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OPTIMAL ELECTRICITY SUPPLY SOLUTIONS FOR REMOTE AREAS IN KSA

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ABSTRACT

This paper presents a techno-economic evaluation of the electricity generation options available to meet electricity demand in three remote areas not interconnected to the main power grid of the Kingdom of Saudi Arabia (KSA). It considers two main alternatives: 1) extension of the main grid and 2) development of new generation resources in the isolated local grids. In the analysis, the electricity transmitted by the main grid is generated by oil-fired (or natural gas) combined cycle power plants (90%) and from PV and wind (10%) - consistent with KSA's plans for 2023- while the local isolated grids would include a combination of PV, wind, diesel, oil, HFO and li-ion batteries.

Results show that under most scenarios of capital costs, fuel prices, and costs of air pollution, developing the isolated grids is a better alternative than extending the main grid.

Keywords: renewable energy resources, distributed generation, energy systems for power generation, emissions, optimal energy mix

1. INTRODUCTION

The kingdom of Saudi Arabia has a massive electricity transmission and distribution network [1, 2] that is in a constant need for additional investment, mainly due to fast-growing electricity demand, especially in 23 areas in the northeastern and southern regions that remain disconnected from the main grid.

The current size and annual growth rate of the load in these isolated areas together with the large costs of connecting them to the grid are reasons to consider the development of off-grid infrastructure for distributed electricity generation.

This study conducts a techno-economic evaluation of the options available to meet demand in three remote and isolated areas in Saudi Arabia (listed in Table 1), over the period 2020-2040, in a reliable and sustainable way.

The final goal is to analyze the costs of developing distributed electricity generation versus those of supplying demand through an interconnection with the national power grid operated by the Saudi Electricity Company.

KSA is the world's largest user of crude oil for power generation. Crude oil, diesel and heavy fuel oil (HFO) account for two thirds of the input into electricity generation while natural gas provides most of the remaining share [1]. To meet future demand, the Saudi Electricity Company (SEC) will raise its available power generating capacity to 91 GW by 2021 using different technologies including fossil-fuel combined cycle, integrated solar combined cycle (ISCC), solar PV and wind [2]. Also, in line with Saudi Arabia's Vision 2030, the country has set a target to generate 9.5 gigawatts from renewable energy by 2023 [3-4].

This study determines whether distributed generation in remote-isolated areas is a cost effective alternative to centralized grid electricity supply. Unlike previous studies, we conduct a power flow analysis for a potential interconnection of the isolated networks to determine the technical requirements and costs of transmission lines, shunt reactors, transformers, etc. The total cost of grid extension is then compared with the cost of optimally developing the off-grid system. Also, unlike previous studies, the optimal mix of electricity generation sources is determined based on hourly operations and performance of these technologies to explicitly account for the intermittence of renewable energy sources. In addition, this study attempts to analyze how uncertainty about future fuel prices, emissions costs, and the capital costs of renewable energy technologies affect the optimal choice.

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Table.1 The major isolated areas studied

Isolated load name	Region	Existing system (data of 2018)			Estimated Distance from grid (Km)	Annual Growth rate (%) (2020-2040)
		Capacity (MW)	Peak load (MW)	Generation (MWh)		
Kharkair	Southern	17	14	49,365	830 (503 from Sharourah)*	1.3%
Aluwaygilah	N. Eastern	28.8	25.3	121,689	145	1.9%
Sharourah	Southern	226	127	656,889	340	2.3%

2. METHOD

The main approach consists of estimating and comparing the costs of main grid extension (MGE) with the costs of developing and operating an optimal combination of resources in the isolated areas (DG).

2.1 Optimal configuration of the isolated (DG) grids

A mixed integer linear program (MILP) model is used to determine the optimal mix of electric power generation technologies for the isolated network of each of the three areas considered. Consistent with the energy resources available in KSA, the model assumes that the only sources of distributed power generation that can be installed are solar PV, wind, diesel, Oil, and HFO engines as well as batteries for energy storage.

The MILP minimizes the total costs of installing new power plants, operating the generators (generation fuel costs, spinning reserve fuel costs, start-up costs, fixed costs, and social costs of air emissions) as well as penalty costs (over-generation, under-generation, un-met spinning reserves) over 21 years, subject to technical constraints. Its solution specifies, on a yearly basis, the optimal installed capacity of each technology considering three scenarios that vary fuel prices, solar and wind costs, energy storage costs, and emissions costs.

