

Development of an energy potential estimation model for concentrated solar plants penetration in the GCC region

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Abstract

The rise of electricity demand and CO₂ emissions in the Middle East and North Africa region has made it necessary to rely on new energy resources. As the region possesses an abundance of sunlight and vast empty areas, such as deserts, attention has shifted towards solar technologies. Although some renewable energy projects in the region are planned, the full potential of the solar and renewables has yet not been well explored. This may be due to a lack of conviction on the part of policy makers in a region where the Gulf Cooperation Countries are rich with fuel and natural gas and, over the years, have been relied upon as a source of cheap and readily available electricity. In this study a model for large-scale application of Concentrated Solar Plants is considered, to calculate maximum energy that Solar Tower CSP can provide in the GCC region. The outcome is to be used to reduce CO₂ emissions and satisfy future demand and extra energy to be used for Hydrogen production and exportation, making the investment in such large scheme profitable.

Keywords: the middle east region, gulf cooperation countries, concentrated solar plants, energy potential.

1. Introduction

The rise of electricity demand and CO₂ emissions in the Middle East and North Africa region shown in Fig. 1[1] has made it necessary to rely on new energy resources [2]. As the region possesses an abundance of sunlight and vast empty areas, such as deserts, attention has shifted towards solar technologies. Although some renewable energy projects in the region are planned, the full potential of the solar and renewables has not yet been well explored. This may be due to a lack of conviction on the part of policy makers in the region, where the Gulf Cooperation Countries (GCC) are rich in fuel and natural gas and, over the years, have been relied upon as a source of cheap and readily available electricity. Currently renewable resources are more costly to apply on a large scale.

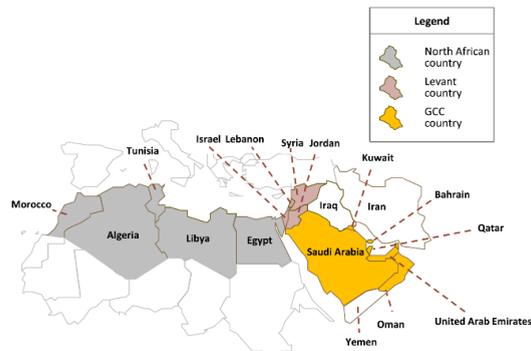


Fig. 1. Countries of the MENA Region [1].

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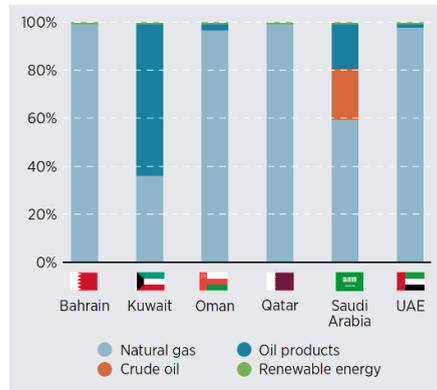


Fig. 2. Electricity generation capacity by fuel source as a percentage of the total in 2016 [3].

As shown in Fig. 2 there is a high dependence on fossil fuel in the GCC region with renewables making up a small fraction of the energy mix [3].

This paper estimates the maximum potential application of solar thermal energy using Concentrates Solar Plants (CSP) in the United Arab Emirates, Saudi Arabia, Kuwait and Oman of the GCC countries. This evaluation employs the solar tower CSP, which are heliostats that concentrate energy from the sun's rays to heat a receiver to high temperatures (see Fig. 3). This heat is transformed first into mechanical energy (by turbines or other engines) and then into electricity [4].

The maximum potential energy for CSP is calculated by estimating the suitable areas for application, that have high average solar radiation throughout the year, low slope and, for purposes of integration, construction and cooling, are close to the main grid, roads and water supply. Also, populated and protected areas such as forests and wildlife lands are excluded following the NREL model [5].

From this calculated energy potential, the projected future electricity demand of the country along with the renewable energy future target is deducted. The remaining energy is used for hydrogen production for export to generate revenue for investment in CSP.

