\, sin\left(360\left(\frac{284+n}{365}\right)\right) \qquad \text{Eq. 2}$$

Then, using the declination values, the hour angle was calculated using the equation 2 below, where ω_s is the hour angle, δ is the declination, and ϕ is the longitude in degrees.

$$\omega_s = cos^{-1}(-tan\delta tan\phi) \qquad \text{Eq. 3}$$

The declination and hour angle values were then used to calculate the extraterrestrial insolation values on the horizontal ($\overline{H}_o$). This was calculated using the equation below, where ω_s is the hour angle, δ is the declination, and ϕ is the longitude in degrees. G_{sc} is the global solar constant with a value of 1367 W/m^2, and n is the day's number in the month. The result, $\overline{H}_o$, has units J/m^2/day, this was converted to kWh/m^2/day by dividing the result by 3.6*10^6 MJ.

$$\overline{H}_o = \frac{24*3600*G_{sc}}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right)\left(cos\phi cos\delta sin\omega_s + \frac{\pi}{180}\omega_s sin\phi sin\delta\right) \qquad \text{Eq. 4}$$

In order to elevate from the horizontal to the plane of the array, $\overline{K_T}$, the average clearness index was calculated. This was done using equation 5 shown below, where $\overline{H}_o$ is the extraterrestrial insolation on the horizontal, and $\overline{H}$ is the average monthly daily insolation at the horizontal, both in kWh/m^2/day.

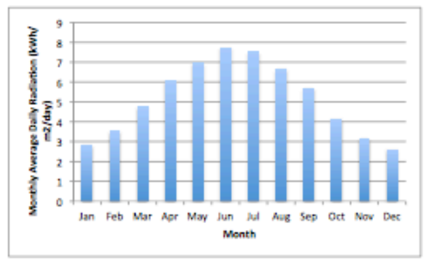
$$\overline{K_T} = \frac{\overline{H}}{\overline{H_o}} \qquad \text{Eq.5}$$

The tables showing the calculation are shown on the next page.

Latitude	29.5	°N
Longitude	35	°E

Month	Surface	Reflectivity	Days in Month	Hbar	n	Declination	Ws	Hbar_o	Kbar_T	Energy at Horizontal	Hbar_d/Hbar	Hbar_d	Ws' (opt)
			No. of Days	kWh/m2/day	Day no.	Deg	Deg	kWh/m2/day		kWh/m2/month	%	kWh/m2/day	Deg
Jan	ripe field crops	0.26	31	2.85	15	-21.26947391	77.27696382	5.929474945	0.48064964	88.35	0.410351155	1.16950079	77.2769638
Feb	ripe field crops	0.26	28	3.54	45	-13.61976641	82.12100171	7.180074045	0.493031127	99.12	0.44571536	1.577832376	82.1210017
Mar	ripe field crops	0.26	31	4.76	74	-2.818878653	88.40366064	8.768348564	0.542861631	147.56	0.399937248	1.903701302	88.4036606
Apr	ripe field crops	0.26	30	6.08	105	9.414893347	95.38307245	10.24772862	0.593302206	182.4	0.355926427	2.164032677	90.7438004
May	ripe field crops	0.26	31	6.98	135	18.79191752	101.0996346	11.11022245	0.628250247	216.38	0.326071895	2.275981828	91.5264876
Jun	dry grass	0.2	30	7.77	166	23.31440992	104.1126392	11.41981753	0.68039616	233.1	0.281360465	2.18617081	91.9334967
Jul	dry grass	0.2	31	7.53	196	21.51733603	102.8889192	11.25631328	0.668957927	233.43	0.29124906	2.193105423	91.7687625
Aug	soils	0.14	31	6.67	227	13.78356417	97.97812678	10.57946426	0.630466708	206.77	0.324182961	2.162300347	91.1004654
Sep	soils	0.14	30	5.7	258	2.216886783	91.25498082	9.314011401	0.611981213	171	0.339943012	1.937675169	90.1736425
Oct	soils	0.14	31	4.17	288	-9.599397234	84.50912747	7.717339697	0.540341641	129.27	0.402185935	1.677115349	84.5091275
Nov	ripe field crops	0.26	30	3.17	319	-19.14781731	78.67083136	6.244527133	0.507644523	95.1	0.383737665	1.216448399	78.6708314
Dec	ripe field crops	0.26	31	2.63	349	-23.33521955	75.8729634	5.567281568	0.472402908	81.53	0.418791617	1.101421953	75.8729634
Annually				61.85						1884.01			

