

## Review

# Gulf Cooperation Council Countries' Climate Change Mitigation Challenges and Exploration of Solar and Wind Energy Resource Potential

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**Abstract:** Climate change mitigation is one of the most critical challenges of this century. The unprecedented global effects of climate change are wide-ranging, including changing weather patterns that threaten food production, increased risk of catastrophic floods, and rising sea levels. Adapting to these impacts will be more difficult and costly in the future if radical changes are not made now. This review paper evaluates the Gulf Cooperation Council (GCC) countries' potential for solar and wind energy resources to meet climate change mitigation requirements and assesses the ability of the GCC region to shift towards low-carbon technologies. The review demonstrates that the GCC region is characterized by abundant solar energy resources. The northwestern, southeastern, and western mountains of the region are highlighted as locations for solar energy application. Oman displays the highest onshore wind speed range, 3–6.3 m s<sup>−1</sup>, and has the highest annual solar radiation of up to 2500 kWh/m<sup>2</sup>. Kuwait has the second highest onshore wind speed range of 4.5–5.5 m s<sup>−1</sup>. The western mountains and northwestern Saudi Arabia have a wind speed range of 3–6 m s<sup>−1</sup>. The United Arab Emirates (UAE) has the second highest annual solar radiation, 2285 kWh/m<sup>2</sup>, while Saudi Arabia and the state of Kuwait have equal annual solar radiation at 2200 kWh/m<sup>2</sup>. This review demonstrates that abundant offshore wind energy resources were observed along the coastal areas of the Arabian Gulf, as well as a potential opportunity for wind energy resource development in the Red Sea, which was characterized by high performance. In addition, the GCC countries will not be able to control and address the interrelated issues of climate change in the future if they do not eliminate fossil fuel consumption, adhere to the Paris Agreement, and implement plans to utilize their natural resources to meet these challenges.



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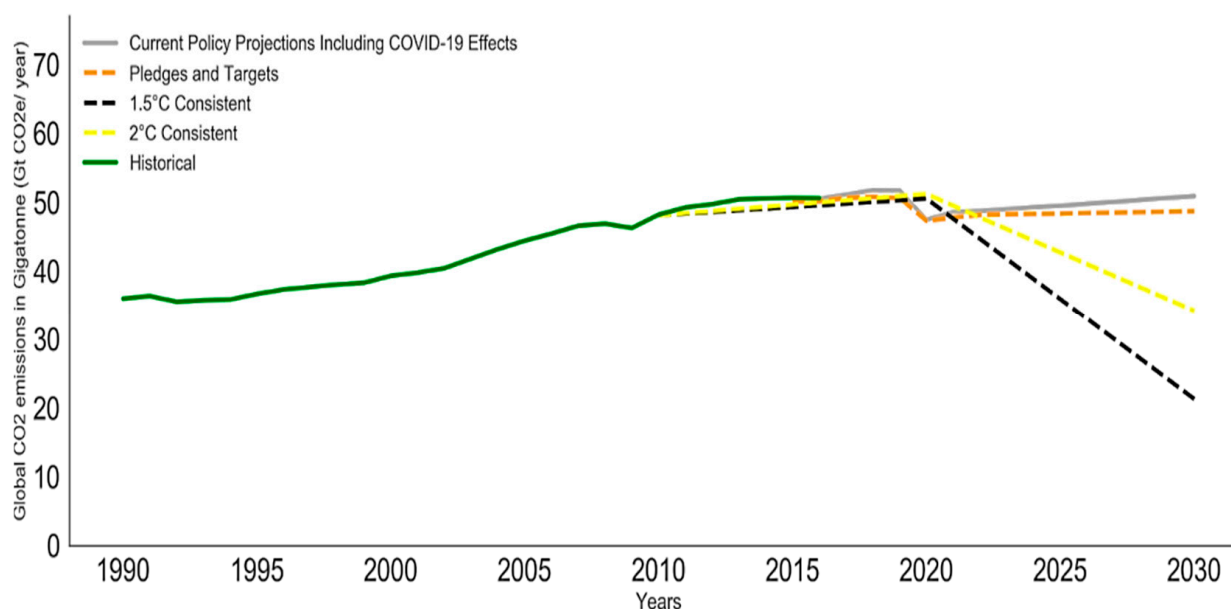


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## 1. Introduction

In the 21st century, the shift in global energy networks to low-carbon technologies is considered a significant challenge [1]. Climate change issues have forced nations around the world to explore more low-carbon and sustainable energy options. The average global temperature could increase by up to 6 °C by the end of this century, if the world continues emitting greenhouse gases at today's levels [2], and the average global temperature increase must not exceed 2 °C to avoid the most dangerous impacts of climate change [2]. In addition, the Paris Agreement on climate change (December 2015) and the International Panel on Climate Change (IPCC) (2018) strive to restrict the increase in global temperature to below 2 °C—or ideally below 1.5 °C [3]—which means that global emissions must be reduced to at least 50% below the recorded level in 1990, with the goal of reaching zero emissions by 2050. A number of international organizations support this goal, such as the United Nations Environment Program (UNEP) (2018). Figure 1 provides more details regarding the carbon dioxide (CO<sub>2</sub>) performance and the temperature reduction plan, including the effects of COVID-19 during the international lockdown. The United States (USA), European

Union (EU), China, and Russia are the largest producers of CO<sub>2</sub> emissions. Saudi Arabia, the USA, Canada, and South Korea are the largest producers of CO<sub>2</sub> per capita. The CO<sub>2</sub> per capita in Saudi Arabia is 18 tons, versus 16.6 tons for the USA [4]. In addition, Canada and South Korea are at 15.3 and 12.4 tons, respectively. Coal provides approximately 60% of the energy in China; however, renewable energy is rising at a faster pace [4]. Based on the Global Carbon Project [4], China was the largest source of CO<sub>2</sub> emission in 2018, at 27%, and its emissions are growing; however, China is firmly on target to reach its peak reduction emissions by 2030 in accordance with its Paris Agreement commitments. The USA's global share of CO<sub>2</sub> emissions surged in 2018 to 15%, but CO<sub>2</sub> has fallen in the last decade due to the decline in coal consumption in favor of renewable energy and natural gas. However, President Donald Trump scaled back measures to curtail greenhouse gas emissions and withdrew the nation from the Paris Agreement. On his very first day in office, President Biden recommitted to the Paris Agreement. In 2018, the EU recorded a 9% global share of CO<sub>2</sub> emissions, representing a reduction of 20% since 1990, which means that the EU is on track to reach its Paris Agreement goals. The global share of CO<sub>2</sub> emissions was recorded at 7% for India, indicating that it has contributed to climate change to a much lesser extent compared to other large countries. Despite the fact that its energy and coal consumption are rising rapidly, India is emerging as a competitor in sustainable energy technologies. Russia recorded a 5% global share of CO<sub>2</sub> emissions in 2018, and the climate action tracker (CAT) reported that Russia has made significant renewable energy investments. Since the collapse of industry after the break-up of the Soviet Union, CO<sub>2</sub> emissions are continuing to plunge. The Global Carbon Project [4] reported a 2% global share each of CO<sub>2</sub> emissions for Iran, South Korea, Saudi Arabia, and Canada, whereas Japan was at 3%. Values of 2–3% of the global share of CO<sub>2</sub> emissions would be high compared to other countries, such as the United Kingdom, Italy, France, Poland, Australia, Turkey, Brazil, South Africa, and Mexico, which produce a global share of CO<sub>2</sub> emissions of 1% each [5] yet have higher total populations. However, no country has been able to reach zero emissions. The rest of the world accounted for around 21% of the global share of CO<sub>2</sub> emissions [5].



**Figure 1.** The global CO<sub>2</sub> performance and the temperature reduction plan (data obtained from climate action tracker (2020)). The 2030 Emissions Gap. Updated September 2020. Copyright © 2020 Climate Analytics and New Climate Institute. All rights reserved [6]).

To support the transition towards decarbonization technologies, governments around the world (industrialized and nonindustrialized countries) must issue the world's first-ever

legally binding target to eliminate CO<sub>2</sub> emissions by 80% by 2050. A strong and effective global framework is required to achieve this decarbonization transition and to prevent climate change issues. The aim of this review paper is to analyze the transition towards decarbonization technologies by evaluating the potential solar and wind resources in the GCC countries to foster environmental sustainability and climate change mitigation in the region. This paper is composed of the following eight main sections: Section 2 describes the GCC's consumption growth; Section 3 discusses the GCC region's geographical factors; Section 4 presents the GCC's potential solar and wind energy resources, as well as the effects of dust and clouds; Section 5 discusses solar and wind energy power generation; Section 6 discusses climate justice; Section 7 provides an overall discussion; finally, Section 8 contains the conclusions.

