Dispatchable renewable energy from CSP and CSP+EGS in the Kingdom of Saudi Arabia

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Abstract. Renewable energy is part of the national sustainable energy mix for the Kingdom of Saudi Arabia (KSA). Relevant contributors are wind, and more importantly solar photovoltaic. Wind and solar photovoltaic (PV) are cheap, but they are suffering from variability, unpredictability, and in the case of solar PV, also intermittency. As the lithium-ion battery energy storage needed to make a stable grid only accepting these supplies is unaffordable, dispatchable renewable energy technologies are under study. Concentrated solar power (CSP) with thermal energy storage (TES) is the most promising opportunity. Requesting significant R&D, but having a large potential, enhanced geothermal systems (EGS) may help in the future, especially if coupled to CSP. Other relevant help may come from waste valorization. A renewable only grid managed by artificial intelligence (AI) operator will have to couple variable, unpredictable, and intermittent renewable energy supplies with battery energy storage and dispatchable renewable energy.

1. Introduction
Renewable energy is part of the national sustainable energy mix for the Kingdom of Saudi Arabia (KSA). Wind and solar photovoltaic (PV) are the most widespread renewable energy supply. The average wind energy resource for KSA is acceptable [1], [2], Fig. 1, while the average solar energy resource is good [3], [4], Fig. 2. The average wind speed or the average direct normal irradiance is only a rough indication of the average wind energy or solar energy that can be collected in wind energy or solar energy facility.

While solar PV energy facilities also use to some extent global horizontal irradiation, concentrated solar power (CSP) facilities only use the direct normal irradiance and are more susceptible to clouds coverage.

Both wind speed and direction and direct normal irradiance are affected by variability and unpredictability, with solar also affected by intermittency. Their use in a balanced grid renewable energy only must account for this variability, intermittency, and unpredictability [5]. It is not enough that the annual wind plus solar PV energy production matches the grid consumption. At any time supply and demand must be balanced. This can only be achieved (1) by using energy storage and (2) by adding to the wind and solar PV also stable and controllable renewable energy [6].

While superficially the problem of a renewable energy only grid has been so far limited to the build-up of a relevant capacity (i.e. nominal generating power) of wind and solar PV facilities, it is of paramount importance to understand the role of energy storage [5]. Without energy storage, for roughly 12 hours a day without sunlight, when the wind is low, there is no electricity supply.
Figure 1. Wind speed at 100 m (top) and 200 m (bottom) hub height across KSA from the global wind atlas. Images reproduced modified from [2]. Credit GWA. Creative Commons Attribution 4.0 International license, CC BY 4.0.

Figure 2. Direct Normal Irradiance (top) and global horizontal irradiation (GHI) across KSA from the global solar atlas. Images reproduced modified from [4]. Credit GSA. Creative Commons Attribution 4.0 International license, CC BY 4.0.
This work aims to discuss the best opportunities to deliver renewable energy only grid in KSA in terms of the levelised cost of electricity (LCOE).

2. Volatile Wind and Solar PV

Projections of costs and performances of alternatives are taken from the united states United States (U.S.) Department of Energy’s Office of Energy Efficiency and Renewable Energy National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB). Fig. 3 and 4 present the NREL ATB for wind and solar PV.

Fig. 3. presents the NREL ATB cost and performance of land-based wind [7]. The capacity factors are overrated by NREL (0.41 is their claimed grid average of 2017, vs. our estimation of about 0.33 [8], [9], [10]). We may better take an LCOE of 40 $/MWh as a realistic estimation of near future costs.

In areas of already established wind energy, such as the US, the best sites for land-based wind are being saturated, and worse resource or more expensive land is an issue of further developments. Sand, dust, and extreme temperatures are additional issues of KSA that may affect costs. Energy storage costs are not included.

![Figure 3. NREL ATB cost and performance of land-based wind. Image reproduced modified from [7]. Credit NREL.](image1)

When reference is made to recently built power plants in the US, the CapEx is underestimated, the capacity factor overrated vs. the about 0.33 delivered, and the LCOE is consequently underestimated.

Fig. 4. presents the NREL ATB cost and performance of utility-scale solar PV [11].

![Figure 4. NREL ATB cost and performance of utility-scale solar photovoltaic. Image reproduced modified from [11]. Credit NREL.](image2)

When reference is made to recently built power plants in the US, the CapEx is underestimated, the capacity factor is however less than the delivered 0.3-0.32, and the LCOE is underestimated. While present capacity factors are not overrated here (our present estimation is also about the same 0.3 [12]), the present LCOE is well above 30 $/MWh [12]. Same as wind, we may better take an LCOE of 40 $/MWh as a realistic estimation of near future costs. Sand, dust, and extreme temperatures are additional issues of KSA that may affect costs. Energy storage costs are not included.