2.2 Grid Interconnection Requirements and Costs

The PSSE simulation model, developed by Siemens PTI, is used to represent the interconnected KSA grid in 2020, assuming that all the current plans to expand the transmission system have been implemented. The model represents 362 high voltage buses (mostly 380KV buses), 793 power generators, and 1,732 transmission lines with a total length of 112,430 KM. To this baseline system of 2020, we add an interconnection to each of the isolated areas. A simulation of this modified power system provides information on the generation and transmission capacity requirements to maintain reliability during system's peak load. Then these results are used to estimate the total costs of the MGE option (including the costs of capital, generation, operations and maintenance, and cost of emissions.

Table 2 lists assumptions about generation and transmission lines characteristics and costs (in 2015 dollars). It is assumed that 90% of the electricity that would be supplied by the main grid to the newly interconnected loads would come from oil-fired combined cycle power plants, [5] while the remaining 10% would be generated by either PV or wind which will be integrated into the main grid and represent 10% of the installed capacity by 2023 [3, 6]. In a sensitivity analysis, we consider the case in which natural-gas replaces the 90% of electricity coming from oil. The grid connected solar PV is assumed to be located in Tabouk (GHI of 2308.4 kWh/m2/yr) [7]. The grid-connected wind power is assumed to be sited in the Waad Alshamal area (average wind speed of 7.46 m/s at 92 m height).

We assume capital costs of the new fossil-fired combustion engines will stay constant but their annual operating and maintenance costs will vary according to three scenarios for fuel prices described in section 2.4. The three scenarios of wind and solar capital costs result in different assumptions about the type of resource that generates 10% of the electricity from the main grid.

Table.2 Assumptions on technical characteristics and costs of fossil fired generation and Transmission lines

Parameters / Location	Sharourah	Kharkair	Aluwaygilah
T/L length (Km)	340	503	145
T/L voltage rating (KV)	380	132	132
T/L cap cost ($K/Km)*	400	180	180
Annual T/L O&M cost (% of Capex)*	5	5	5
Substation/Transformer cost ($K)*	5,500	3,980	3,980
Shunt reactor ($K/MVar)*	21	21	21
T/L power losses (%)**	8	8	8
Capital costs of centrally dispatched Fuel Oil Combined Cycle power plants to meet new load ($K/MW)***	848.5	848.5	848.5
Annual non-fuel O&M costs of grid-connected oil-fired CCPPs ($K/MW)***	10.22	10.22	10.22
Energy efficiency of Fuel Oil Combined Cycle power plants (%)***	52	52	52
Fuel costs of grid-connected oil-fired CCPPs ($K/MWh)***	Depend on year and oil price assumptions		
Capital costs of developing a PV solar facility in the city of Tabouk ****	Depend on year and assumptions on solar PV capital costs. How much is installed depends on the cost of wind		
Capital costs of developing a wind farm in the area of Waad Alshamal ****	Depend on year and assumptions on wind power's capital costs. How much is installed depends on the cost of PV solar		

* These cost figures were obtained from SEC and are consistent with estimates from (WECC) [8] with the exception of the transmission line capital costs, which are about 1/3 of those in the US due to lower labor costs. Cost assumed for year 2020. ** The transmission lines losses are based on average values reported by SEC over the last five years [9]. *** The capital cost and efficiency are from [5]. Cost is converted to 2015 dollars applying a discount rate of 7%. It is 1.7% lower than the cost in [10]. Annual O&M costs are as in [10]. **** See section 2.7 for costs assumptions. Expected capacity factors for solar PV and wind in the 1st year are 22% and 47%, respectively.

2.3. Fossil-fired generators in the DG grid

The electricity in the isolated areas is currently generated from diesel/oil engines owned or rented by the SEC. It is assumed that all new and replacement plants will be combustion turbines similar to a Wärtsilä engine, which have high efficiency (47-49%), high operational flexibility, and can run using gas, oil, HFO and Diesel [11]. This engine has no minimum run time, its minimum down time is 5 minutes, and can start/stop many times per day with no impact on O&M [11]. It has an effective ramp rate of 50% per minute, and when it is preheated, it can be synchronized with the grid in 30 seconds, reaching full output in 3 minutes [11, 12]. Thus, it is assumed that it has zero start-up cost [12] and a minimum continuous loading of 30% [11,13].
This new combustion engine is assumed to have a heat-rate equal to 8,508 Btu/KWh [11]. Its greenhouse gas emissions rates from burning diesel, oil or HFO are assumed to be as reported in [14].