## 2. Consumption Growth of the GCC

The accelerated increase in the consumption of conventional energy will lead to the depletion of fossil fuel resources. Jackson et al. [7] mention that 90% of CO<sub>2</sub> emissions result from human activities, such as cement production and fossil fuel burning. Despite the fact that coal consumption has declined considerably in recent years, the persistent increase in fossil fuel energy usage far outstrips the increase in low-carbon technologies and activities. Per-capita emissions continue to grow in the wealthier oil-producing nations, such as the Gulf Cooperation Council (GCC) region: Saudi Arabia, Oman, the United Arab Emirates (UAE), Kuwait, Qatar, and Bahrain. The council was established in May 1981 [8]. The purpose of the GCC is to achieve unity among its members based on their common shared goals, the geographical location, their oil wealth, and their similar rooted identities. Table 1 summarizes the GCC countries' details. The energy consumption per capita in the GCC region is estimated to be around 2.5 times that in the EU, making it the highest in the world [9,10]. The low cost of energy and government subsidies, as well as the abundance of fossil fuel sources, introduced and supported the huge growth in energy consumption in the region. Bekhet et al. [11] report that CO<sub>2</sub> emissions are increasing in Saudi Arabia, Oman, Qatar, and Kuwait due to the growth in energy consumption, which has resulted in the deterioration of environmental quality. Furthermore, Qader [12] mentions that the GCC region contributes significantly to the global CO<sub>2</sub> emissions produced by the combustion of oil and gas due to the conversion sectors and energy extraction, such as oil drilling and power generation. These countries are fully dependent on burning fossil fuel sources, which escalates CO<sub>2</sub> emissions in the region. It is estimated that the GCC region has two-thirds of the worldwide reserve of crude oil and a quarter of the world's natural gas [13,14]. The GCC region has a significant associated reserve of natural gas and nonassociated gas sources; however, the majority of the GCC countries are now faced with a shortage of domestic natural gas supply due to high demand, with the exception of Qatar. Approximately 12% of overall fuel demand is expended on desalination in the GCC countries, varying from 10% in Saudi Arabia to around 30% in Qatar. The region is unusual in its strong dependence on thermal desalination and electricity generation from fossil fuel sources. Ghaffour et al. [15] and Shatat et al. [16] suggest using renewable energy for power generation and running desalination systems, which can reduce conventional energy consumption in the region. The GCC region requires clean water production technology that supports a shift toward renewable energy sources. Al-Maamary et al. [17] state that renewable energy (solar and wind) can be a viable alternative to fossil fuels in the region in the future. Of course, the geographical location of the region has very favorable characteristics for solar and wind energy, which must be taken into consideration. Griffiths [13] mentions that, while the GCC countries are particularly active with regard to international climate change issues, they have not made any promises to mitigate greenhouse gas emissions. In fact, the GCC countries play a significant role in the global energy sector, and are extremely susceptible to several energy issues related to their economy. Lilliestam and Patt [9] believe that the GCC region has huge fossil fuel sources and enormous solar and wind energy potential, and the delay in implementing renewable energy is due to bureaucratic reasons.

Renewable energy technologies in the GCC region have been a subject of particular interest among researchers [18–22]. Blazquez et al. [23] report that implementing renewable energy deployment will support the gross domestic product (GDP) of countries such as Saudi Arabia and suggest that it would have a positive impact on the region in the long term. Another study conducted by Griffiths [24] mentions that, while each member country in the GCC region has ambitions and targets regarding decarbonization energy technologies, transitions have been minimal to date. Table 2 presents the GCC future target to reduce CO<sub>2</sub> emissions, which depends on two main factors: (i) reducing power consumption and (ii) improving efficiency for corporations and individuals [25]. Improving efficiency includes using steam turbines and combined cycle turbines in power plants for electricity generation instead of old fuel turbines and natural gas instead of crude oil. Acceleration of the deployment of decarbonization energy technologies is the responsibility of all countries, but particularly those that are industrialized and oil-exporting. Although most developed countries have well-formulated decarbonization energy and sustainability policies, such policies face many barriers. Malik et al. [26] expect that applying renewable energy in the GCC region will reduce greenhouse gas emissions by between 5 and 247 million tons of CO<sub>2</sub> equivalent by 2030. According to Patlitzianas et al. [27], despite the huge potential in the GCC region, the development of renewable energy has been relatively low. However, the GCC governments and the public have begun to realize the imperative of placing climate change issues on the list of priorities in the social and economic developmental process. The inspirational fulfilment of renewable energy targets will achieve climate change mitigation pledges and environmental sustainability. The GCC economy requires diversification to eliminate dependency on a single resource and mitigate the loss of oil export revenue. The main reasons for the diversification of energy systems are related to commitments regarding the diminishing hydrocarbon reserve and climate change mitigation, and, of course, the abundance of solar and wind energy resources.

Table 1. GCC countries' details [28,29].

Country	Area (km <sup>2</sup> )	Population (Millions)	GDP (Billion USD)	GDP per Capita (Thousand USD)	Oil Reserve (Billion Barrels)	Gas Reserve (Billion Cubic Feet)	Gas and Oil Share in GDP (%)	Gas and Oil Share in Revenues (%)
Saudi Arabia	2,149,690	33.5	646	21	266	8588	48	90
Oman	309,500	4.5	70	17	5	931	48	82
UAE	71,002	9.5	370	48	98	6091	36	76
Kuwait	17,818	4.2	114	29	102	1784	52	94
Qatar	11,600	2.6	165	59	25	24,299	56	61
Bahrain	778.3	1.6	31	23	0.12	92	44	80
GCC total	2,560,388	55.9	1396	197	496.12	41,785	284	483

Table 2. GCC future target to reduce CO<sub>2</sub> emissions [18,25].

Country	Target	Year
Saudi Arabia	Reduce power consumption by 8%	2021
	Reduce peak demand by 14%	2021
Oman	Reduce greenhouse gas (GHG) emissions by 2%	2030
	Reduce the power consumption in Dubai by 30%	2030
UAE	Reduce power consumption by 40%	2050
	Improve the efficiency for corporates and individuals by 40%	2050
	Reduce the electricity generation carbon footprint by 70%	2050
Kuwait	Reduce power consumption by 30%	2030
	Improve power generation efficiency by 15%	2030
Qatar	Reduce the per-capita power consumption by 8%	2022
Bahrain	Reduce the power consumption by 6%	2025

### 3. The GCC Region's Geographical Factors

The GCC countries' geographical location serves as the point that links the West to the East [30]. The advantages of the GCC region stem from its strategic geographical location



at one of the world's most important crossroads. The GCC region is located in the Arabian Peninsula southwest of Asia between latitudes 13° and 32° north of the equator and longitudes 35° and 60° east of Greenwich [31]. The GCC region covers a large area of desert that occupies most of the Arabian Peninsula wilderness in western Asia. The regional grouping constitutes approximately 2.5 million km<sup>2</sup> of land area, representing 82% of the Arabian Peninsula's total area [32]. The region's land mass represents a rectangular shape of 2000 km along the Tropic of Cancer, with a north–south axis of 2300 km in length [32]. In addition, the GCC region overlooks three important waterways: the western Red Sea, the eastern Arabian Gulf, and the southern Arabian Sea. The GCC region overlooks the Arabian Gulf, occupying its western coast area from Oman to Kuwait. The main Arabian Gulf is composed of the Straits of Hormuz in the inner Arabian Gulf and Oman Gulf, that is, the outer Gulf. According to Riad [32], since the 1950s, the Straits of Hormuz in the Arabian Gulf have been of exceptional global importance, unsurpassed by any other seaway due to being oil tankers' waterway to the world. The vital aspects of the Arabian Gulf to the GCC region and the entire globe are obvious. All of the eastern coastlines of the Red Sea overlook Saudi Arabia (except the short Yemeni coast), from Gizan in the south of Saudi Arabia to the tip of the Aqaba Gulf represent the critical border zones of Saudi Arabia with Jordan, Egypt, and the occupied Palestinian territories [32]. The northern boundaries of Kuwait and Saudi Arabia are generally viewed as marking the borders of the GCC region. In addition, the Red Sea front brings the GCC region in contact with the Suez Canal in Egypt, which links the Red Sea with the Mediterranean Sea. The facts of geography and the strategic location of the region are points in the GCC countries' favor, and they have huge amounts of natural resources. All of the countries have a large open area and overlook large beaches, which means they all have coastal areas on the Arabian Gulf, thereby explaining why the peninsular region is called "the Island of the Arabs." However, major difficulties arise with the ambitious development of renewable energy projects. Moreover, renewable energy resources differ across the geographical locations, which means that not all of the renewable energy technologies will be convenient for every place; for instance, the GCC countries have desert and subtropical desert regions. The diversity of geographical locations may have advantages in the GCC region in that various renewable energy techniques can be applied in different parts of the region. In addition, most of the GCC region's areas are incompatible with settled agriculture due to a lack of water and are not of enormous significance, which means that the construction of new renewable energy projects will not affect the agricultural sectors; furthermore, there are no forests in the region that are suitable for deforestation. The absence of geographical barriers or obstructions, the infrastructure available, and the tax laws in the GCC region all contribute to a favorable climate for new project development.