3. Battery Storage

An enormous battery energy storage would be needed to make stable the grid, as variability, intermittency, and unpredictability of wind and solar supply, also at the grid level, is huge.
The NREL ATB [13] is unreliable. It is not representative of any real-world battery for a grid that must work without combustion fuels, where solar PV only works for 12 hours a day, and wind may go up or down for days.

To exemplify the need for storage, Fig. 5. Presents on top, the power supply to the Australian Energy Market Operator (AEMO) grid during December 2020 [14]. Middle and bottom, are the grid average capacity factors of solar PV plants and wind [15], [16].

Solar PV plants are highly correlated. During the 12 hours of daylight, about one half of the production must be stored for up to 12 hours. Wind is certainly better. Plants are less correlated, but sometimes low wind may last also a couple of days, same of high winds. Without considering the peaks and valleys of the demand, wind and solar power above the annual average must be stored, to compensate for the power below the average.

Fig. 6. Presents on top, the power supply to the AEMO grid during December 20, 2020 [14]. Middle and bottom, the total supply of solar PV plants and rooftop photovoltaic, and wind [14]. December is a summer month in Australia.
Fig. 6. Top, power supply to the Australian Energy Market Operator (AEMO) grid during December 20, 2020. Middle and bottom, the total supply of solar PV plants and rooftop photovoltaic, and wind. Images reproduced modified from [14], [15], [16]. Courtesy Andrew Miskelly.

The AEMO grid stretches over more than 5,000 km covering the states of SA, VIC, TAS, NSW, and QLD. The installed capacity of roof-top solar PV panels is much larger than solar PV plants. Their annual average capacity factor is about 0.10–0.15. The annual average capacity factor of wind is about 0.33, the annual average capacity factor of solar PV plants is about 0.3. The coefficient of variability is well above unity for wind, and even larger for solar.

The grid demand is covered by variable, unpredictable and intermittent wind, solar, and rooftop solar, plus baseload and dispatchable energy supply from black coal, brown coal, natural gas, natural gas/diesel, natural gas/fuel oil, hydro, coal seam methane, diesel, kerosene, waste coal mine gas, and bagasse.

The very limited battery energy storage is not used for stabilizing the grid, but simply to maximize the profit of the operator purchasing electricity in periods of low price and reselling in periods of peak price, being the AEMO a free market.

The battery energy storage of Australia includes the world's largest, best available technology, the Lithium-ion battery of Hornsdale Power Reserve. This facility is now a 150MW/194MWh facility. It was constructed in 2017 to supply 129 MWh at 100 MW. It was expanded in 2020 to an additional 64.5 MWh and 50 MW. The cost of the latest expansion is AUS$ 71 million for 64.5 MWh and 50 MW, i.e. US$ 52 million for 64.5 MWh of nominal storable energy [17].

If we consider actual capacity is less than nominal capacity, and a longer life requires operation at a fraction of full to zero charges, the use of this battery to stabilize the operation of a solar PV plant producing electricity only 12 h a day with a 50% charging/discharging daily cycle would cost (15 years’ lifetime) 294.5 $/MWh [17].
In extreme temperature conditions (very high temperatures, sand, and dust), lifetime is expected to be much less. While there are no relevant experiences of the lifespan of Lithium-Ion batteries for power plants, passenger car batteries that have a normal life span of 5 years in Australia are replaced annually in KSA.

In the harsh environment of Saudi Arabia, a battery energy storage facility is expected to have a life of fewer than 15 years. A more likely life is 10 years, bringing the recharging costs to almost 450 $/MWh. Thus, the idea of balancing a grid wind and solar PV by using lithium-ion batteries is not practicable. The requirements in terms of energy are large, and similarly large are the costs in terms of economy and environment (batteries are not environmentally friendly on the Life Cycle Analysis “cradle–to–grave” assessment). This solution is practically impossible [5], [17], [18]. Number of batteries must be limited, and dispatchable renewables are needed.

4. Dispatchable Solar CSP

It is of paramount relevance to add dispatchable renewable energy to reduce reliance on batteries that cannot be made available. An artificial intelligence (AI) grid manager is certainly welcomed to accommodate supply and condition consumption [6]. However, the AI manager may only reduce the need for dispatchable supply, or the storable supply for subsequent delivery, not to work without dispatchable supply and battery storage with the only variable, intermittent and unpredictable supply by wind and solar photovoltaic.

CSP with TES is the dispatchable renewable energy with the highest technology readiness level, even if suffering from substandard components [19], [20], [21]. Fig. 7 presents the NREL ATB cost and performance of concentrated solar plants [22].