Ws' value 1	Ws' value 2	Rb top	Rb bottom	Ws'(20) value 1	Ws'(20) value 2
77.27696382	88.25363093	0.868043883	0.550232484	77.27696382	86.26502409
82.12100171	88.91312271	0.933426311	0.671700168	82.12100171	87.67627395
88.40366064	89.77913688	0.989434383	0.831600177	88.40366064	89.52789518
95.38307245	90.7438004	1.003658243	0.98894347	95.38307245	91.59005208
101.0996346	91.52648759	0.983634925	1.088446064	101.0996346	93.26428644
104.1126392	91.9334967	0.964588562	1.129300142	104.1126392	94.13570536
102.8889192	91.76876247	0.972877902	1.11363171	102.8889192	93.78292302
97.97812678	91.10046541	0.99762849	1.037736251	97.97812678	92.35278991
91.25498082	90.17364254	1.000950355	0.899833551	91.25498082	90.37116745
84.50912747	89.24134876	0.959282363	0.73311339	84.50912747	88.37819411
78.67083136	88.44234615	0.888291384	0.584408044	78.67083136	86.66900853
75.8729634	88.06457016	0.846777483	0.516697328	75.8729634	85.86015409



Sun hrs (opt)	5.404997311
Sun hrs (hor)	5.154166667

Rb (opt)	Hbar_T (opt)	Beta (opt)	Ws'(20)	Rb(20)	Hbar_T (20)	Energy at optimal	Electric production Opt	Electric production H	Money Made H	Money Made Opt	Cost of electricity
	kWh/m2/day	Deg	Deg		kWh/m2/day	kWh/m2/month	kWh	kWh	$	$	$/kWh
1.577594759	3.800536695	25.0235591	77.27696382	1.482619514	3.807726657	117.8166376	21.20699476	15.903	3.1806	4.241398952	0.2
1.389647281	4.273697985		82.12100171	1.330649753	4.284729268	119.6635436	21.53943784	17.8416	3.56832	4.307887569	
1.189795782	5.270851292		88.40366064	1.169054691	5.282028033	163.39639	29.41135021	26.5608	5.31216	5.882270042	
1.014879287	6.110893925		91.59005208	1.027033696	6.120680185	183.3268177	32.99882719	32.832	6.5664	6.599765439	
0.903705711	6.505385255		93.26428644	0.935564267	6.513123583	201.6669429	36.30004972	38.9484	7.78968	7.260009945	
0.854147207	6.925913223		94.13570536	0.894402137	6.936520633	207.7773967	37.3999314	41.958	8.3916	7.47998628	
0.873608297	6.823212867		93.78292302	0.910597593	6.834742044	211.5195989	38.0735278	42.0174	8.40348	7.61470556	
0.961350718	6.4381234		92.35278991	0.983131165	6.458736827	199.5818254	35.92472857	37.2186	7.44372	7.184945714	
1.112372787	6.069294515		90.37116745	1.106416711	6.088417515	182.0788355	32.77419038	30.78	6.156	6.554838077	
1.308504762	4.887754183		84.50912747	1.265039886	4.906099295	151.5203797	27.27366834	23.2686	4.65372	5.454733668	
1.51998487	4.167407868		78.67083136	1.436037558	4.173989538	125.0222361	22.50400249	17.118	3.4236	4.500800498	
1.638826905	3.586896519		75.8729634	1.532130338	3.59390394	111.1937921	20.01488257	14.6754	2.93508	4.002976515	
									0	0	
	64.85996773				65.00069752	1974.564396	355.4215913	339.1218	67.82436	71.08431826	

7.2 Appendix B: Initial Wind Data

Initially, the area selected as the location for the proposed wind farm was the city of Al Aqaba in the South of Jordan. Monthly wind speeds were obtained at anemometer height of 10m, these speeds are monthly averages across the years 1989-1997 [24]. While monthly averages instead of hourly time series data is less accurate, no such data was currently available for any location on Jordan. The average monthly wind speeds for Al Aqaba are displayed in the figure below.