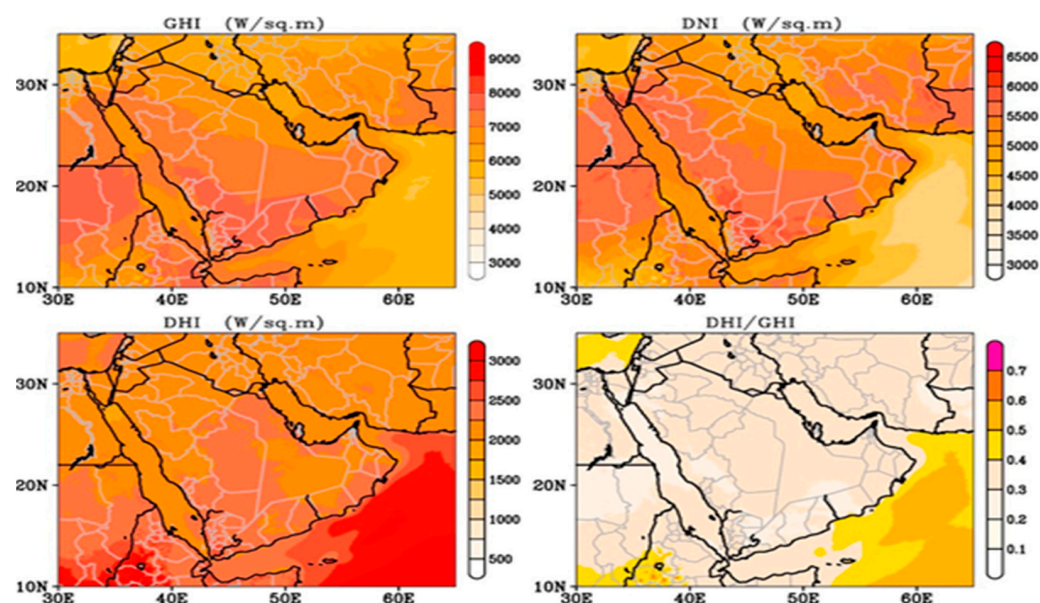
#### 4. The GCC's Solar and Wind Energy Resource Potential

In the GCC region, the development of solar and wind energy projects has been relatively low in spite of the significant geographical potential, which could provide effective solutions to consequent electricity consumption growth, unprecedented high energy costs, and climate change issues. According to Patlitzianas et al. [27], while the GCC countries have not considered renewable energy as a clean development mechanism solution to these issues for many years, something seems to have changed recently due to their accession to the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC), which put climate change issues at the top of the list of priorities. As a result, the GCC countries are raising their level of ambition to accelerate the deployment of renewable energy. The imperatives for enhancing sustainable progress to tackle climate change are further strengthening the momentum of a renewable energy transition in this region. The GCC countries must capitalize on their promising resources for renewable energy generation, along with applications for transport, buildings, cooling, and direct heat. Renewable energies have made striking gains in the GCC region over the past five years and are expected to be competitive with conventional energy technologies

over the next five years. The ambition of each country differs, as do market size and readiness, while the overall picture is the same across the region.

#### 4.1. Solar Energy

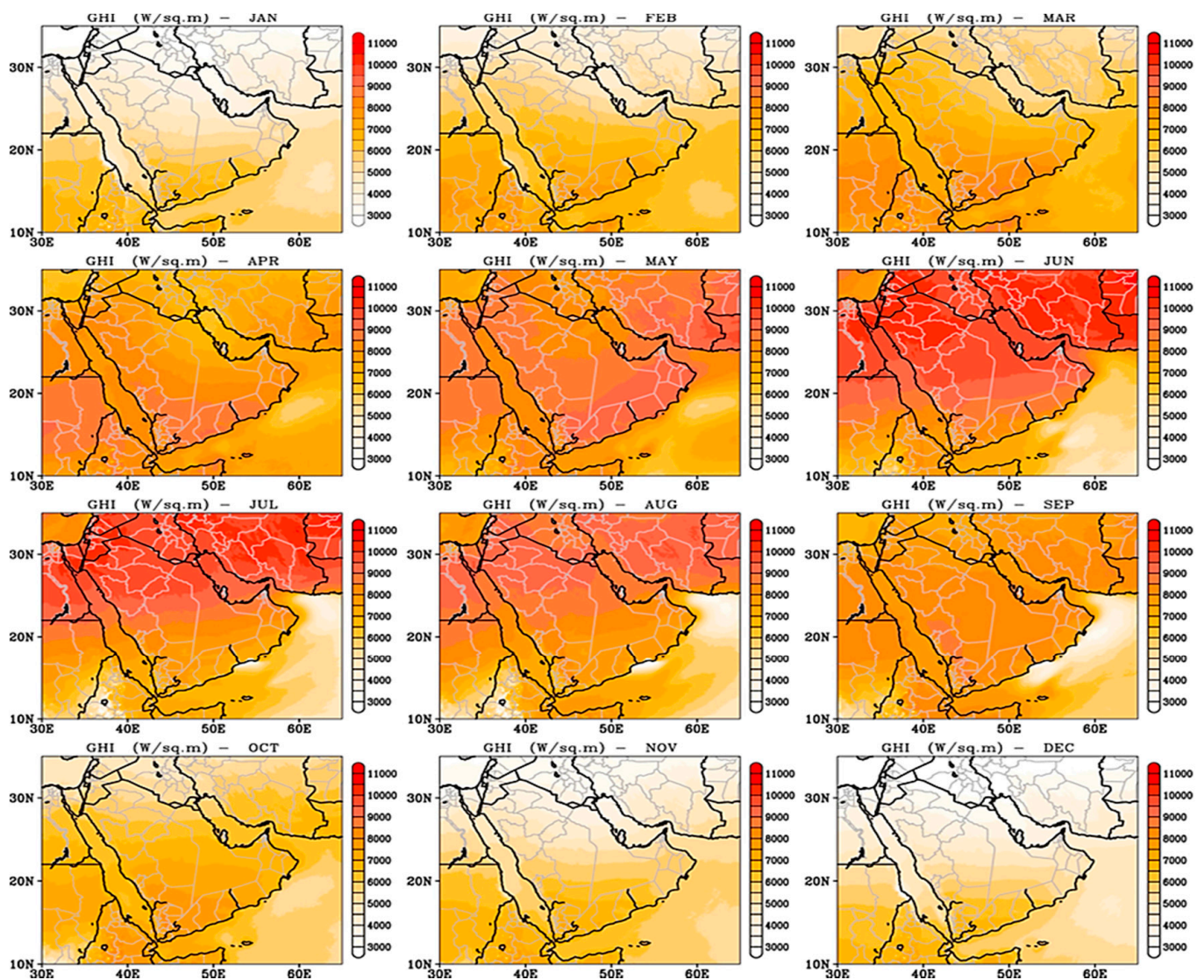
The importance of implementing large-scale photovoltaic (PV), concentrating solar power (CSP) and other solar energy applications and their economic benefits across several territories around the world has been analyzed in many previous studies [33–42]. The success of worldwide governments in developing solar energy technology primarily relies on the in-depth awareness of solar intensity levels and the distribution of global solar radiation, which is a challenging task due to the fact that, to date, the information on a global scale is limited. Singh et al. [43] and Meltzer et al. [44] mention that, based on the geographic location of the GCC region and the annual insolation (aggregated hours of sun, adjusted for solar intensity), the region is among those with the highest solar potential in the world due to the large annual availability of solar radiation. The annual average global solar radiation in the GCC region is estimated at 6 kWh/m<sup>2</sup> per day, and the direct normal irradiance (DNI) is around 4.5 kW/m<sup>2</sup> per day [44]. The abundance of solar energy resources depends on the sun's irradiance parameters and spectral distribution. Prăvălie et al. [45] mention that if the countries of the Arabian Peninsula collaborate strongly to this end, not only would Saudi Arabia be able to become a main solar energy hotspot in Asia, but the whole GCC region would be able to achieve this. Among the alternative renewable energy sources in the GCC region, solar energy stands out. Doukas et al. [46] mention that the GCC countries have a remarkable opportunity for the use of alternative energy sources, in particular solar energy, and, therefore, should take a more proactive role in terms of investment in emerging technologies. According to Al-Badi et al. [47] and Alnaser and Alnaser [48], the highest annual solar radiation range, 2200 to 2500 kWh/m<sup>2</sup>, was recorded in Oman. In addition, the UAE has the second highest annual solar radiation of 2285 kWh/m<sup>2</sup>, which is supported by average sunshine of 10 h per day [49,50] due to its location. Saudi Arabia and Kuwait have relatively equal annual solar radiation of 2200 kWh/m<sup>2</sup> [31,51,52]. Kuwait is characterized by high average daily sunshine, around 12 h per day. A mean of nearly 2180 kWh/m<sup>2</sup> for annual solar radiation was recorded in Bahrain [53]. Furthermore, the lowest value of annual average solar radiation was observed in Qatar at 2113 kWh/m<sup>2</sup>/year, with average daily sunshine of 9.5 h [54]. Nowadays, the GCC countries give special and increasing attention to the adoption of solar energy in order to reduce the energy cost of the growth demand. Dasari et al. [55] stated that the total annual mean of global horizontal irradiance (GHI) over the Arabian Peninsula, including the GCC region, is between 6 and 8.5 kW/m<sup>2</sup>, and the DNI is between 3 and 6.5 kW/m<sup>2</sup>. The values of diffuse direct horizontal irradiance (DHI) are high among the majority locations of the region and curtailed along the Red Sea and surrounding coastal shorelines, at 1.2 and 4 kW/m<sup>2</sup>, respectively [55]. This study provided comprehensive evaluation of the solar energy resources with high-resolution spatial data over the GCC region on the basis of analysis of historical data spanning 37 years for the period 1980–2017, gathered from 46 in situ radiometer stations over the region and supported by assimilative weather research. Figure 2 summarizes the performance of GHI, DNI, and DHI in W/m<sup>2</sup>, including the diffuse fraction (DHI/GHI) of the GCC region. The diffuse fraction (DHI to GHI ratio) indicates enhanced cloud cover and/or a higher aerosol load over the average duration [56] and is high over the northern locations and low over the southern parts of the central GCC region during the winter, while it is high across the southern and central regions, and low over the north during the summer [55]. The main elements that drive DHI variability are the clouds over the northern part of the GCC region in the winter and the loading of aerosols over the southern and central portions of the GCC during the summer due to desert dust. According to Dasari et al. [55], the evaluations of different parameters of solar radiation and aerosol characteristics suggest that there are considerable solar energy potential resources in the region, with the southeast and northwest identified as the most appropriate locations for exploiting solar energy and as the areas with minimal cloud coverage across the GCC countries.



**Figure 2.** The annual mean of global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) in  $\text{W/m}^2$  and the performance of the diffuse fraction (DHI/GHI) over 37 years (1980–2017) in the GCC region. Copyright © 2021 Elsevier [55].

