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Harnessing the energy transition from total dependence on fossil to renewable energy in the Arabian Gulf region, considering population, climate change impacts, ecological and carbon footprints, and United Nations' Sustainable Development Goals

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Abstract

The aim of this research is to investigate various issues related to oil consumption and environmental impacts in the Gulf Cooperation Council (GCC) countries, in relation to population, climate change impacts, United Nations Sustainable Development Goals (UN's SDGs), and ecological and carbon footprints. The GCC countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates) are almost entirely dependent on fossil energy sources (oil and natural gas) domestically, industrially, commercially, economically, and transportation-wise. Although the total population of the GCC countries is around 60 million, making up only 0.76% of the world's population (8 billion), they do consume 5.15 million barrels per day (bbl/d) of oil, forming nearly 5.8% of the world's daily consumption, which is around 88.4 million bbl/d as of 2021. Moreover, daily per capita consumption of oil in the GCC countries is about 0.09 barrels, while it is about 0.06 barrels in the USA. These figures indicate that the GCC's countries combined and per capita, although not industrialized and small in population, consume large quantities of oil, compared to other countries of the world that are industrialized and/or densely populated, such as the USA, India, Japan, Russia, and Germany. The high rates of oil consumption in the GCC countries, associated with the highest per capita ecological and carbon footprints worldwide, have led to negative impacts on the environment, climate, and public health. The results of this work show that some of the GCC countries have the highest per capita ecological and carbon footprints. Thus, the GCC countries should effectively reduce their dependence on fossil energy sources and gradually replace them with renewable energy sources, especially photovoltaic (PV) solar energy. Furthermore, the statistics presented in this article and the outcomes reached uncover that the GCC countries lag behind with regard to various indicators of the UN's SDGs. This implies the GCC countries are not taking adequate actions to encounter environmental problems, in order to fulfill some of the UN's SDGs by 2030.

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Highlights

- Investigates energy and environmental issues in the six Gulf Cooperation Council (GCC) countries in the Middle East region, West Asia, as being considered, globally, a very important, strategic, and volatile region. These countries are Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.
- Discloses that the Middle East region, including the GCC countries, produces more oil than any other world's region, accounting for just under a third of the global oil production in 2020; at 31.3%, constituting a slightly larger share of global production than it was 10 years ago.
- Investigates the oil consumption in the GCC countries, in comparison with other countries that are much greater in population and/or industrial advancements.
- Contributes to the areas of energy and the environment, with views affecting strategic environmental assessment of the efficiency of energy conversion systems to support energy and environmental policies.
- Contributes to views on, and deeper understanding of, climate change impacts, ecological and carbon footprints, pollution control, energy system efficiencies, and energy management, in terms of optimization, economic control, and pollution control.
- Focuses on the usage of fossil energy sources (oil and natural gas), with deep views on renewable energy sources and sustainable development, taking into account population and the United Nations' Sustainable Development Goals (UN's SDGs), as well as the ecological and carbon footprints.
- Indicates that the GCC's high rates of oil consumption have resulted in negative impacts on the environment and the climate, in terms of high ecological and carbon footprints, considering the fact that some of the GCC's countries have the highest per capita ecological and carbon footprints.
- Suggests, as part of a decarbonization strategy, that the GCC countries need to accelerate their efforts towards achieving the UN's SDGs and climate change performance.
- Concludes that the GCC countries should reduce their dependence on fossil energy sources and, thus, gradually shift to renewable energy sources, particularly photovoltaic solar energy.

Keywords GCC Countries, Population, Fossil energy production and consumption, Green energy, Ecological and carbon footprints, Decarbonization and energy strategies, Climate change impacts and the United Nations' Sustainable Development Goals (UN's SDGs)

Introduction

Background

The Gulf Cooperation Council (GCC) – an intergovernmental political and economic entity in the form of a federation in the Arab Gulf region (AG, also known as the Persian Gulf) – was established in 1981 and includes six Arab states: Bahrain, Kuwait, Oman, Qatar, Kingdom of Saudi Arabia (KSA), and the United Arab Emirates (UAE). The six countries (Fig. 1) have similar characteristics ethnically, socially, economically, historically, culturally, and religiously.