![Figure 7. NREL ATB cost and performance of concentrated solar plants. Image reproduced modified from [22]. Credit NREL.](image)

The LCOE and capacity factor by NREL optimistic, as optimistic is the cost reduction trend. Dispatchability is limited for the proposed design with 10 h of TES by molten salt and a relatively small solar field of heliostats feeding a central tower receiver. Past designs were not very successful [19], [20], [21]. However, things can be easily improved.

CSP is certainly the most promising renewable energy technology thanks to dispatchability. It only suffers from some cases of sub-standard components and poor performances that weigh negatively against competing technologies that are more developed and widespread such as wind and solar photovoltaic.

The major obstacle in CSP development is to regain confidence against recent bad reputation and mature reliable industrial products, that are well within reach but need attention. Plants such as SEGS that have been operating for more than 30 years are ignored [19], and plants such as Crescent Dunes [21], shut down after less than 4 years, are always mentioned in every debate on renewable energy.

An LCOE of 80 $/MWh is a realistic estimation of near future costs of plants built by using quality components, with an increased size of the solar field and tower relative to the size of the turbine to deliver perfectly dispatchable electricity with potentially capacity factors approaching 1 (constant delivery over the year).

The constant delivery assumption is a simplified hypothesis to permit an easy computation of the LCOE. If for example CSP with TES is integrated with PV, PV may cover the day and CSP with TES...
the night. The specialization of the plant changes the costs and the electricity production, and thus the LCOE.

Further R&D is ongoing in concentrated solar power, mostly on the use of higher solar concentrator, novel higher temperature molten salt/liquid metals heat transfer/heat storage fluids, and higher temperature efficiency power cycles, either advanced-ultra-supercritical steam or supercritical carbon dioxide.

TES has definitively much smaller economic and environmental costs than battery energy storage, and this is particularly true for KSA, where sand, dust, and extreme temperatures make much shorter the life span of batteries. This is the reason why TES may become competitive also to store energy from solar PV converting electricity to thermal energy and back to electricity (see [40] and similar technologies being proposed).

Simple simulations by using SAM [41] may help to quantify the benefits of TES. The Annual Technology Baseline (ATB) from the National Renewable Energy Laboratory (NREL) for CSP is a solar tower with 10 hours of molten salt TES, the temperature of the hot tank 579 °C, hybrid condenser, reference thermal efficiency 41% [22]. We may consider the resource of Tabuk, KSA, close to the planned location of NEOM City. We may assume 0% taxation and a 30 years lifespan. The LCOE is 92.1 $/MWh. The annual average capacity factor is 0.57, the annual average standard deviation is 0.50 (hourly resolution), Fig. 8. This solution permits some dispatchability, with generation covering the full daylight plus part of the night, producing electricity from over 18 hours during the summer to slightly less than 14 hours during the winter. This solution can further be specialized, for example, to cover most of the night, and only part of the daylight time.

By oversizing the solar field about the optimum SAM values, the annual average capacity factor increases, while the standard deviation of the capacity factor reduces, same as the LCOE. The LCOE can go down to 76.9 $/MWh. The annual mean capacity factor is 0.95, the annual standard deviation is 0.24 (hourly resolution), Fig. 9. Now, electricity is produced over the full 24 hours during summer and shoulder months, and over almost 22 hours a day during winter.

Without a battery, solar PV electricity is only available the 12 hours of daylight. If we take the cost of solar PV 60 $/MWh, or also 40 $/MWh, to have electricity all the day would cost in between (40+40+294.5)/2=187.25 and (60+60+294.5)/2=207.25 $/MWh.

By coupling daylight solar PV and night CSP with TES, the cost for having electricity all day would be around (40+92.1)/2=66.05 and (60+92.1)/2=76.05 $/MWh. With the 60 $/MWh, a much more realistic present LCOE of solar PV than the 40 $/MWh, numbers are very close to using the solar concentrated with extended TES and expanded solar field, that is about 76.9 $/MWh.

While a certain amount of battery energy storage will be always needed to compensate for the remaining variability and also further adapt to the changes in grid demand, it is evident as a grid renewable energy only cannot be done solar PV, wind, and batteries, but must accommodate baseload/dispatchable renewable energy, such as CSP with TES, reducing the number of batteries needed as well as the supply by wind and solar PV.
**5. Dispatchable EGS+CSP**

While other contributors are being considered, such as biomass and waste, as well as nuclear, that is, however, a technology, for now, non-renewable, it is eventually the so far completely neglected geothermal energy [23], [24], [25] that can provide significant support to CSP with TES to address the downfalls of wind and solar photovoltaic.

Despite publicized since 2015 [26], there is not yet a reliable public domain global map of geothermal resource given in terms of temperature vs. depth except than for the US. KSA has some areas with potentials.

**Fig. 10.** presents the NREL ATB cost and performance of conventional geothermal plants hydro flash [27]. An LCOE of 60 $/MWh is given by NREL as present costs with capacity factors of about 1, to go further down to 40 $/MWh within two decades.