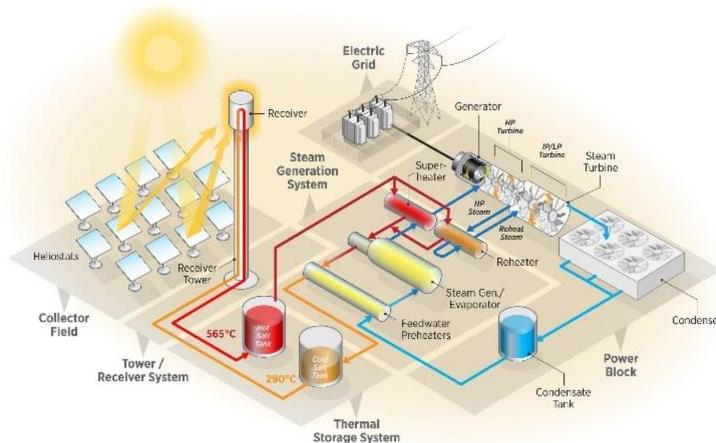


Fig. 3. Tower CSP concept [4].

2. Methodology and Assumptions

In order to evaluate the maximum technical potential for Concentrated Solar Power (CSP) in the GCC region, the following energy generation equation was used [5]:

$$\text{Available land [km}^2\text{]} \times \text{Power density [MW/km}^2\text{]} \times \text{Region capacity factor [\%]} \times 8760 \text{ [hours per year]} \quad (1)$$

The final area to be included in the study was derived through analysis of Geographical Information System (GIS) data, as shown in Fig. 4. First only areas with 5 MW/km²/day and higher were included [5], as solar thermal technologies such as CSP only operate at high temperatures [4]. Using data for the year 2018, these areas were calculated by processing Digital Elevation Maps (DEM) through the ‘solar radiation analyst’ tool in GIS. Next, areas with a slope of over 3%, protected areas and Populated areas within 5km radius were excluded [6]. Finally, three cases were created, with areas with (10, 25, 40 km) distance from main roads, wetlands and electrical grid network. Only electric grids operating at 220 and 400 kV were considered in this study. After exclusions, resulting areas for each case were intersected with previous results of high radiation areas, thus giving the suitable areas for application. In the interest of obtaining useful data, analysis through GIS was carried out several times to improve accuracy.

The power density for the tower system concentrated solar plants with 6 hours of storage with wet cooling is 22.38 MW/km² [7]. While 13.3 MW/km² for tower technology with a dry cooling system was assumed [7]. The energy potential for both technologies were calculated with the water requirements for both cooling technologies [7] [8], to help consider which technology is best for each country in every case.

Region capacity factor was extracted from NREL data based on SAM model [5], as shown in Table 1.

After the maximum technical potential energy for the whole region was calculated for each different case, future demand for the year 2023 was subtracted from final result [9], along with the percentage of current energy production which each country’s policy makers pledge for CO₂ emission reduction, which are 27% for the UAE, 10% for Saudi Arabia, 10% for Oman, and 15% for Kuwait [2]. This leaves the extra energy for Hydrogen production.

In the follow up phase of the study, the extra energy was used for hydrogen production, generating revenues from export, thus making the investment in large application of CSP more attractive for policy makers. Alkaline Electrolysis was chosen for hydrogen production. It is widely used and suitable for mass production. In this paper the capacity of electrolyzer chosen is 52.5 kWh/kg which is equivalent to about 75% efficiency [10].

Table 1. Capacity factors [5].

CLASS	MW/km ² /day	Capacity Factor
1	5-6.25	0.315
2	6.25-7.25	0.393
3	7.25-7.5	0.428
4	7.5-7.75	0.434
5	> 7.75	0.448