The high rates of oil consumption in the GCC countries have led negatively to significant impacts on the environment and climate, in terms of the Ecological/Environmental Footprint (EFP) which is higher than many other countries around the world, as some GCC countries have the highest per capita EFP (EFP/ca).

The continuous increase in population growth leads to the expansion of the built environment that requires more energy to generate power through the need for transportation, due to long commutes through the increase in the number of vehicles. Traditionally, hydrocarbon based technologies have been used to meet energy demand. However, the negative environmental impacts caused by such an approach have shifted the industry towards more sustainable technologies [2, 3].

The GCC countries continued to intensify efforts to reduce their dependence on fossil energy sources (oil and natural gas), and gradually switch to renewable energy sources and technologies (REST), especially solar photovoltaic (PV), taking into account the fact that the GCC countries are exposed to sunshine almost all year round. Focusing investment efforts on renewable energy projects, such as REST, will eliminate those countries' total reliance on fossil energy sources. REST accreditation will reinforce the GCC countries' commitment to air pollution mitigation's mechanisms and policies and, thus, commitment to climate action. This can be achieved through the use of solar panels which, in turn, protect ecosystems and reduce forests' degradation [4].

The progress of renewable energy and its contributions to achieving the United Nation's Sustainable

Fig. 1 A sketch map (with no scale) of the GCC's six Arab countries in the region of the Arabian Gulf (AG) [1]

Development Goals (UN's SDGs) must be assessed and monitored by each of the GCC countries. This will lead to economic and social developments in the region. Moreover, the modernization of energy services can be successfully facilitated by using REST. For example, renewable solar energy can help heat water and dry crops. More than that, the transportation sector and other service processes (such as cooling, heating, cooking, lighting, and water pumping) can be facilitated through the use of biofuels, biomass, and biogas modern technologies. REST developments can provide companies with efficient means to supply self-generated energy on site, allowing excess energy to be transported for sale and, thus, providing an additional source of income for companies. This helps reduce business dependence on a limited number of energy suppliers.

Such policies, which involve the implementation of various mechanisms, must be taken in light of the UN's SDGs, in order to successfully combat the effects of climate change and global warming, and reduce EFPs. Below are more details.

Study goals and methodological framework

The current study took a broad view of the energy situation in the Gulf Cooperation Council's countries: demographically, environmentally, economically, and socially. It highlights the consumption of fossil fuels in the GCC countries, in relation to population, societies, economies, climate change impacts, ecological and carbon footprints, and other issues as well. Thus, it offers critical analyzes to policy- and strategy-makers in the region and beyond, as well as to academics and undergraduate and postgraduate students in various disciplines of knowledge and study, such as energy, the environment, industry, policy-making, socioeconomics, conflicts and geopolitics, and other related fields as well.

To achieve the objectives of this study, a specific and systematic methodological framework was developed and implemented, while structured guidelines were followed. Accordingly, analyzes were made of the available data on the energy situation in the GCC countries. Approaches were also presented on how to develop some technologies and scenarios to solve energy problems in the GCC countries. Moreover, recommendations and proposals are presented to develop a better future and wellbeing for the people of the GCC countries, as well as for the region and the world at large.

It is recommended that policy- and decision-makers in the GCC countries take firm steps and serious actions towards efficient and governed utilization of energy, in terms of policy legislation and implementation of mechanisms to adapt green, clean energy sources that help build green economies. This paper is timely, as the United Nations Climate Change Conference (COP27) took place in Sharm El-Sheikh, Egypt, just a few months ago (6–18 November 2022) [5], and as COP26 took place in Glasgow, UK (31 October–13 November 2021) [6, 7], and as COP26 came out with the conclusion: *"The approved texts are a compromise. They reflect the interests, the conditions, the contradictions, and the state of political will in the world today"* [8]. Furthermore, the world is preparing itself for COP28 that will take place in the Gulf region

shortly; i.e. in Dubai, UAE, 30 November –12 December 2023.