There are considerable alterations in the values of DNI and GHI between the winter and summer that indicate a high seasonal variance in the solar energy potential across the GCC region due to the sensitivity of the regional climate. Figures 3 and 4 provide more details on the monthly behavior of DNI and GHI. Moreover, the monthly values of DNI, GHI, and DHI exhibited gradual development from January to April, with higher values occurring from May to September [55]. Between February and November, the position of the highest mean values of DHI shifted to the south, while from January to September, the position of maximum mean values of GHI and DNI migrated from the south to the north. The high values of DHI from April to September are due to the effect of dust across the southern and central regions during the summer and the winter's cloud impacts on the northern region. The transition seasons, spring and fall, show intermediate DNI and GHI values from winter to summer; however, their distributions present considerable similarity with the winter. GHI and DNI have higher percentage values of the variations' coefficient over the north of the region during winter and can reach around 17% south of  $15^\circ \text{N}$  during the summer due to the monsoon-related clouds and the distribution of dust. The northwestern and southeastern parts of the region are more desirable for harvesting solar energy despite the presence of some dust. The evaluation of various solar irradiance parameters gives an overview of the solar energy resource potential across the GCC region, thereby promoting significant sustainable opportunities to develop solar energy applications in the GCC region. Nonetheless, insufficient awareness, a paucity of experience, and technological deficiencies have hampered the comprehensive evaluation of solar energy characterization across the region. The analysis of long-term solar energy resource conditions over the GCC region can develop viable renewable energy projects' capabilities and fill the territorial gaps of solar resources. Furthermore, the Arab Peninsula, in particular the GCC countries with their 2030 future plans, are among the fastest-growing solar energy markets. This research indicates significant details for policy makers and researchers to establish effective strategies for the harvesting of renewable energy.





**Figure 3.** The monthly performance of GHI ( $\text{W/m}^2$ ) over 37 years (1980–2017) in the GCC region. Copyright © 2021 Elsevier [55].

#### 4.2. Effects of Dust and Clouds

The impact of clouds and dust is identified in relation to the geographical location and local conditions, which are extremely clear in the solar irradiance diurnal variation [57]. Moreover, the clouds, dust particles, and high humidity in the atmosphere eliminate the solar intensity [58]. The solar radiation's intermittencies are related to the issues of dust and sand deposition on PV panels. Moreover, if the dust particles are mixed with severe fog, it could be worse during the winter months, thus affecting the PV panels' performance. However, clouds and dust are the main factors that determine the installation feasibility of solar energy projects [59–62]. The real challenge is reported by Middleton [63] and Prospero et al. [64], that is, the Arabian Peninsula (including the circumambient deserts) is one of the dustiest areas in the world. The dust emissions are triggered by other external factors, such as regional storms caused by large-scale instabilities of the atmosphere and high-speed wind in some cases [65–67]. Awad and Mashat [68] mention that, as an influence on the strong pressure system gradient between the Arabian Peninsula's thermal low pressure and the Azores' high pressure, a huge amount of dust is transported to Asia from the Northeast African desert. Notaro et al. [69] identified three main sources of dust that can impact the region during the year: the Rub Al Khali Desert, which is a large regional

source of dust; the deserts of Iraq, which are major dust sources for northern and eastern Saudi Arabia; the Saharan Desert, which is the main remote source of dust for western Saudi Arabia. Moreover, Mashat and Awad [70] categorize Arabian Peninsula locations into permanent and temporary dust locations, and the eastern region is identified as a permanent source of dust. Table 3 provides more details on GCC countries and the effective locations' average annual dust. The presence of clouds and dust over the GCC region is attributable to storms that have a major influence on a substantial portion of the region. Figure 5 shows the coverage of cloud and the aerosol optical depth (AOD) performance, which indicates the areas with high sky index clearness over the GCC region. Mainly, the high values of the AOD across the southern region of the GCC occur during the summer months [55] and are caused by the loads of aerosol and clouds that are correlated with the Indian summer monsoon [71,72]. A clear sky supported by lower AOD values prevails over the northern region of the GCC, except in some summer months, when the dust is carried by the winds of the Shamal, which act as a solar irradiance opaque filter [73]. The increasing diffuse fraction values are caused by the clouds that occur as a consequence of the mid-latitude weather systems during the winter over the northern region (see Figure 2). Furthermore, seasonal variations in the diurnal patterns of the clearness index that affects the convective cycles' performance are evident in all parts of the region. The northwestern region is characterized by the symmetrical uniform clearness index during the entire year with low difference, excluding the winter period (November to February), while high uncertainty is observable during the daytime. The clearness indicator shows major diurnal variation in the summer (June to September) in southwestern Saudi Arabia and high diurnal variation in the eastern region between October and March [55]. During low-dust periods, the southern surface wind is dominant, while the prevailing wind during heavy-dust activities across the eastern part of the Peninsula is a northern surface wind. The eastern region has high diurnal variabilities during the year, with high cloud coverage and greater AOD values in some cases. In addition, the southwestern region is influenced by more cloud coverage and higher AOD, and the northwestern Red Sea is impacted by a mid-latitude cloud system in the winter. The clouds and dust over the southern region and the dust over the northern region play a significant role in modulating the high diffuse fractions.

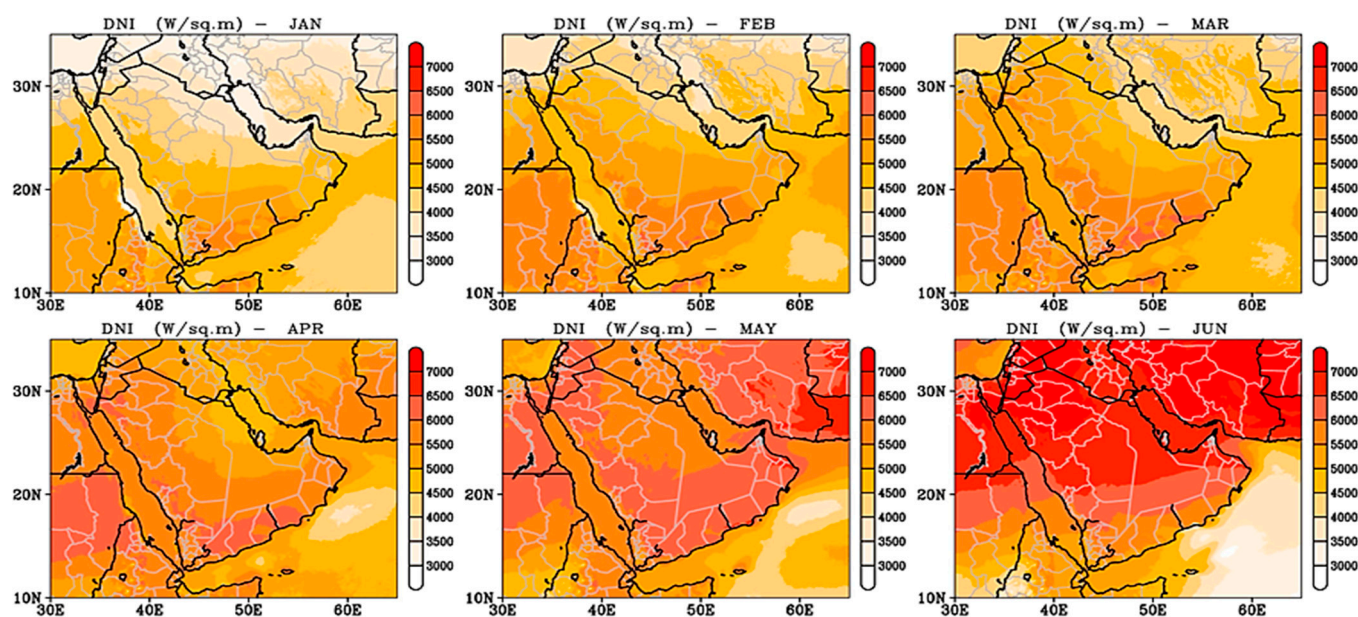
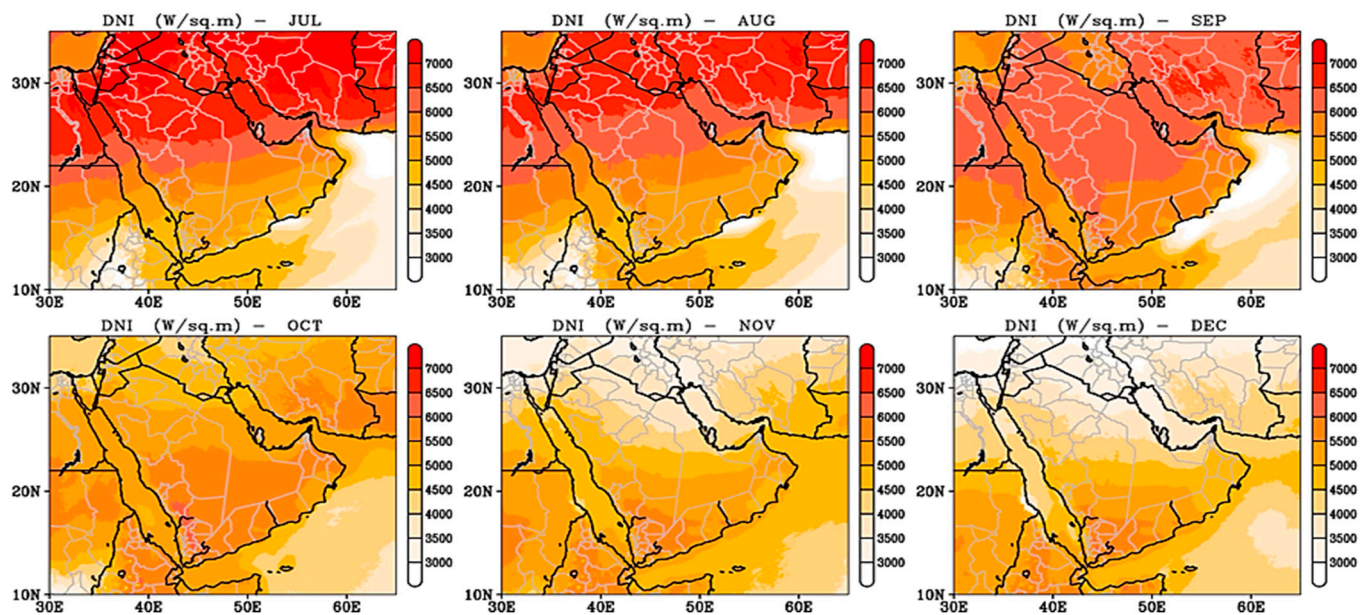