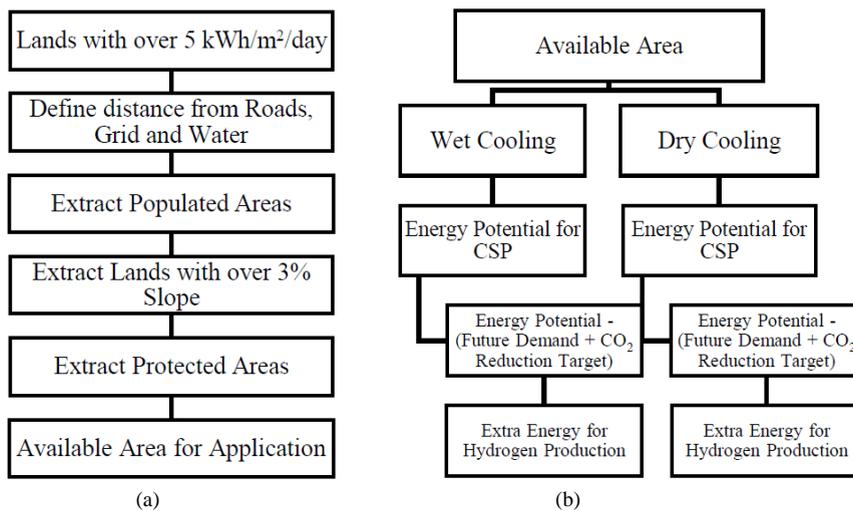


Fig. 4. Methodology (a) Part a; (b) Part b.

3. Results and Discussions

Using data of the GCC obtained for GIS analyses, the Direct Normal Irradiance (DNI) for the year 2018 was calculated for each country of the study, as shown in Fig. 5. Solar data was used to make two sets of areas, one with less than 5 kWh/m²/day, and the other with over 5 kWh/m²/day. Then using a Digital Elevation Map (DEM) of each country, the slope results were obtained, then classified into two categories, lands with less than 3% slope, and over 3% slope.

Fig. 6 shows the slope results along with roads, wetlands, electric transmission network, populated areas and protected areas.

A buffer area with radius of 10, 25 and 40km were created around roads, grid networks and wetlands for each case, and then each buffer zone was intersected with the areas of suitable direct solar irradiation and suitable slope. After that, protected areas and 5km buffer areas around populated areas were removed from the results. Figs. 7, 8, 9 and 10. shows the result of lands-use optimization in all four countries' suitable areas for CSP application.

Using equation (1), each countries' maximum technical potential for Concentrated Solar Power was estimated for each case, for wet cooling technology and dry cooling as shown in Figs. 8, 10, 12 and 14.

Projected electricity demand for the year 2023 by APICORP is around 46 GW for the UAE, 104 GW for KSA, 16 GW for Oman and 22 GW for Kuwait [9]. The extra demand from the year 2018 [11], along with renewable energy target of the production of the year 2023 were deducted from results.

Extra energy from each case was then used for hydrogen production based on previous assumptions as shown in Tables 2,3,4 and 5 for all cooling technologies.