Research methodology

Study design and setting

This paper examines various issues related to oil consumption and environmental impacts in the six GCC countries. The factors and indicators under consideration are population, the effects of climate change, the UN's SDGs, and ecological and carbon footprints.

The total population of the GCC countries is around 60 million [9], making up only 0.76% of the world's population (approximately 8 billion) [10], with daily consumption of 5.15 million barrels of oil; roughly 5.8% of the world's daily consumption, which is about 88.4 million barrels per day (bbl/d) as of 2021. Daily per capita consumption of oil in the GCC countries is about 0.09 bbl, while it is about 0.06 barrels in the USA [11].

The GCC countries are in the early stages of exploring new technological and energy innovations in order to promote sustainable regional consumption of oil and reduce its environmental impacts amongst the GCC countries. It can be argued that sustainable energy consumption, economic growth, and trade flows around the world are due to the tremendous results of innovative technological advances in the twentieth and twenty-first centuries. Thus, the primary interest in the body of literature has been to identify the main factors that influence the pace of technological improvements over time, and how they promote sustainable green economies [12]. Also, the challenge of transitioning to a low-carbon future is amongst the hot topics for discussions nowadays.

The GCC countries were chosen as sample countries, because these countries have similar social and economic conditions and national culture, which will benefit the countries of the bloc in cooperation towards sustainable digital and technological innovations. The GCC region is very open and widely internationally connected. These bloc countries have become the hub of the developing economies of the world [13]. The selection of the GCC countries for the purpose of the current study is not only due to a greater understanding of the region itself, but also due to its important implications for sustainable developments in the GCC countries themselves, as well as at the regional and international levels.

The GCC countries are formidably known for their oil wealth. However, with the uncertainties associated with global instability and related fluctuations in global oil prices due to the transition of energy from fossil energies to green energies, as well as the geopolitical instabilities worldwide, the countries of the Gulf Cooperation Council's bloc need to make a lot of efforts towards diversifying the mass of their oil wealth in different economic portfolios, including green energy sources and technologies. Table 1 presents the impact of the GCC countries on the global energy transition on economic growth between 2010 and 2020.

Instability in the GCC region's reliant on unsustainable fossil fuels has suffered dramatic declines and unstable national GDP growth (Table 1). For example, in 2020, all GCC's six countries recorded a negative GDP (Table 1). Table 1 shows that in 2020, Bahrain recoded its GDP at -5.08518, Kuwait at -8.68526, Oman at -3.20094, Saudi Arabia at -4.10658, Qatar at -3.5576, and the UAE at -6.1345, compared to, for example, 2010 as Bahrain had a GDP of 4.334299, Kuwait of -2.37026, Oman of 1.713985, Saudi Arabia of 5.039484, Qatar of 19.59233, and the UAE of 1.60285.

Table 1 Annual GCC's Gross Domestic Product (GDP) growth (in %) for the years 2010–2020 (Source: Authors' computation with data from the World Development Indicators' Database 2022 [14]

Year	Bahrain	Kuwait	Oman	Saudi Arabia	Qatar	United Arab Emirates
2010	4.334299	-2.37026	1.713985	5.039484	19.59233	1.602850048
2011	1.983515	9.628407	2.89461	9.996847	13.37518	6.928508599
2012	3.728108	6.625818	8.863122	5.411445	4.730012	4.483791985
2013	5.41684	1.1493	5.227704	2.699255	5.556041	5.053077855
2014	4.350391	0.500877	1.292252	3.652482	5.334323	4.41008526
2015	2.485379	0.59302	5.017058	4.106409	4.753346	5.060334864
2016	3.558128	2.925868	5.046424	1.670625	3.064192	2.984216091
2017	4.29095	-4.71211	0.304058	-0.7415	-1.4976	2.373551057
2018	2.136701	1.246129	1.287104	2.434111	1.234872	1.189855642
2019	2.141377	0.427464	-1.12921	0.331436	0.688241	3.411538686
2020	-5.08518	-8.68526	-3.20094	-4.10658	-3.5576	-6.134500803

Observations and data analyses

Hydrocarbons reserves in the GCC countries

Crude oil is one of the most valuable commodities in modern life and the modern world. Hence, it has been ranked as the most traded commodity in the world, becoming, for nearly a century, a necessity, based on the fact that hydrocarbons (oil and natural gas) are known as the "bloodstream of modern life," as being the engine of the world economies, industrialization, and development. Known as "black gold," because of the value it holds, crude oil is processed into gasoline, diesel, and a host of versatile petrochemicals that reach deep into the daily lives of people around the world.