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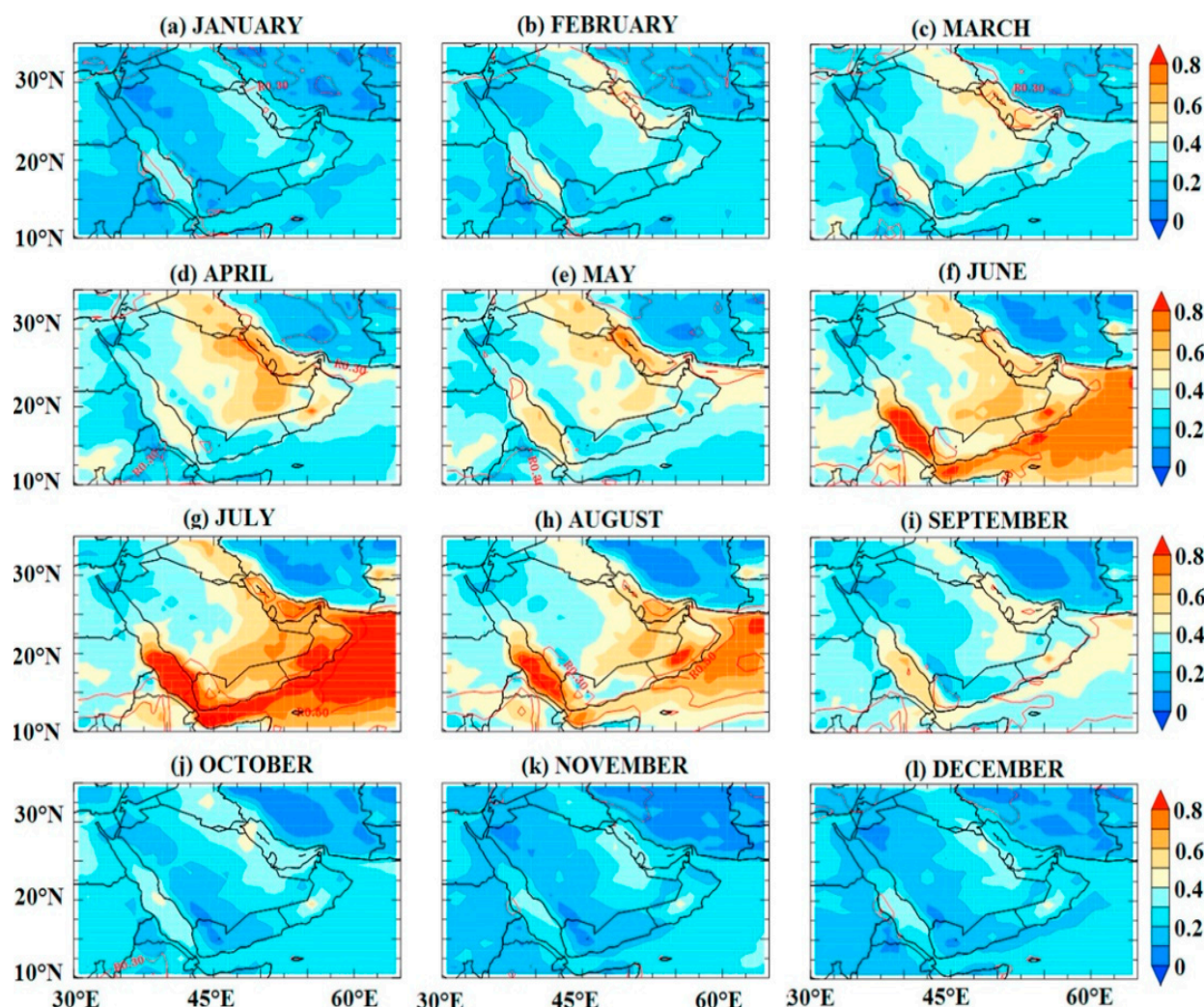


**Figure 4.** The monthly performance of DNI ( $\text{W/m}^2$ ) over 37 years (1980–2017) in the GCC region. Copyright © 2021 Elsevier [55].

**Table 3.** Average annual dust in GCC countries and effective locations.

No	Location	Region/City	Annual Dust ( $\text{tons km}^{-2}$ )	Reference
1	Saudi Arabia	Central Riyadh	392	[74]
		Northeastern Riyadh	454	[75]
		Najran *	420	This study
		Sharurah *	416	This study
		Wadi Al-Dawasir *	382	This study
		Al-Baha *	298	This study
		Hail *	298	This study
		Jeddah *	267	This study
		Yenbo *	198	This study
		Tabuk *	164	This study
		Turaif *	271	This study
		Al Ahsa *	355	This study
2	Oman	Hafar Al Batin *	397	This study
		Arar *	279	This study
3	UAE	Fahal coastal area	89	[76]
4	UAE	Coastal areas of UAE *	256	This study
5	Kuwait	Central (Kuwait City)	216–339	[77]
6	Qatar	Doha	50–113	[78,79]
7	Bahrain	Bahrain	60–144	[80]
8	Arabian Gulf	Northern parts of Arabian Gulf	373	[81]
9	Sahara Desert	western and southern Sahara Desert	913–10,446	[82,83]
10	Red Sea	Red Sea	43.3	[84]
11	Iraq	Baghdad	220	[85]
		Um Qasr	193	[86]

\* The dust values were calculated in this study (see Section 7).

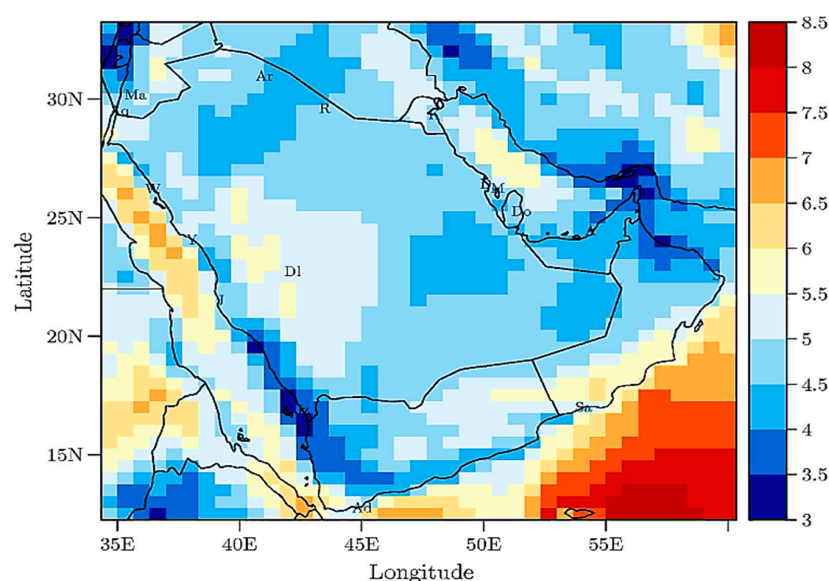


**Figure 5.** Monthly means of aerosol optical depth (AOD) and clearness of the sky over the GCC region computed for 2003–2017. Copyright © 2021 Elsevier [55].