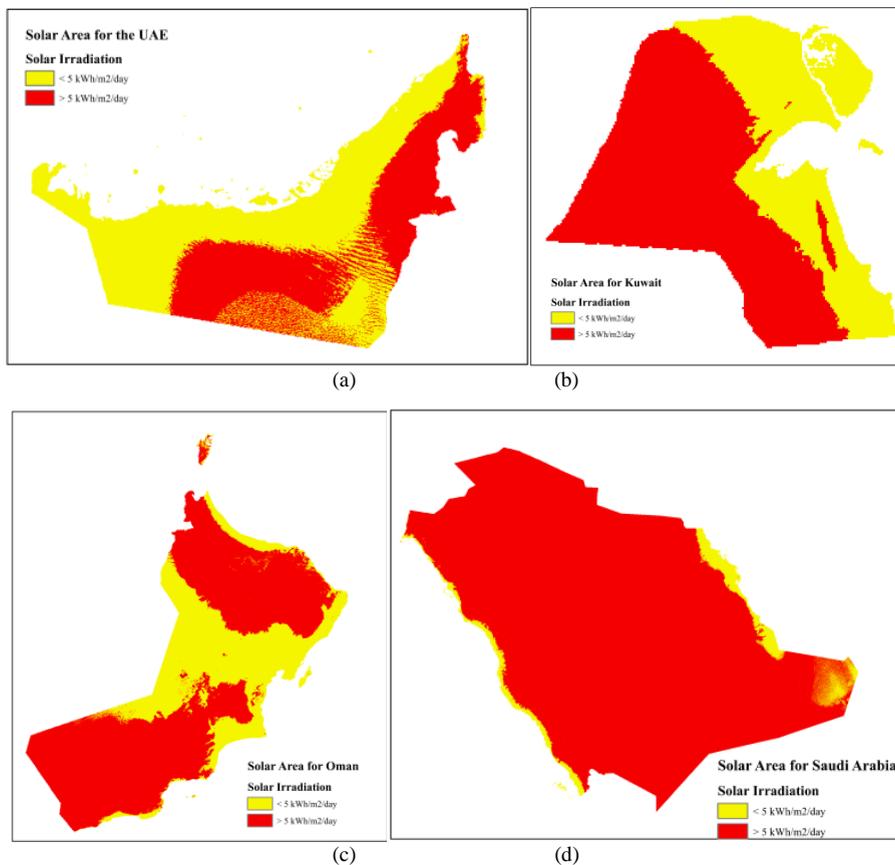


Fig. 5. Direct Normal Irradiance (DNI) for the year 2018 for (a) United Arab Emirates, (b) Kuwait, (c) Oman and (d) Saudi Arabia.

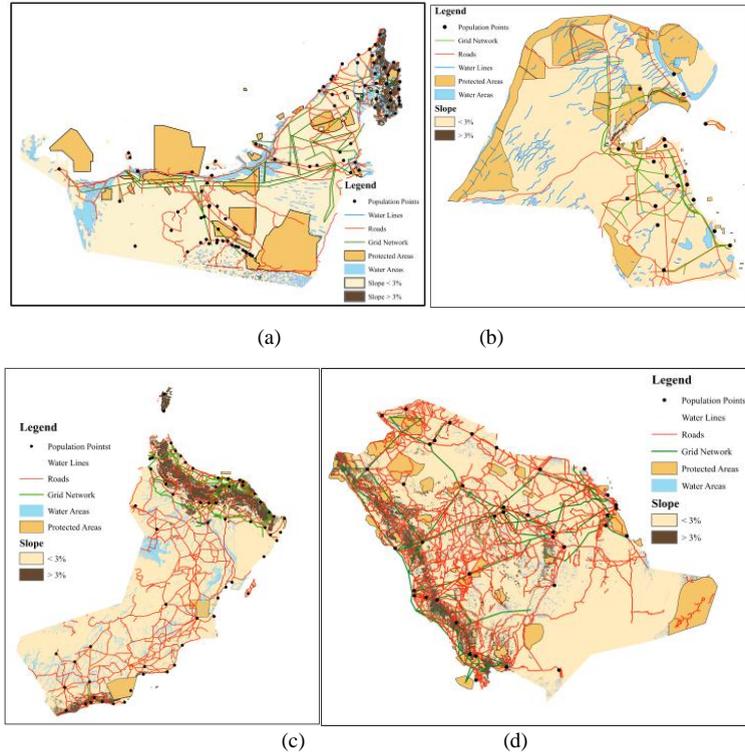


Fig. 6. Land-use data including: slope, populated areas, wetlands, grid network and protected areas. for (a) United Arab Emirates, (b) Kuwait, (c) Oman and (d) Saudi Arabia.

3.1. United Arab Emirates

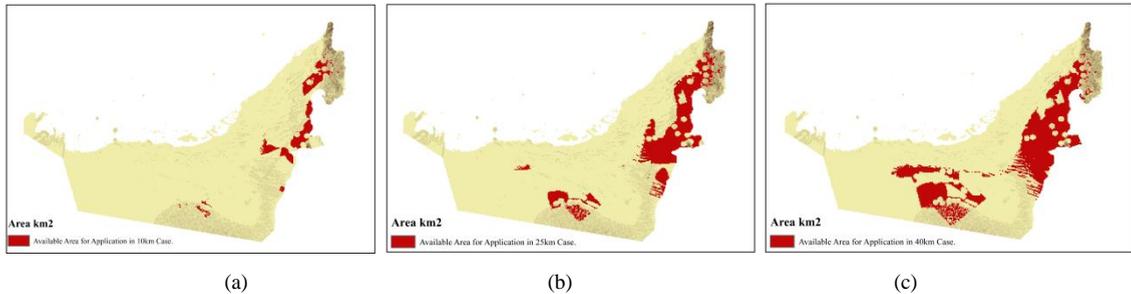


Fig. 7. Available Area for CSP application in the UAE for (a) 10km case, (b) 25km case and (c) 40km case.

Table 2. UAE’s results for CSP energy potential for each case, with wet cooling and dry cooling technologies along with water requirements for each technology.