2.4. PV Generation in the DG grid

The hourly electricity generation from PV panels is estimated using an equation that takes into account the solar irradiance hitting the tilted surface of the polycrystalline modules and temperature as in [15,17].

The values of module temperature, T_c, are estimated for each hour of the year according to [16] using data on ambient temperature, GHI, and wind speed. The hourly direct irradiance hitting the tilted module surface are estimated based on the hourly GHI values and the position of the sun relative to the tilted module as in [17]. The PV system is assumed to experience an annual compound rate of efficiency decay of 0.5% as in [18].
Hourly GHI, ambient temperature and wind speed for all locations are assumed to be equal to those measured by Saudi Aramco in 2016 and consistent with [19].

2.5. PV Generation in the DG grid

The hourly electricity generation from converting wind power into rotational energy in the wind turbine is estimated using a standard equation as in [20].
Hourly wind speeds and other atmospheric conditions are assumed to be equal as those measured by Saudi Aramco in 2016, which are consistent with [21]. The wind turbine is assumed to be similar to a GE 2.75-120 wind turbine [22] which has a rotor diameter of 120 m, achieves a high power coefficient and can be installed at heights of 85-139 m, in areas with low wind resources such as the remote areas under study [23].

2.6. Battery Energy Storage in the DG grid

The energy storage system considered in this study is a lithium-ion battery unit with round trip efficiency of 86%, 4% annual performance degradation, 10 years lifetime, charging/discharging duration of 4 hours and 100% of depth of battery discharge (DOD) (i.e. battery can fully discharge all of its energy content) [24, 25]. When installed, it would compensate for fluctuations in electricity generation from the intermittent renewable energy and to sudden changes in the load, providing both energy and spinning reserves

2.7. Capital Costs for all new generation

The capital costs of the combustion engine are assumed to be 1,200 K$/MW and the annual fixed costs are assumed to be 12.24-13.00 K$/MW consistent with [26-28, 13]. The weighted average cost of capital (WACC) is assumed to be 7% with 20 years to maturity and inflation rate of 2% consistent with the values used by Electricity Cogeneration Regulatory Authority (ECRA) in assessing new power plants projects including renewable energy.

The projected solar PV and wind's capital and O&M costs over 2020-2040 period are based on low, mid, and high values reported in [29]. The projected capital and O&M costs of the lithium-ion (Li-ion) battery over 2020-2040 period are similar to those in [30] which estimated low, average and high costs for Li-ion battery whose learning rate is projected to be 12±3% over 2020-2040.

2.8. Prices of fossil fuels for both MEG and DG options

We consider three oil-price scenarios based on the reference case, low and high oil price cases presented in the OPEC 2016 world oil outlook (WOO) [31]. Estimates of annual average prices of natural gas corresponding to reference, high and low oil price scenarios are from [32] as suggested by [33]. Diesel's prices are assumed to be 37% higher than oil prices while HFO prices are 27% lower than oil prices as in [34]. The costs of transporting fuel to the remote areas from the Aramco distribution network are assumed to be 0.024 $/KM [35] per barrel.

2.8 Cost of GHG emissions

Although KSA does not account for the cost of GHG emissions, this study considers scenarios were emissions of CO_2, N_2O and CH_4 are priced at the value estimated by the US Environmental Protection Department [36] under 3% and 2.5% discount rates. The social costs are converted to 2015 dollar value, from 2007 dollar value at conversion rate of 1.143 based on Consumer Price Index (CPI-U) data which is provided by the U.S. Department of Labor/Bureau of Labor Statistic [37].

2.9. Assumptions to maintain reliability of the DG

To ensure there is enough power generation capacity to satisfy electricity demand reliably (i.e., to ensure resource adequacy) it is assumed that at all times, power generation capacity exceeds the expected peak load by 12% [6]. Similarly, to ensure operational reliability, it is assumed that each isolated network has at all times power generation spinning reserves equal to the maximum value between the capacity of the largest synchronized unit and the sum of 3% of the total demand and 5% of total renewable energy as recommended by the 3+5 rule of NREL [38].

2.9. Scenarios considered

The model assumes two cases of fossil-fuel use in the main grid and three scenarios for fossil fuel prices, capital costs of new generation and GHG costs. In the first case, oil is used as a source for the combined cycle power plant (CCPP) providing 90% of electricity generation in the main grid, while in the second case it is replaced with natural gas. The two cases are considered in combination with three scenarios that vary in assumptions regarding future fuel prices, costs of GHG emissions, and capital costs of solar, wind, and batteries.