#### 4.3. Wind Energy

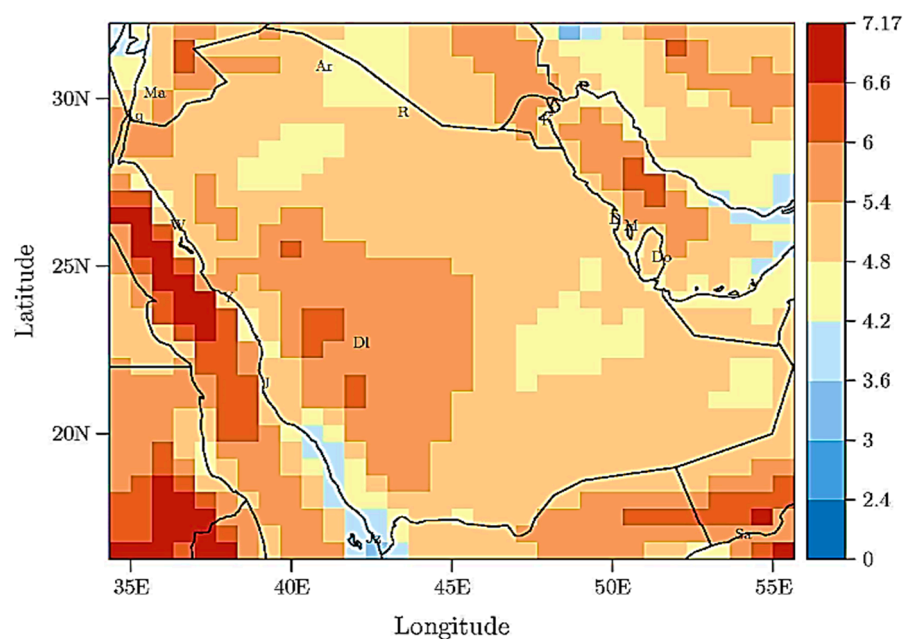
The power generation from wind energy in the GCC countries is estimated to grow dramatically in the future, and it is expected that this will introduce significant challenges, such as intermittency and unrecognized locations of high wind abundance. These challenges are rarely identified in the assessment of wind resources in the Middle East, including the GCC region, due to sparse meteorological observations and varying record lengths [87]. However, energizing the GCC countries requires developing wind farms through careful utilization of wind energy resources. To promote wind energy implementation in the GCC region, the Masdar Institute and other researchers have conducted several studies on the feasibility and potential of wind energy and other low-carbon technologies [88–95]. However, the majority of these studies are focused on the coastal locations in the GCC region. Al-Nassar et al. [96] mention that there are trends toward commercial investment in offshore wind farms in most GCC countries due to the reasonably good offshore wind potential. In addition, Al-Salem et al. [97] examined the Arabian Gulf's wind energy map based on an analysis of historical data from 1979–2015 and found that the central locations of the Arabian Gulf have a high annual average wind speed ( $8\text{--}9\text{ m s}^{-1}$ ), with the highest wind speed recorded at 50 m elevation. The study provided valuable information on wind energy resources in the Arabian Gulf. In addition, the wind energy potential in the coastal areas of Saudi Arabia was studied by Rehman and Ahmad [93]. They pinpointed Yanbo and Dhahran as the best locations for wind resources. Another 20 sites across Saudi Arabia

were studied by Rehman et al. [98] to assess wind power costs. The 20 locations cover three regions in Saudi Arabia: the eastern, central, and western regions. Langodan et al. [99], Jiang et al. [100], Dasari et al. [101], Langodan et al. [102], Menezes et al. [103], and Zhai and Bowe [104] investigated the potential resources, including wind energy, in the Red Sea and adjoining regions. These comprehensive studies discuss the advantages and significance of the Red Sea for the GCC region. Research was performed by Rehman et al. [94] to evaluate wind resources at a height of 60 m for Rafha, Saudi Arabia. They found that the wind speeds in Rafha vary between 2.5 and 4.9 m s<sup>-1</sup>. Yip et al. [87] conducted a comprehensive study to assess wind resource characterization in the Arabian Peninsula, including the GCC region. Furthermore, Nematollahi et al. [105] and Munawwar and Ghedira [106] mention that Oman is among the top countries for wind potential and that Kuwait has abundant wind energy resources. Northwestern Saudi Arabia and the Red Sea coast have an abundance of wind resources. Ouarda et al. [107] and Gastli et al. [108] report that the UAE and northeastern Oman show low to average wind energy resources. Figure 6 presents the highlighted wind speed ranges in Oman (3–6.3 m s<sup>-1</sup>), Kuwait (4.5–5.5 m s<sup>-1</sup>), and northwestern Saudi Arabia (3–6 m s<sup>-1</sup>) at a height of 50 m. The sites that are characterized by greater height displayed higher wind speeds; thus, the measurement scale and the height of wind turbines are important. Moreover, Shawon et al. [109] conducted a study of the wind technology deployment potential of all of the GCC countries and noted that these countries are good candidates for wind energy applications. Additionally, they observed that the wind speeds ranged between 2.35 and 5.1 m s<sup>-1</sup> at a height of 10 m. These studies highlight wind resource locations and opportunities for accelerating and supporting further wind energy applications in the region. Figures 6 and 7 show more details of average wind speeds of the GCC region at heights of 50–100 m. This indicates that wind energy distribution in the region is heterogeneous and clustered in specific locations. Furthermore, wind energy resources in the GCC region are described in detail while assessing suitable technologies for the region. In particular, the western mountains of the GCC region offer an abundance of wind energy resources. High wind energy is detected along the coastal areas of the Arabian Gulf. In general, wind energy resources in the Arabian Gulf coast area are variable when compared to wind energy along the Red Sea shoreline at the same latitude. It is worth noting that the GCC countries all overlook the Arabian Gulf, which is characterized by high wind speeds. The GCC region is characterized by different wind speed performance due to various aspects, such as resolution, climatic scales, metrics of temporal variations in the wind, annual variability, and intermittency.



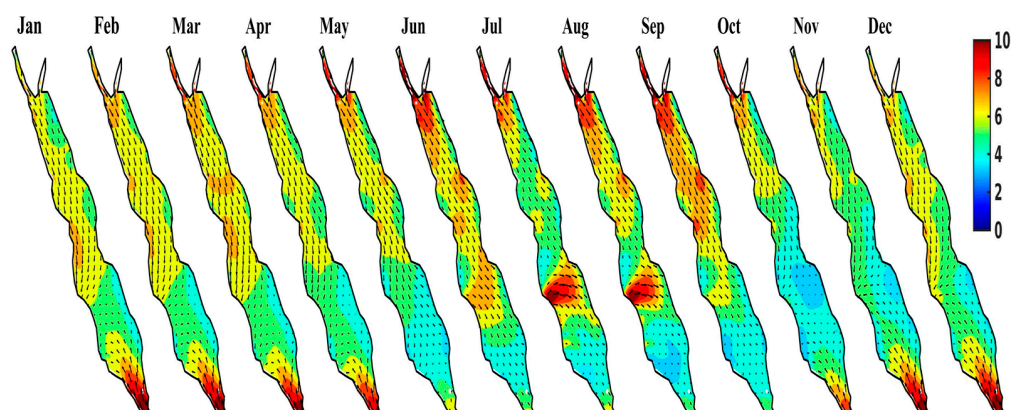
**Figure 6.** Average wind speed (m s<sup>-1</sup>) of the GCC region is computed at 50 m. Copyright © 2021 Elsevier [87].





**Figure 7.** Average wind speed ( $\text{m s}^{-1}$ ) of the GCC region is computed at 100 m. Copyright © 2021 Elsevier [87].

Furthermore, there are distinctive diurnal wind energy variations in each part of the region, and diurnal pattern variations with the seasons. Figure 8 presents the average monthly wind speed over the Red Sea in the GCC region at a height of 50–120 m based on an analysis of historical data spanning 18 years. An assessment of the spatial distribution of wind energy in the Red Sea shows that related energy concentrations usually occur in three main locations during the 18 years of observations, where the density of wind energy is stronger compared to other locations of the Red Sea, as shown in Figure 8. Moreover, it was observed that there is a stronger southeast wind over the southern Red Sea and weaker northwest wind along the northern Red Sea throughout El Niño periods and a weaker southeast wind along the southern Red Sea with stronger northwest wind speed along the northern Red Sea throughout La Niña periods. The mountain chains overlooking the Red Sea affect the prevailing local wind speed patterns and reconstruct the Red Sea into a practical and realistic wind channel, where the prevailing wind speeds are on the main axis. However, the monthly wind speed performance over the Red Sea shows a great opportunity for the harvesting of wind energy from the Red Sea due to more significant potential wind speed locations. The most suitable sites for wind energy applications are in Saudi Arabia, the only GCC country located on the Red Sea.



**Figure 8.** Average monthly wind speed ( $\text{m s}^{-1}$ ) over the Red Sea in the GCC region at a height of 50–120 m, based on historical data spanning 18 years. Copyright © 2021 Elsevier [99].

## 5. Solar and Wind Power Generation

Despite the substantial solar and wind energy resources available in the GCC region, the use of those resources is extremely low. Based on the data from a 2019 International Renewable Energy Agency (IRENA) report, the total electrical power generated from renewable energy (solar and wind energy) represents only 0.6% of total energy generation in the GCC [25,110]. Power consumption in the GCC has grown at an average annual rate of 8%, higher than any region globally [111]. To meet that demand, the GCC countries will need to add 100 gigawatts (GW) of installed power generation capacity in the future [111]. Elrahmani et al. [110] reported that the GCC region has a potential wind power generation of 5230 megawatts (MW), assuming power generation under conditions of low to average wind speed. Potential power generation from solar power is 15,550 MW, 96.7% of the total renewable energy generation in the GCC.

However, these estimates may be low because of the abundant wind and solar resources in the region. Recently, the GCC countries recognized the significance of renewable energy in their power generation systems. Critical factors contributing to the need for renewable alternatives include the need for economic diversity, continued urban expansion, the increasing growth in the rate of power consumption, the continued decline in solar and wind energy costs, and the need to reduce the region's carbon footprint. Recently, GCC countries announced plans for solar and wind energy development through 2030. The plans call for an installed solar generating capacity of 65,490 MW and 5230 MW of wind generating energy. The plan's objectives are summarized in Table 4 [25,112,113]. In addition, all the GCC countries have specifically focused on solar energy as a comprehensive solution for all the energy issues due to significantly high annual rates of solar radiation in the region [48]. Figures 9 and 10 show the current energy generation from solar and wind energy in the GCC region for 2010–2019. In addition, Figures 11 and 12 show the development of the installed capacity for solar and wind energy in the GCC region for the period of 2010–2019 [114]. Based on Figures 9–12, the region had 146 GW as its total power installed capacity in 2017, while solar and wind energy represented 1% of the total installed capacity at 867 MW, which is a very small percentage. In 2018, the UAE increased its share from solar and wind energy installed capacity to 68% of its total installed capacity, while Saudi Arabia accounted for 16% and Kuwait for 9%. While this growth is not substantial in terms of installed solar and wind energy capacity, it does reflect a nearly four-fold increase from 2014 and this is expected to increase at the end of 2021 due to the GCC future targets in Table 4.