Category	10km	25km	40km
Area km ²	3,145	10,180	16,207
Energy Potential GWh (Wet)	194,220	628,669	1,000,869
Water Requirement m ³ /MWh x 10 ³ (Wet)	543,816	1,760,275	2,802,434
Produced liquid Hydrogen kg x10 ⁶ (Wet)	1,458.33	9,733.548	16,823.072
Energy Potential GWh (Dry)	115,421	373,606	594,797
Water Requirement m ³ /MWh x10 ³ (Dry)	28,855	93,401	148,699
Produced liquid Hydrogen kg x10 ⁶ (Dry)	0	4,875.205	9,088.367

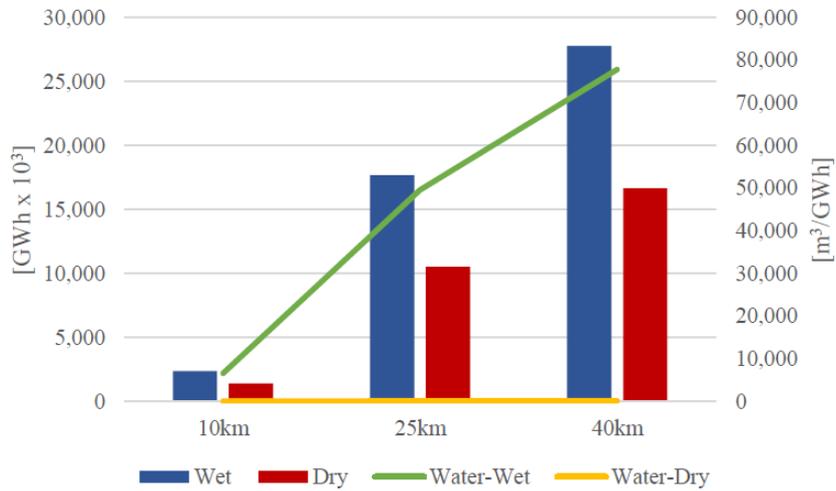


Fig. 8. Comparison for energy potential and water requirements for wet and dry cooling technologies in the UAE.

3.2. Kuwait

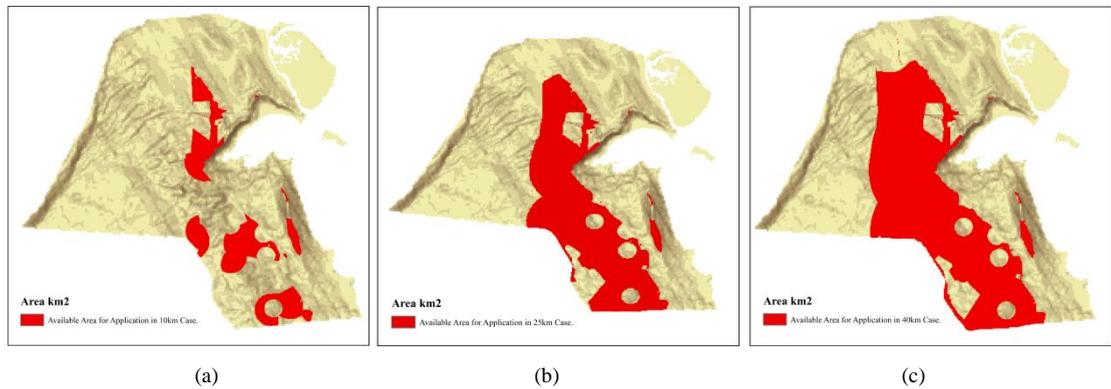


Fig. 9. Available Area for CSP application in Kuwait for (a) 10km case, (b) 25km case and (c) 40km case.

Table 3. Kuwait’s results for CSP energy potential for each case, with wet cooling and dry cooling technologies along with water requirements for each technology.