The first scenario is a "Reference Scenario" that assumes oil prices equal to those presented under the reference case in [31], air emission social costs assuming a 3% discount rate, solar PV and wind turbine costs from the mid scenario in [29], and Li-ion battery costs under the average scenario in [30]. The second scenario, named "Renewable Scenario" assumes prices and capital costs that favor the growth of renewables. It considers high oil prices (from the high price case of [31]), low costs of air emissions (social costs calculated using a 2.5% discount rate), low capital costs for solar PV and wind (corresponding to the low scenario in [29]), and the lowest capital costs for Li-ion battery energy storage (low in [30]). The third scenario, named "Fossil-Fuel Scenario" assumes conditions favorable to fossil fuels. It assumes low oil prices (corresponding to the low oil price in [31]) a cost of zero for GHG emissions, the highest capital costs for PV and wind (high scenario in [29]), and highest capital costs for Li-ion battery (high in [30]).

2.10. Results & Discussion

Figure.1 presents the total costs for the off-grid distributed generation (DG) option under all scenarios, shown in gray bars. The total costs of extending the main grid (i.e., main grid-extension MGE option) which are indicated by orange dashes (assuming grid is fueled by an oil-fired CCPP). The orange circles in percentage represent the cost ratios of off-grid DG to the main grid-extension (MGE) (assuming an oil-fired CCPP option). The results show that under all scenarios and for all areas, the DG option is more economic than the MGE option, assuming the main grid is fueled by oil-fired CCPP (i.e. most likely option for the main grid). It is also clear that longer transmission lines make the DG option more economic. For Kharkair, the most remote area, the advantage of DG is high; costs are 40-50% lower. For Sharourah, the second most remote area, DG costs are 32-34% lower. For Aluwaygilah, which requires transmission lines half as long, DG costs 19-45% less.

The difference between the costs of DG and MGE is almost the same for both the Reference and Renewable

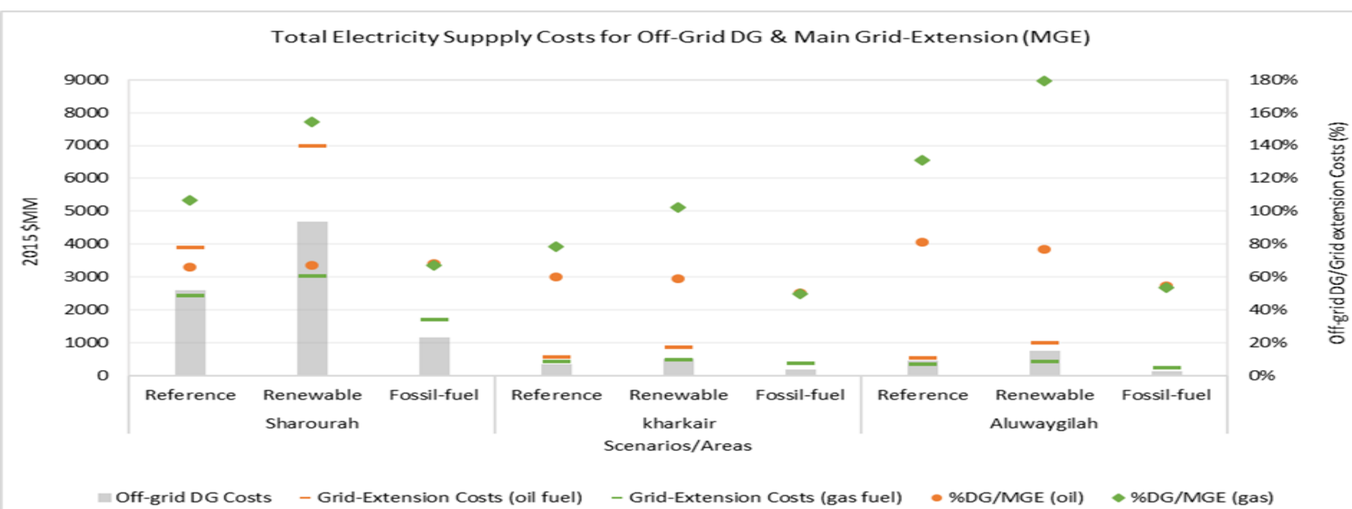

Figure.1 Total costs of supplying electricity to the remote areas by either off-grid DG or main grid-extension MGE (with CCPP fueled by oil or gas) under three scenarios: Reference, Renewable Favorable, Fossil-fuel Favorable. The left-axis applies to the grey bars (costs of DG) and orange dashes (costs of GE). The right axis applies to the orange circles and green diamonds, which indicate the ratio of the cost of DG to the cost of MGE.