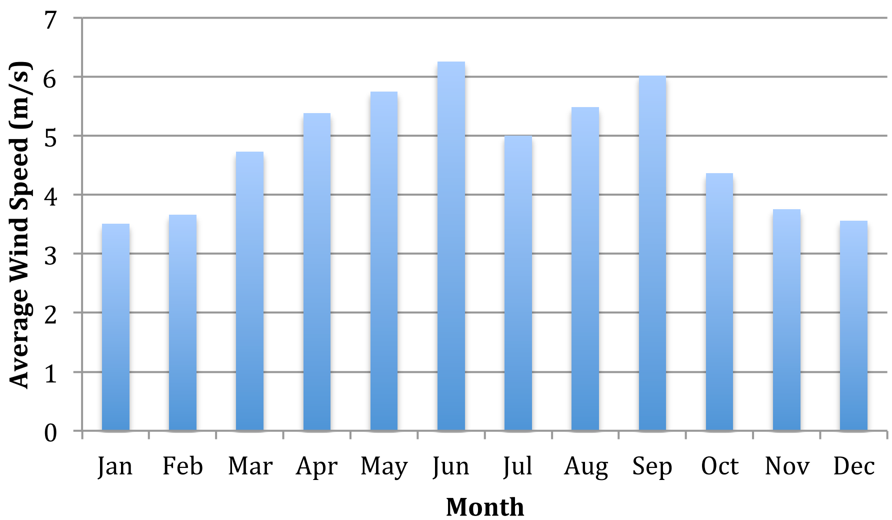


Figure 11: monthly average wind speeds for Al Aqaba (m/s).

In order to account for the variability of the wind, the data were modeled using a Weibull distribution. Modeling the wind data using the Weibull distribution informs us of the probability of a certain wind speed occurring at the given location. The modeling was done using R software such that the scale factor “k”, which is one of the parameters of the Weibull distribution, was calculated to be around 1.2 and input into HOMER. The details of the R modeling are displayed below.

The Weibull distribution function is as follows:

$$f(v) = [\left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \mathbf{exp}\left[-\left(\frac{v}{c}\right)^{k}\right]] \qquad \text{Eq. 1}$$

Where "*f(v)*" is the probability of wind speed "v" taking place at the given location, "k" is the scale factor and "c" is the shape factor.

The R code used for modeling is displayed below:

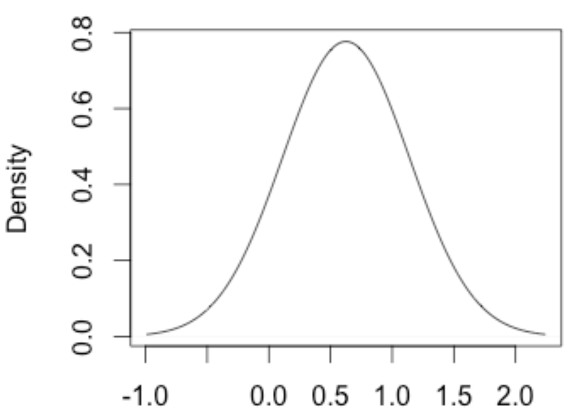
```
install.packages(c("MASS", "car"))
library(MASS)
library(car)

set.seed(333)
rw<-rweibull(12, shape=1.5, scale=1)
plot(density(rw, bw=0.5, cut=0), las=1, lwd=2,col="steelblue")
fitdistr(rw, densfun="weibull", lower = 0)

ra<-rweibull(aqaba, shape=1.835, scale=0.7)
plot(density(ra, bw=0.5))
fitdistr(ra, densfun="weibull")
qqPlot(ra, distribution="weibull", scale=1.835, shape=0.7)

k <- (sd(ra)/mean(ra))^(-1.086)
c <- mean(ra)/(gamma(1+1/k))
k
c
```

The Weibull distribution of the wind speeds is displayed below:



7.3 Appendix C: Past Modeling Results

HOMER software was used to model various base case scenarios to investigate the renewable energy potentials of Jordan in a quantitative manner; the HOMER component diagram is displayed in figure 8. The model was developed to meet the capital city's electric demand and incorporated all current generators as well as a proposed 300MW wind farm and a 300MW solar power plant.