Arab countries in the Middle East and North Africa (including the Gulf countries, Iraq, Yemen, Syria, Egypt, Algeria, Libya, Sudan and Tunisia, as well as other countries that have negligible amounts of reserved oil) currently absorb about 744 billion barrels (Bbbl) (Table 2). If Iran is added, as a non-Arab Middle Eastern country (with oil reserves of 157.8 Bbbl, constituting 9.1% of global reserves, and with a reserve-to-production ratio (R/P) of 139.8), the oil reserves of the Middle East and North Africa (MENA) region together are approximately 902 Bbbl, making up about 52% of the world's total proven oil reserves, which are 1,732.4 Bbbl (or approximately 1.73 trillion barrels) [15].

In terms of production, the Middle East produces more oil than any other region worldwide, accounting for just under a third of global oil production in 2020; that is by 31.3% [17]. Overall, oil production in the Middle East makes up a slightly larger share of global production than it did ten years ago, but the contribution to global oil production has risen steadily in North America, mainly due to oil production from oil shale [18], while it is declining in all other regions of the world.

By the end of 2018, the GCC countries had accumulated proven crude oil reserves of 497 billion barrels, representing approximately 34% of the world's proven crude oil reserves [19]. Table 2 shows that the GCC countries had by the end of 2020 more than 527 Bbbl, which is equivalent to 30.5% of global reserves. Due to its huge reserves of hydrocarbons (oil and natural gas), the Gulf region is very important as it plays remarkable geopolitical and economic roles on the regional and global scales.

The following is a brief presentation of the hydrocarbons (oil and natural gas) situation in each of the GCC countries.

KSA: It has the largest oil reserves in the Middle East. At 297.5 billion barrels, the Kingdom of Saudi Arabia makes up 17.2% of global reserves in 2020 (Table 2). This puts KSA in second place amongst the countries with the largest proven global oil reserves – right after Venezuela (Fig. 2).

Table 2 Proved oil reserves in the GCC countries and other Middle Eastern countries (separately and jointly), in addition to the share of the world's total and the ratio of reserve to production (R/P) [15, 16]

Country	Oil Reserves at End of 2020 (billion bbl)	Share of World's Total (%)	R/P (Ratio)
Bahrain[a]	0.125	0.0	5.5
Kuwait	101.5	5.9	103.2
Oman	5.4	0.3	15.4
Qatar	25.2	1.5	38.1
Saudi Arabia	297.5	17.2	73.6
UAE	97.8	5.6	73.1
Total in GCC Countries	**527.525**	**30.5**	
Iraq	145.0	8.4	96.3
Yemen	3.0	0.2	86.7
Syria	2.5	0.1	158.8
Egypt	3.1	0.2	14.0
Other Middle East Countries	0.2	0.0	2.6
Total in Middle East Region	**681.325**	**39.4**	
Algeria	12.2	0.7	25.0
Libya	48.4	2.8	339.2
Sudan	1.5	0.1	47.9
Tunisia	0.4	0.0	32.7
Total in other Arab countries	**62.5**	**3.6**	
Total in all Arab countries	**743.825**	**43**	

[a] The Bahrain data is for the year 2016 [16]