![NREL ATB cost and performance of conventional geothermal plants hydro flash. Image reproduced modified from [27]. Credit NREL.](image)

The NREL ATB for geothermal is based on the highly speculative Geovision report [25]. Thus, numbers have to be taken with care.

While hydrothermal systems are naturally occurring, enhanced geothermal systems (EGS) are created in zones where there is heat but not fluid flow. The concept of EGS is presented in **Fig. 11.** [25].

**Fig. 12.** Presents the NREL ATB cost and performance of deep EGS flash [27]. Deep EGS is the potentially most rewarding system, with a present LCOE of 170 $/MWh supposed to drop to 50 $/MWh within two decades in the Advanced Technology Innovation Scenario.
The EGS advantage is that a geothermal resource of basically any temperature and flow rate can be engineered where there are hot rocks also at many kilometers depth.

Hydraulic fracturing technologies that have been successful for hydrocarbon exploitation (albeit with environmental concern) can be further developed for fracking for geothermal energy. This gives geothermal energy a completely new perspective.

KSA has not too much water (there are no rivers nor lakes) but there are hot rocks [28], [29], [30], and therefore potentials for EGS, at least in selected areas. It is worth mentioning that the working fluid has not to be necessarily water, but it can also be CO$_2$, a product of hydrocarbon power plants with carbon capture. Supercritical CO$_2$ for fracking, recovering shale gas, or tight gas/oil, has been suggested by many [31], [32], [33], [34]. Fracking for geothermal energy by supercritical CO$_2$ has been similarly proposed [35], [36]. Apart from a few downfalls, CO$_2$ has some advantages vs. water for EGS. It permits a larger power output. There are reduced parasitic losses. It permits carbon sequestration. It reduces water use.

It minimizes scaling and corrosion of power plant components dissolving fewer minerals and other substances.
It is worth mentioning that while most of the present geothermal power plants are working with efficiencies much less than 20% because of the low temperature of the hot source (efficiency of a Carnot machine) and the impossibility to use well-developed components of combustion fuel power plants (or CSP plants), deep EGS may deliver a geothermal fluid of temperature approaching 400 °C for a thermal efficiency about double neglecting the power for pumping down and up the geothermal fluid, that however benefits from the buoyancy effect, Fig. 13.

![Figure 13. Thermodynamic analysis of a Rankine power plant using off-the-shelf components to deliver a 37% efficiency excluding geothermal fluid pumping. Geothermal fluid temperature 391 °C, ambient air temperature 35 °C](image1)

It has been already suggested to couple geothermal energy with solar energy [37], [38], [39]. In this case, the temperature of the steam to the turbine can be further increased, and thus the thermal efficiency can also surpass 40%, Fig. 14.

![Figure 14. Thermodynamic analysis of a Rankine power plant using off-the-shelf components to deliver a 40% efficiency excluding geothermal fluid pumping and CSP solar tower with TES pumping. Geothermal fluid temperature 391 °C, temperature hot TES 565 °C, ambient air temperature 35 °C](image2)
In this case, the heat flux from the geothermal fluid is complemented by the heat flux from the solar field through the TES increasing the temperature of the steam to the turbine to about 565 °C.

It must be noted as the technology readiness level for EGS in KSA is presently low, but subjected to abrupt changes if EGS could expand rapidly in the US as could be the case [25]. The technology readiness level of hybrid solar geothermal is much less than EGS. Hybrid solar geothermal is a highly speculative and risky solution, about the same as saltwater pumped hydro. TES may also be applied to EGS, with or without hybridization with concentrated solar power, to permit dispatchability in addition to baseload.

6. Conclusions
This work has shown as the optimal configuration of a renewable energy only grid includes variable renewables such as wind and solar PV, a limited amount of batteries, and dispatchable renewable, such as CSP, EGS+CSP and biomass/waste, all supervised by an artificial intelligence manager also conditioning the grid demand, Fig. 15.

Wind and solar PV energy are cheaper but they are suffering from variability, intermittency, and unpredictability. The lithium-ion battery energy storage needed to make a stable grid of renewable energy only wind and solar PV is unaffordable. Thus, baseload/dispatchable renewable energy is needed. CSP with thermal energy storage is the most promising renewable energy technology to consider targeting a renewable energy only grid because of achievable dispatchability and technology readiness level. Requesting significant R&D, but having a large potential, EGS may further support dispatchable concentrated solar power, wind, and solar PV energy supply in a renewable only grid managed by an AI operator.

While EGS has a present technology level relatively low, dramatic growth in the US could pave the road for similar growth in KSA. Nuclear, biomass, and waste, but also cleaner energy from hydrocarbons may certainly help during the transition until the present and future renewable energy technologies will be made better.

![Figure 15. Renewable energy only grid scheme.](image)

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