Category	10km	25km	40km
Area km ²	1,617	5,067	5,705
Energy Potential GWh (Wet)	99,858	312,914	352,314
Water Requirement m ³ /MWh x 10 ³ (Wet)	279,603	876,160	986,480
Produced liquid Hydrogen kg x10 ⁶ (Wet)	1,214.412	5,272.622	18,102.45
Energy Potential GWh (Dry)	59,344	185,959	209,373
Water Requirement m ³ /MWh x10 ³ (Dry)	14,836	46,489	52,343

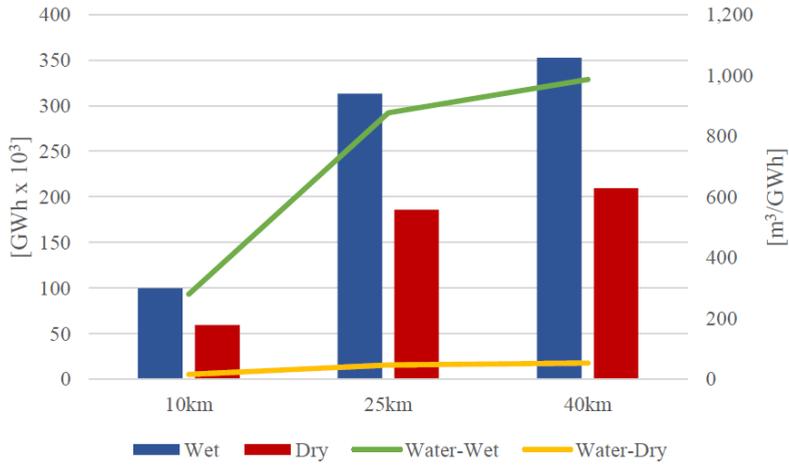


Fig. 10. Comparison for energy potential and water requirements for wet and dry cooling technologies in Kuwait.

3.3 Oman

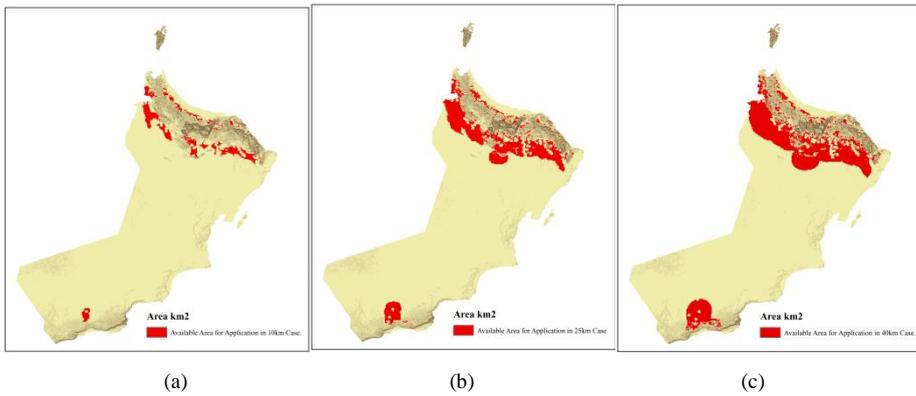


Fig. 11. Available Area for CSP application in Oman for (a) 10km case, (b) 25km case and (c) 40km case.

Table 4. Oman’s results for CSP energy potential for each case, with wet cooling and dry cooling technologies along with water requirements for each technology.

Category	10km	25km	40km
Area km ²	9,941	28,740	43,013
Energy Potential GWh (Wet)	613,910	1,774,849	2,656,283
Water Requirement m ³ /MWh x 10 ³ (Wet)	1,718,948	4,969,578	7,437,594
Produced liquid Hydrogen kg x 10 ⁶ (Wet)	10,579.465	32,692.6	49,481.8
Energy Potential GWh (Dry)	364,835	1,054,758	1,578,578
Water Requirement m ³ /MWh x 10 ³ (Dry)	91,208	263,689	394,644
Produced liquid Hydrogen kg x 10 ⁶ (Dry)	5,835.18	18,976.57	28,954.1

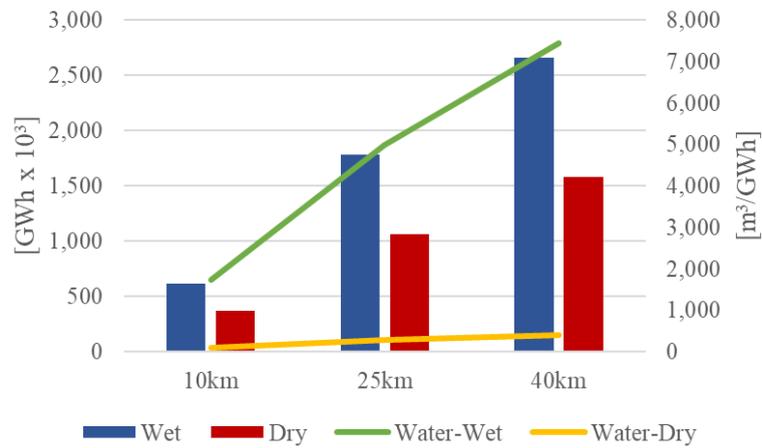


Fig. 12. Comparison for energy potential and water requirements for wet and dry cooling technologies in Oman.