**Table 4.** Projected installed capacity in 2030 from solar and wind energy in the GCC region [25,112,113].

Country	Solar (MW)			Wind (MW)	Total
	CSP	Utility PV	Building Integrated PV		
Saudi Arabia	9500	10,500	750	3500	24,250
Oman	770	2420	990	1210	5390
UAE	6000	18,900	4200	300	29,400
Kuwait	1000	5800	1000	200	8000
Qatar	600	2250	150	-	3000
Bahrain	70	520	70	20	680
GCC Total	17,940	40,390	7160	5230	70,720



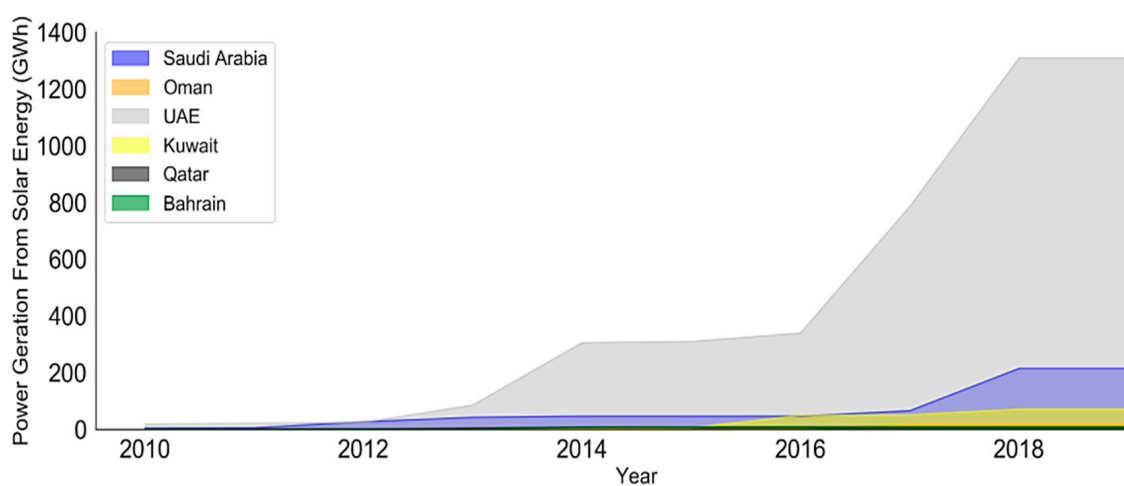


Figure 9. Energy generation from solar energy in GCC region, 2010–2019.

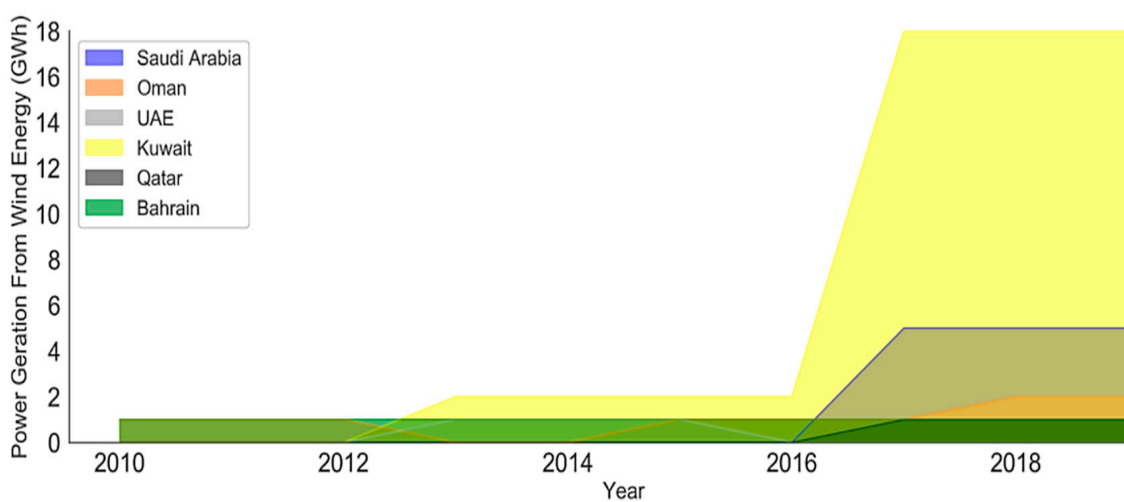


Figure 10. Energy generation from wind energy in GCC region, 2010–2019.

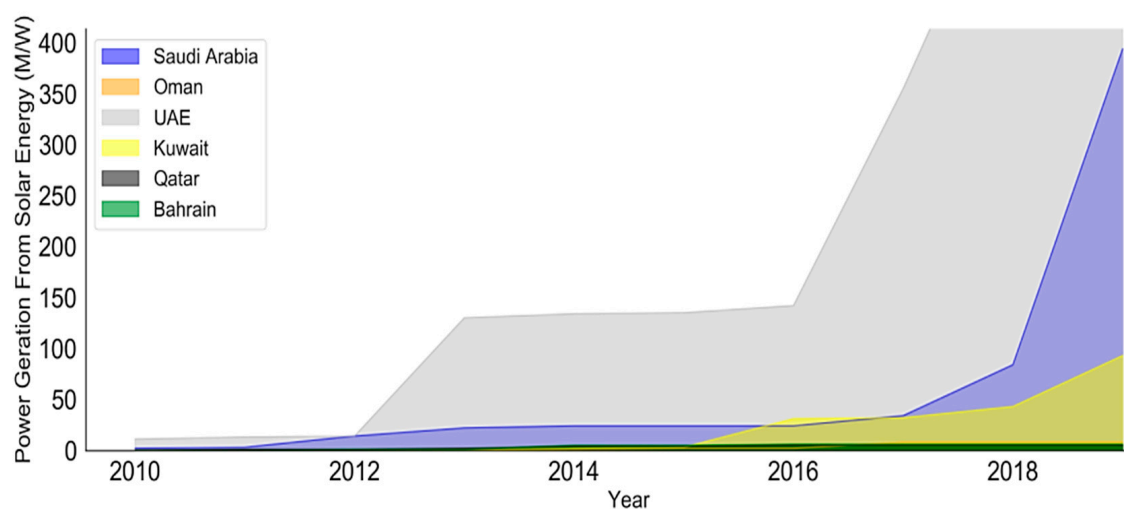
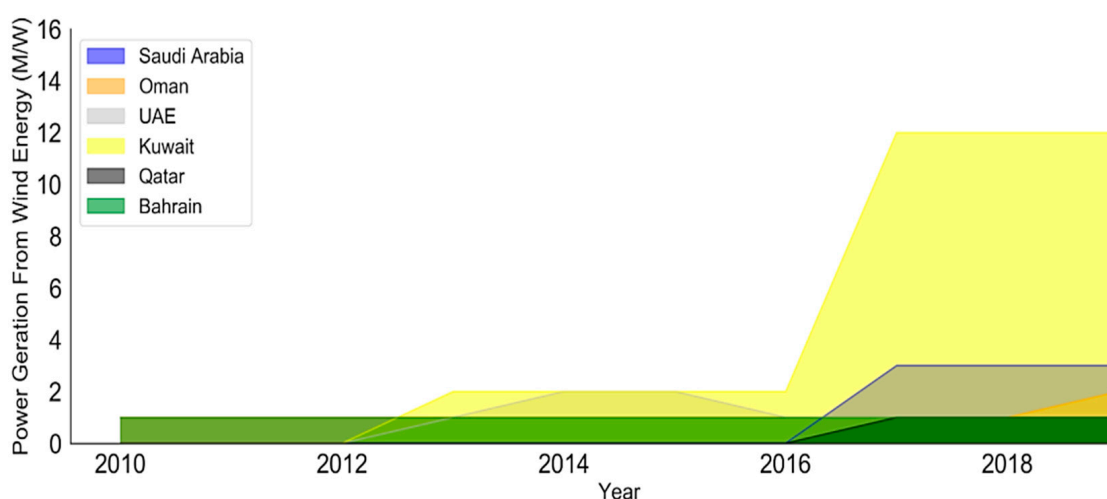


Figure 11. Power installed capacity from solar energy in GCC region, 2010–2019.



**Figure 12.** Power installed capacity from wind energy in GCC region, 2010–2019.

## 6. Climate Justice

The pursuit of climate justice forces us to ask serious questions about how we properly measure and address environmental inequality. Climate justice politics are rife with controversy about the existence and geographic scope of both the issue and its potential remedies. Adger [115] mentioned that the UNFCCC is the main body organizing international cooperation in response to the dangers of global climate change. Adaptation is used as a justification for international transfers in the convention framework to compensate for and brace for future or actual impacts. The argument that improving sustainability would improve adaptive capability and that planning activities are a vital part of overall adaptation can be used to justify this strategy [115]. Schlosberg [116] reported that environmental justice campaigns are not solely concerned with individual consumer approaches to climate change issues—they do not just imply the use of solar panels on rooftops. Schlosberg [116] believes that the emphasis must be on developing innovative sustainable strategies and structures—practices and institutions that reflect not only environmental justice values, but also a wider definition of sustainability. In addition, effort must be put into eliminating harmful activities, such as coal mining and burning, mining corporations' misdeeds, and controlling the growth of consumption. As the main producers and exporters of oil and gas, the GCC countries will be constantly criticized by the international community and the environmental lobbying groups. The region needs new environmental regulations, as well as increased governmental support, including accelerating the pace of renewable energy projects. In the GCC region, more sustainability legislation and cooperation with the international community are required to address climate change issues and to close the gaps in the current environmental laws.