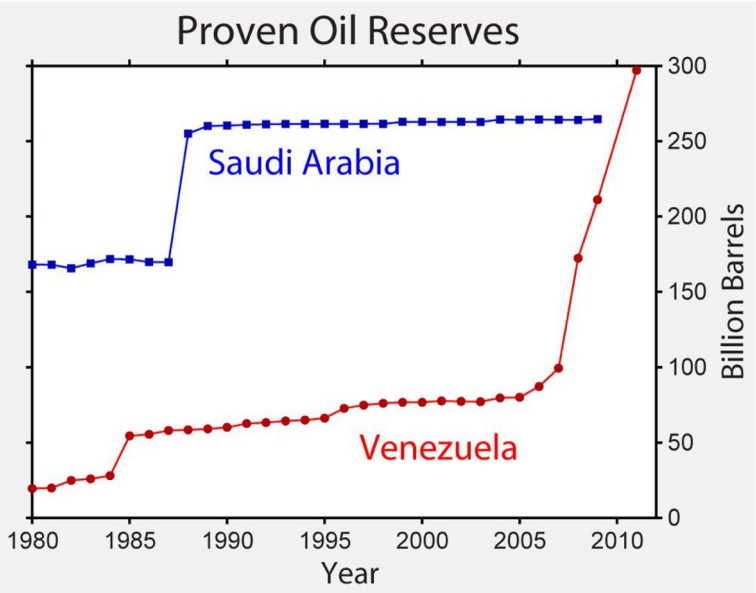

Fig. 2 Proven oil reserves (in billion barrels – Bbbl) in the Kingdom of Saudi Arabia (KSA) (in blue) and in Venezuela (in red) for the period of 1980–2016 [20]

Venezuela has approximately 303.8 billion barrels, constituting 17.5% of the global reserves of oil and will serve the country for the next 500 years [15]. Saudi Arabia is the largest exporter of oil, according to the Organization of the Petroleum Exporting Countries (OPEC) [21]. As of 2018, Saudi Arabia was the leading supplier of crude oil worldwide, with an export value of over USD 183 billion [22], producing 12.3 million barrels per day (bbl/d) since 2018 [23]. In 2021, ARAMCO's oil production averaged 12.3 million barrels per day [24]. The breakeven price of Saudi oil per barrel was less than half of its main global competitors; namely Russia and Venezuela. However, Saudi revenues from oil production decreased in 2021, reaching USD 161.7 billion [25]. In 2022, Saudi oil revenues reached USD 326 billion – the highest level since Crown Prince Mohammed bin Salman took office in June 2017 [26], as it produced 10.44 million bbl/d [27]. Though the Saudi oil production in 2022 was less than that in previous years, the revenues were much greater because of the high oil prices.

It is noteworthy to mention that the Russian-Ukrainian war has provided good opportunities for the oil industry in the Gulf region, and these are not as trivial as they might seem at first glance. In fact, in 2022 the demand for Saudi and Emirati oil increased dramatically as they could provide an alternative to Russian supplies in both Europe and Asia. Accordingly, higher oil prices greatly benefit the GCC countries, allowing them to refill coffers emptied by the COVID-19 pandemic, although extremely high prices always create the risk of market overheating and instability [28].

Some of the major oil fields in Saudi Arabia are: 1) The onshore Ghawar oil field – the largest in the country and the world, producing mostly from carbonate rock deposits since 1951; 2) The offshore Safaniya field producing since 1957; and 3) The Shaybah field (Shabah) onshore oil producing since 1998 [29, 30].

Kuwait: Despite being a small country, Kuwait is a major contributor to the world's oil reserves. It is the fourth largest oil reserve in the Middle East after Saudi Arabia, Iran, and Iraq. Kuwaiti oil reserves reached 101.5 billion barrels in 2020, representing 5.9% of global oil reserves (Table 2). Regarded as the second largest oil field in the world, the Ratqa field, located in northern Kuwait, was developed and started production in 2020. The state-owned Kuwait Oil Company (KOC) has launched several new projects as it seeks to expand its reach. Its oil production capacity will increase to 4 million barrels per day by 2040 – up from 2.43 million bbl/d in 2021 [31]. KOC plans to invest in the Burgan field to boost capacity through improved oil recovery methods, such as injection of seawater and carbon dioxide (CO_2) into wells [32]. The Burgan field, which has been in operation since 1938, is located in southern Kuwait and can produce up to 1.7 million bbl/d. The Wafra oil field, located within the onshore Partitioned Neutral Zone (PNZ) in southern Kuwait, covers an area of approximately 5,000 km^2, including discoveries south of Al-Fawaris, south of Umm-Gudair, Al-Humma and Arq [30, 31].