3.4 Saudi Arabia

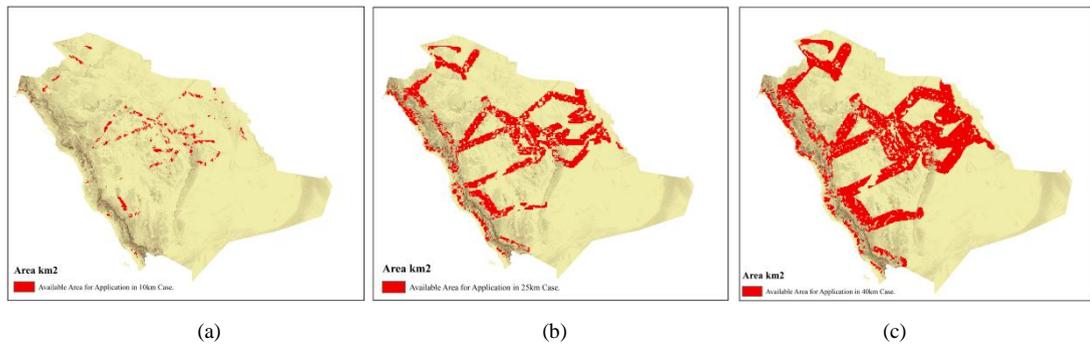


Fig. 13. Available Area for CSP application in Saudi Arabia for (a) 10km case, (b) 25km case and (c) 40km case.

Table 5. Saudi Arabia's results for CSP energy potential for each case, with wet cooling and dry cooling technologies along with water requirements for each technology.

Category	10km	25km	40km
Area km ²	38,113	286,294	449,436
Energy Potential GWh (Wet)	2,353,682	17,680,192	27,755,087
Water Requirement m ³ /MWh x 10 ³ (Wet)	6,590,311	49,504,539	77,714,244
Produced liquid Hydrogen kg x 10 ⁶ (Wet)	42,254.677	334,188.2	526,091
Energy Potential GWh (Dry)	1,398,747	10,506,995	16,649,431
Water Requirement m ³ /MWh x 10 ³ (Dry)	349,687	2,626,749	4,162,357
Produced liquid Hydrogen kg x 10 ⁶ (Dry)	24,065.44	197,555.877	314,554.658

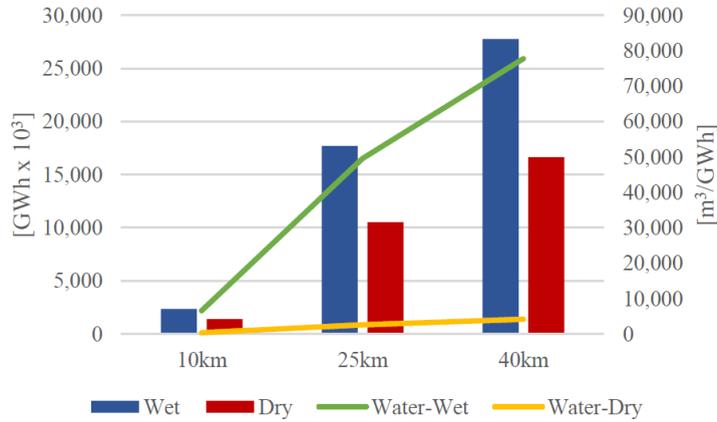


Fig. 14. Comparison for energy potential and water requirements for wet and dry cooling technologies in Saudi Arabia.