scenarios assuming the MGE burns oil (i.e., the orange dots for the Reference and Renewable scenarios are close). The superiority of the DG option is of course enhanced under the assumptions of the Renewable scenario. However, contrary to what could be expected, under a Fossil-Fuel scenario, low fossil fuel prices favor (in Aluwaygilah and Kharkair) or at least not significantly hinder (in Sharourah) the economics of the DG grid extension. This is because although a decline in the price of fossil fuels reduces both the operational expenses of the main grid and the costs of purchasing and transporting fuel to the remote areas, it has more impact in the costs of the DG. As fuel prices decline, the costs of extending the transmission lines become a larger component of the total cost of implementing the MGE option. This does not happen in Sharourah because its load is the largest and thus the total cost of fuel achieved in the MGE –even under a low price scenario- is still a large share of the total costs.

The analysis shows that the DG option is a better alternative and that the range of assumptions made about fuel prices have little impact on this result. Indeed, if average oil prices in the period 2020-2040 dropped from 81 $/bbl under the reference case to 24 $/bbl under the fossil-fuel case, the economics of DG would improve.

Under this assumption, a scenario with low fossil fuel prices makes MGE more economic than DG as indicated by a comparison of all the green diamonds in Figure 1 (i.e., green diamond is more than 100% for the reference and renewable scenarios).

The total costs for the main grid-extension (MGE) option when the CCPP uses gas instead of oil are indicated by green dashes. Under a renewable scenario, the ratio of oil prices to natural gas prices is on average 27, while under the reference and fossil fuel scenarios is 17 and 6. The position of the green dots shows that high oil-to-natural gas price ratios largely improve the economics of MGE with respect to DG. Under the fossil fuel scenario, a low oil-to-gas price ratio makes the costs of MGE with gas-fired and oil-fire CCPP be equal.

Indeed, assuming the CCPP in the main grid burns natural gas and the load in the interconnected areas is twice as high, makes extending the grid more economic for Sharourah and Aluwaygilah under all scenarios except the fossil-fuel scenario (i.e. low fuel prices). Under a scenario of low fuel prices, the DG option is a better choice because of the low cost of oil relative to gas. However, in Kharkair, under the reference and fossil-fuel scenarios, the DG option continues to be more economic due to low load and long distance from the main grid. Under the renewable scenario, it results in an insignificant cost difference between DG and MGE (MGE is 2% lower).

The DG option also presents an interesting result in terms of the levelized cost of electricity and the optimal energy mix. Although the capital and fixed O&M costs of an HFO engine are higher than for diesel and oil engines, lower HFO fuel prices reduce the marginal costs for this technology, and make it the least-cost fossil-fired technology. There is also a small share of power generation from diesel engines which are an economic alternative to meet the spinning and non-spinning reserve requirements. Results also show that the high efficiency of the GE wind technology, coupled with a reduction in future capital costs, makes the cost of wind powered electricity competitive with fossil-fuels, even in these remote areas where wind speeds are relatively low. We find that the capacity factor of GE wind turbines installed at 92 meters in Sharourah, Kharkair and Aluwaygilah would be 24%, 26%, 29%, respectively.

The analysis shows that PV is the least cost option under the reference and renewable scenario while an HFO engine is the least cost option under the fossil-fuel scenario. Li-ion batteries are not part of an optimal system under any condition due to their high capital costs relative to those of efficient HFO/diesel engines.

The results indicate that due to their low LCOE, both solar and wind will provide a considerable share of the electricity in all areas under the reference and the renewable scenarios. Under the reference scenario, their share ranges from 20% in Sharourah to 30% in Kharkair. These shares increase under the renewable scenario to 40% and 50%. Under the reference and renewable scenarios average annual curtailment ranges from 5% in Sharourah to 9% in Kharkair. The hourly load profile indicates that both solar PV and wind units perform well in the spring season but they produce less electricity during the summer season when loads in these isolated areas reach their peaks.

3. CONCLUSIONS

Under most plausible scenarios, developing local isolated grids with PV and wind is more economic than extending the main grid to serve remote areas in KSA. Under a scenario that makes the development of renewables more attractive, the least-cost energy mix includes more than 300 MW of DG PV and wind. So, the regions isolated from the main power grid of KSA are a great place for deploying a portion of the large renewable electricity generation capacity the country intends to have in the future as part of the Vision 2030.

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