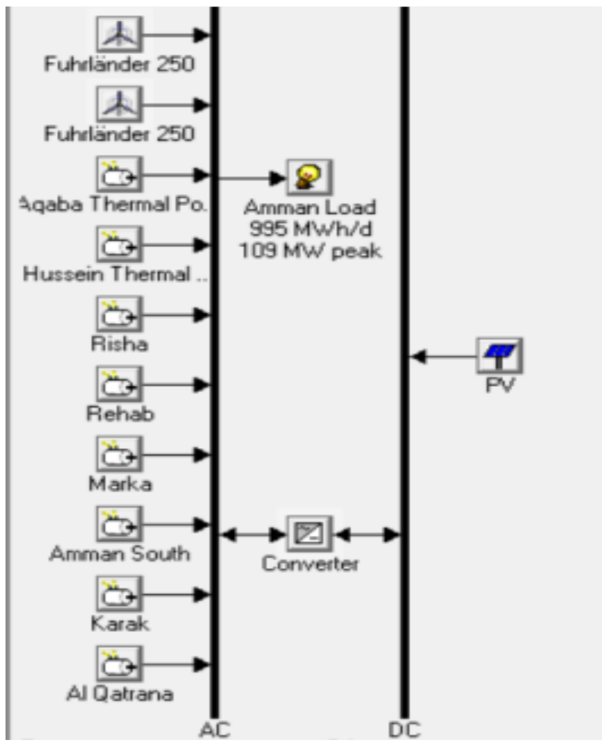


Figure 9: component diagram of the case modeled by HOMER.

Upon modeling the system in HOMER with a minimum of 30% renewables constraint, the optimization results returned a system that utilized the photovoltaics, wind farm, and Marka, Amman South and Karak power stations. The electric demand modeled was 363,144,736 kWh/yr and the system was capable of meeting 100% of the electricity demanded. The system also generated a significant amount of excess electricity (around 800 thousand KWh/year), which was to be expected given the load was only modeled for the capital city while the generation capacity was modeled for the entire country. The monthly average electric production of the system is displayed in the figure 13.

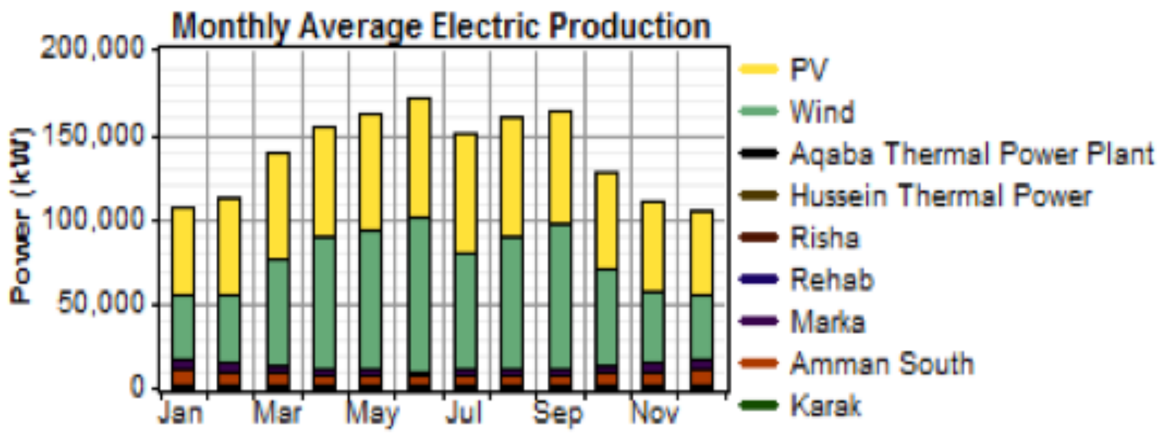


Figure 13: the monthly average electric production of the system.