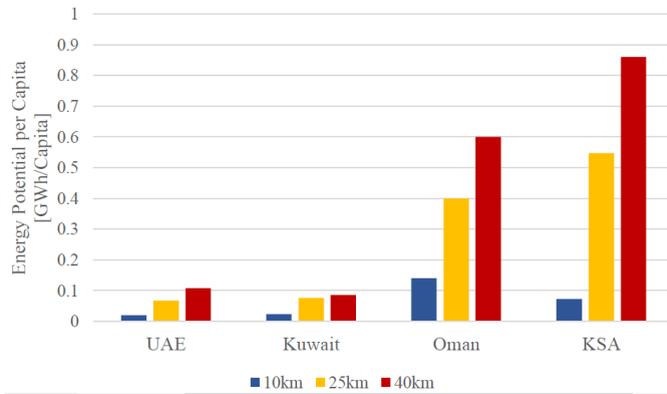


Fig. 15. Comparison for energy potential in all cases for wet cooling CSP for the GCC countries per Capita for the year 2016.

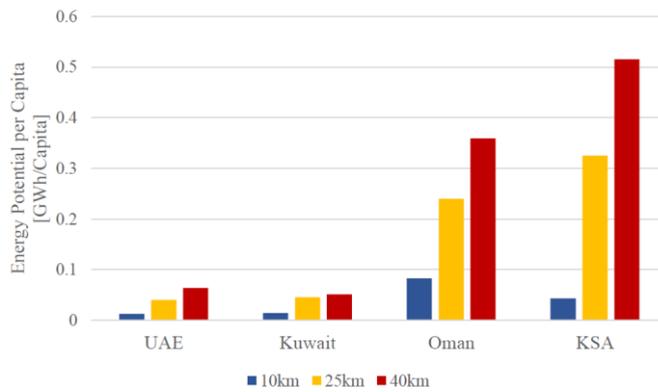


Fig. 16. Comparison for energy potential in all cases for dry cooling CSP for the GCC countries per Capita for the year 2016.

4. Conclusions

This study set out with the aim of assessing the potential of large-scale CSP application in the GCC region. Focusing on the United Arab Emirates, Kuwait, Oman and Saudi Arabia the estimation of the

potential starts with the calculation of available lands for application, where Geographical Information System is used to estimate the lands with high solar radiation of over 5 kWh/m²/day. This is followed by excluding areas with slope over 3%, areas within a 5km radius of population, and protected.

The results show that large areas of land in the GCC are rich with high solar radiation and a low slope. The land-use study is conducted for three different cases, depending on the distance from roads, wetlands and the grid network. After obtaining available land information, equation (1) is used to calculate the potential energy outcome for each case. Results show that the potential energy could cover future demand for electricity for all countries. Even with cuts to replace already existent conventional plants due to the CO₂ reduction pledges made by each countries' government, a huge amount of energy, is left for the investment in liquid hydrogen production for export. The most conservative estimates are equivalent to around 0.4 Gigaton of hydrogen for Kuwait, 5 Gigaton for Oman and 24 Gigaton for Saudi Arabia, while UAE need to use 2nd and 3rd cases for liquid hydrogen production of 4 Gigaton and 9 Gigatons respectively. These amounts of produced liquid hydrogen would be enough to cover the expense of large-scale CSP application and necessary infrastructure investment (e.g. roads, grid lines, water supplies), while still generating considerable revenues. Such revenue might be reinvested in the construction of desalination plants necessary for water supply in areas far from wetlands.

The limitations of large application shown by this study is materialized in first water requirements for wet cooling technology for all the studies countries, as water is scarce in such countries making dry cooling technology more attractive, although energy outcome is less than the one from wet cooling. The difference in the UAE and Kuwait is not very large, but in Oman and Saudi Arabia it is more obvious due to the larger areas that are suitable for application.

The second obstacle is electrical grid access, for the UAE a new grid is needed to be able to produce liquid hydrogen from extra energy in the dry cooling scenario, so the 25km and 40km cases could be used.

For Saudi Arabia and Oman, a new grid system reaching across both countries is needed to explore the real maximum potential of CSP and other renewables, as solar irradiation is very high all-over Saudi Arabia and Oman, but electrical grid is limiting access to all areas with high irradiance and favorable slope.

Future work will extend to cover the potential of concentrated solar thermal energy in other Middle East countries and assess the limitations of CSP applications in this region.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

A. Joubi and K. Okajima designed the study. A. Joubi performed the analytic calculations and the numerical simulations. K. Okajima verified the results and supervised the work. All authors approved the manuscript to be published and agree to be accountable for all aspects of the work.

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