## 7. Discussion

In this review paper, several previous studies were reviewed. The paper assesses the potential for solar and wind energy in the GCC region. Topics include dust fallout, solar, and wind energy performance, with data from 37 years in the GCC, and the potential for solar and wind energy as alternative solutions to reduce CO<sub>2</sub> emissions and the growth in fossil fuel consumption. The studies were divided into two groups: (1) those covering the entire GCC as a unified region, using high-quality tools and geographical maps, such as in [55,71,87], and (2) those covering specific cities or locations in the GCC region.

Both types of studies provide comprehensive details for the GCC region and highlight the issue of dust fallout over time. Moreover, the review's findings demonstrate that compliance with the Paris Agreement under the United Nations Framework Convention on Climate Change would be feasible in the GCC region, given its significant potential for

solar and wind energy. Based on this review, the area from the southeast to the northwest part of the GCC region is the most suitable for solar energy production, despite the potential for dust fallout.

Oman receives substantial annual solar radiation of up to 2500 kWh/m<sup>2</sup>, followed by the UAE, with 2285 kWh/m<sup>2</sup>. Saudi Arabia and Kuwait have the same levels, up to 2200 kWh/m<sup>2</sup>. Bahrain has a mean annual solar radiation of 2180 kWh/m<sup>2</sup>, and Qatar receives 2113 kWh/m<sup>2</sup>/year. In addition, encouraging solar energy radiation rates were recorded in western locations and the Red Sea's southwestern shores. These findings indicate significant solar energy resources that can support the energy needs of the entire region.

Dust fallout is a concern in the region during the summer months. However, it should be noted that the periodic waves of dust and clouds do not cover the entire GCC region at the same time due to relative differences in geographic features and terrain and the large distances between them. However, the northwestern GCC region is characterized by clearer skies. Substantial diurnal variability was recorded in southwestern and eastern locations throughout the year.

The highest annual dust amount was recorded as 454 tons km<sup>-2</sup> in northeast Riyadh. Kuwait received the second highest annual amount of dust in the region at 216–339 tons km<sup>-2</sup>, followed by the UAE, which received 256 tons km<sup>-2</sup>. The lowest amount of dust was recorded in Qatar at 50–113 tons km<sup>-2</sup> and Bahrain at 60–144 tons km<sup>-2</sup>. Table 3 shows the annual dust amounts for several locations, based on the data obtained from previous studies. We calculated the annual dust fallout at some locations in Table 3 using the following equation,  $A = w \times 31.85$ , based on the procedure in [76]. Here, A is the amount of dust fallout in tons/km<sup>2</sup> and w is the weight. The weight (w) values were obtained from [69]. The data for the UAE were obtained from [117] to calculate the dust values.

The impacts of dust increase the construction and maintenance costs of solar energy systems. However, a combination of bifacial panels, solar monitoring panels, and robotic cleaning technology will improve system performance and reduce the effects of dust.

Our review showed that the western mountains of the GCC region are characterized by abundant onshore winds. Oman has the highest recorded average wind speeds of 3–6.3 m s<sup>-1</sup>, followed by Kuwait with 4.5–5.5 m s<sup>-1</sup>. Northwestern Saudi Arabia has relatively abundant onshore winds with speeds of 3–6 m s<sup>-1</sup>. The UAE has the lowest average wind speeds at 3–4.8 m s<sup>-1</sup>. At this speed, wind energy development is not economically viable.

In contrast, offshore winds are substantial along the coastal areas of the Arabian Gulf, which is linked to all of the GCC countries. Persistent and abundant offshore winds were recorded at various locations on the Red Sea coast, with average wind speeds of 4.5–7 m s<sup>-1</sup>. Three primary areas for favorable offshore winds on the Red Sea are characterized by high performance compared to the other coastal locations in the region (see Figures 7 and 8). In particular, the findings of the long-term analysis of offshore wind speed over the Red Sea indicate a great opportunity for Saudi Arabia to harvest energy from the Red Sea due to the presence of more potential wind energy resources in this location.

To achieve the ambitious target of CO<sub>2</sub> reduction and climate change mitigation, it is essential to reduce fossil fuel use and phase out coal consumption. Although the GCC countries are among the largest carbon-producing countries, they do not rely on coal for all of their industrial activities and energy generation, as in the rest of the developed world. Coal produces significant CO<sub>2</sub> emissions compared to other types of fossil fuels. Based on Figures 9–12, GCC countries have not fully utilized their potential energy resources and they must pay more attention to wind and solar energy resources to increase their use of clean energy. One mitigation strategy is to levy a substantial local carbon tax on organizations and companies that produce high rates of CO<sub>2</sub> emissions and increase the current international carbon tax on all countries until the required decrease in CO<sub>2</sub> emissions is achieved.

Reducing energy consumption is essential, especially in countries such as the GCC, which are experiencing growing energy demand. The deployment of solar and wind energy and accelerated decarbonization technologies are critical solutions to climate change. Furthermore, decarbonization processes must be sufficiently developed to have an impact at a scale sufficient to reduce CO<sub>2</sub> emissions. Based on IRENA's 2019 report, and the findings of this review, implementing renewable energy in the GCC region power sector can reduce oil consumption by 23% (354 million barrels) by 2030. Low-carbon technology will lower CO<sub>2</sub> emissions by 22%, equivalent to 136 million tons (MtCO<sub>2</sub>) in the region. In addition, the water used for power generation and oil extraction can be reduced by 17%, equivalent to 11.5 trillion liters. This deployment has a positive impact on the GCC region and the world in terms of supporting climate change mitigation and global sustainability and creating a large number of jobs—around 220,500 in the energy sector, which supports local and global economies.

Adopting stricter regulations, including the reduction in energy subsidies, is one approach. Raising awareness and educating the public about the risks of climate change and its consequences would reduce CO<sub>2</sub> emissions. In addition, granting countries and organizations committed to reducing CO<sub>2</sub> emissions some advantages and powers of encouragement could play a significant role. The desired outcomes are contingent upon the carbon emissions goals set for developing countries, such as those in the GCC; they are distinct from those assigned to developed countries. The GCC is considered a promising region because of its tremendous wealth and significant potential for alternative energy development. That potential must be harnessed to serve its nations, contribute to climate change mitigation, and build a prosperous future. However, the overall impacts are hard to predict, as oil and natural gas extraction may have unexpected consequences.

Progress in the contribution of solar and wind energy in climate change mitigation is expected to be essential for the GCC region due to the government's plans regarding low-carbon technology deployment. Increased solar and wind energy share in the energy generation supply can decrease fossil fuel consumption in the region, tackle the issue of single-resource reliance, and have a positive effect on the environment and economic growth. This review provides background information and opportunities for researchers and policy makers to develop an effective strategy for solar and wind energy in order to support the deployment of low-carbon technologies and improve the traditional energy system in the GCC region. This paper is the second phase of our comprehensive work on the feasibility and evaluation of solar and wind energy resources in the GCC region; the first phase addressed the rapid growth of solar and wind energy infrastructure projects and their development in the region [113].

## 8. Conclusions

The challenges raised by the consumption of fossil fuels are generally similar in each GCC country due to the geographical location, weather conditions, and economic activities. Despite there being many options for mitigating climate change, environmentally and economically, solar and wind energy have the best chance of achieving the projected emission reductions targets at the required rate (see Figure 1). Moreover, the road map to the transition towards decarbonization (solar and wind energy) technologies in this contribution is divided into two categories, the status and nature of the geographical location and weather conditions, with a typical region-wise analysis. This review provides an extended exploration of potential solar and wind energy resources in the GCC region. The paper evaluated the cloud coverage and dust fallout in the area based on 37 years of historical data. The main findings of this review indicate that the annual solar radiation in Oman is up to 2500 kWh/m<sup>2</sup>, the highest solar radiation received in the region. Qatar has the lowest annual solar radiation in the region, 2113 kWh/m<sup>2</sup>/year. In addition, Oman has the highest average wind speeds, 3–6.3 m s<sup>−1</sup>. The UAE has the lowest average wind speeds 3–4.8 m s<sup>−1</sup>, making wind energy economically infeasible there. Saudi Arabia recorded the highest annual dust amount at 454 tons km<sup>−2</sup>, which would have major effects

on solar energy collection systems. The lowest annual dust amount was observed in Qatar at 50–113 tons km<sup>−2</sup>. In addition, the cloud coverage across the GCC countries is minimal over the year. However, the potential value of solar and wind energy resources in the GCC region is considered high compared to the global average. Finally, our analysis proved that there are no real obstacles that prevent the development of decarbonization technologies in the region due to the huge amount of solar and wind energy resources available.

**Author Contributions:** The main parts of this work were written by F.R.A. including the analysis, the evaluation of previous studies that are used in this review, and the first draft of the paper. D.C. supervised this work, improved the quality of the work, and revised the final version of the paper. Both authors have read and agreed to the published version of the manuscript.

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## Abbreviations

COVID-19	Coronavirus-2019
GCC	Gulf Cooperation Council
IPCC	International Panel on Climate Change
UNEP	United Nations Environment Program
UNFCCC	United Nations Framework Convention on Climate Change
IRENA	International Renewable Energy Agency
CAT	Climate Action Tracker
GDP	Gross Domestic Product
CO <sub>2</sub>	Carbon Dioxide
AOD	Aerosol Optical Depth
GHI	Global Horizontal Irradiance
DHI	Direct Horizontal Irradiance
DNI	Direct Normal Irradiance
CSP	Concentrating solar power
PV	Photovoltaic
Gt	Gigaton
Mt	Million Tons
GW	Gigawatts
MW	Megawatts
GHG	Greenhouse Gas
°C	Celsius
A	Amount of Dust Fallout
W	Weight of Dust Fallout

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