The system utilizes a large renewables fraction of 0.9 and so a major advantage to this system is that it has large ramping capabilities as it employs such a large fraction of renewables. Furthermore, the system is very reliable as the unmet load is 0.411kWh/yr and the operating reserve is rather large. The operating reserve is expected to decrease once the entire kingdom's load is modeled, thus decreasing the reliability of the system.

The system also has lower emissions as a result of the large renewables fraction, thus making it a more sustainable option for Jordan's future. The emissions are detailed in the table below.

Table 5: emissions resulting from the system.

Pollutant	Emissions (kg/yr)
Carbon dioxide	114,607,824
Carbon monoxide	282,893
Unburned hydocarbons	31,336
Particulate matter	21,326
Sulfur dioxide	230,152
Nitrogen oxides	2,524,278

The total net present cost of the system was calculated to be $2,183,038,208, while the operating cost was $145,113,536/yr. Similarly, the levelized cost of energy was calculated to be $0.470/kWh. The cash flows summary chart is displayed in figure 14.

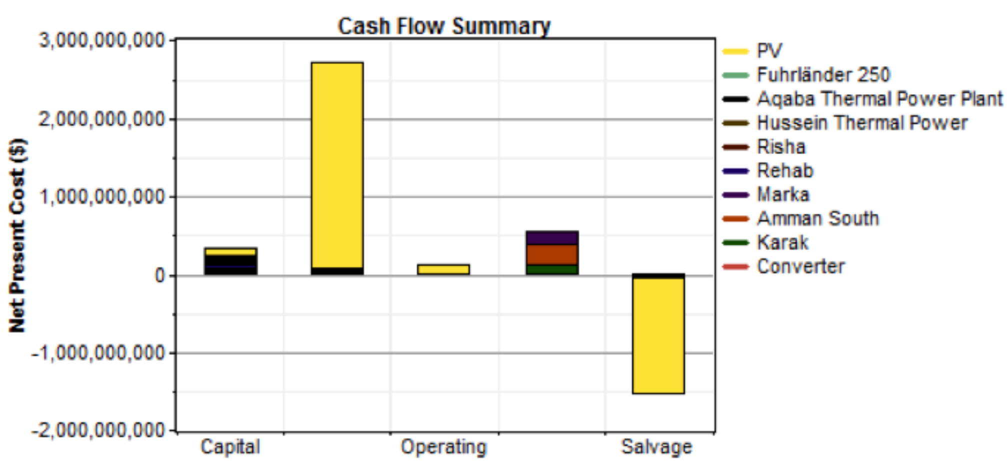


Figure 14: the cash flows diagram for the modeled system.

7.4 Appendix D: Other Trials

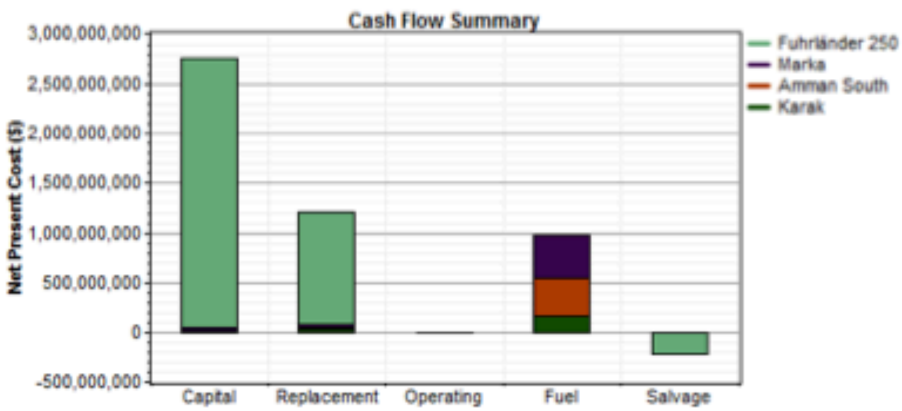
The appendix shows the results of another sensitivity analysis conducted were wind energy was the only renewable incorporated into the grid. This analysis was conducted using the old wind data for the city of Aqaba.

System architecture

Wind turbine	1,200 Fuhrländer 250
Marka	80,000 kW
Amman South	30,000 kW
Karak	20,000 kW

Cost summary

Total net present cost	$ 4,719,360,512
Levelized cost of energy	$ 1.017/kWh
Operating cost	$ 154,306,928/yr



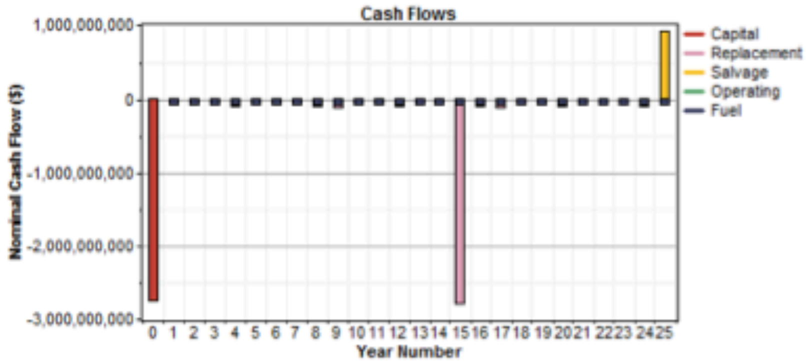
Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($)	($)	($)	($)	($)	($)
Fuhrländer 250	2,700,000,000	1,126,616,576	2,799,556	0	-209,699,056	3,619,717,120
Marka	28,800,000	28,412,204	6,826	436,392,288	-223,680	493,387,552
Amman South	10,800,000	31,624,070	14,838	381,456,224	-1,388,207	422,506,880
Karak	7,200,000	20,405,476	14,121	157,578,896	-1,448,322	183,750,192
System	2,746,799,872	1,207,058,432	2,835,341	975,427,456	-212,759,264	4,719,361,536

Annualized Costs

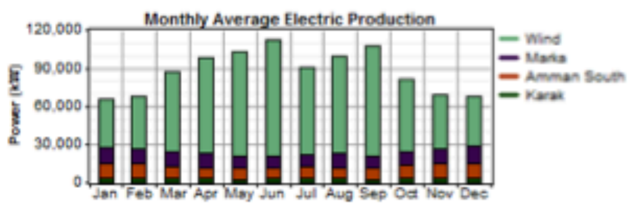
Component	Capital	Replacement	O&M	Fuel	Salvage	Total
	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
Fuhrländer 250	211,212,128	88,131,512	219,000	0	-16,404,068	283,158,592
Marka	2,252,930	2,222,594	534	34,137,536	-17,498	38,596,088

Amman South	844,849	2,473,847	1,161	29,840,068	-108,595	33,051,326
Karak	563,232	1,596,253	1,105	12,326,879	-113,297	14,374,174
System	214,873,136	94,424,216	221,799	76,304,488	-16,643,458	369,180,160



Electrical

Component	Production	Fraction
	(kWh/yr)	
Wind turbines	556,741,504	73%
Marka	95,205,112	12%
Amman South	85,909,336	11%
Karak	27,267,702	4%
Total	765,123,648	100%



Load	Consumption	Fraction
	(kWh/yr)	
AC primary load	363,144,736	100%
Total	363,144,736	100%

Quantity	Value	Units
Excess electricity	401,978,432	kWh/yr
Unmet load	0.626	kWh/yr
Capacity shortage	0.00	kWh/yr
Renewable fraction	0.728	

Emissions

Pollutant	Emissions (kg/yr)
Carbon dioxide	207,149,168
Carbon monoxide	511,318
Unburned hydocarbons	56,638
Particulate matter	38,546
Sulfur dioxide	415,992
Nitrogen oxides	4,562,533