UAE: Under the leadership and supervision of the "Abu Dhabi National Oil Company" (ADNOC), the UAE is amongst the ten largest oil producers in the world, and the fifth largest country in terms of oil reserves at 97.8 billion barrels in 2018 [30], and continues at the same rate in 2020 [15] (Table 2). The UAE, as a member of OPEC and the Gas Exporting Countries Forum (GECF), operates several crude oil fields, including Murban, which is the country's main export. More than 90% of the UAE's reserves are held in the Emirate of Abu Dhabi, followed by the Emirates of Dubai and Sharjah. One of the main crude oil fields in the country is the Upper Zakum field, which is located about 84 km northwest of the Abu Dhabi Islands. This field, which currently produces 640,000 barrels per day, contains an estimated 50 billion barrels of oil reserves [30], constituting almost half of the oil reserves in the UAE (Table 2).

Oman: It ranks 21st in the world, and accounts for about 0.3% of the world's total proven oil reserves, holding approximately 5.4 billion barrels of proven oil reserves as of 2020 (Table 2). Oman has proven reserves equal to 79.4 times its annual consumption, making it 15.4 times more than production (Table 2). This means that without net exports, there would be about 79 years of oil left at current consumption levels, excluding unproven reserves [33, 34]. The Jabal field and Mukhaizna field are amongst the largest oil fields in the Sultanate of Oman, with the first operating since 1968 and the second being discovered by the Petroleum Development Oman (PDO) in 1975, and starting production in the mid-2000s [35]. Each of these Omani oil fields contains 1 billion barrels of recoverable oil – past and future [36].

Qatar: Despite its small area, Qatar has large reserves of oil (25.2 billion barrels) (Table 2), and natural gas estimated at 24.9 trillion cubic meters (TCM) or 865 trillion cubic feet (TCF). In 2017, Qatar produced 1.92 million barrels of oil per day, and 175.7 billion cubic meters (or 6.21 TCF) of natural gas [37]. Most of Qatar's condensate liquids and natural gas are produced from the offshore North Field. Most of Qatar's oil fields are offshore fields, with the only exception being the Dukhan field, which has been in operation since 1988, with 2.2 billion barrels of recoverable oil past and future [36]. In 2016, Qatar Petroleum (QP) announced that it had awarded a 30% stake in a new 25-year contract to the French Oil Company – TOTAL – to operate the 300,000 barrels per day in Al Shaheen oil field [37]. According to Qatar National Bank (QNB), available reserves allow Qatar to maintain its current production for another 138 years [37].

Bahrain: Although Bahrain is one of the smallest oil exporting countries in the Gulf region, it is the oldest oil producer in the GCC countries, with the establishment of the Bahrain Petroleum Company (BAPCO) in 1929, and with the start of production in the 1930s from the Awali oil field, with a billion barrels of past and future recoverable oil [36]. Bahrain's hydrocarbon wealth is relatively small, with a production of about 198,000 barrels per day, of which about 150,000 bbl/d comes from an offshore field that is shared with Saudi Arabia [23]. Onshore oil reserves in Bahrain are estimated at around 125 million barrels (Table 2), which, at the current production rate, would last less than seven years, making the new discovery very significant. A new discovery shows that deposits in Bahrain are estimated to be at least 80 billion barrels of tight oil and 10–20 trillion cubic feet of natural gas [23, 38, 39].

GCC countries' demography, land area, and oil production and consumption

As mentioned earlier, the total population of the GCC countries is about 60 million, living on a total area of about 2.6 million km^2, with a population density of approximately 24 persons/km^2 (pe/km^2) (Table 3), and a GDP of approximately USD 3.5 trillion [40].

Table 3 The six countries of the Gulf Cooperation Council, in terms of population, global population share, land area, population density, daily oil production, and daily oil consumption [9, 41–43]

Country	Population (≈ in million, as of 21 June 2022)	Global Population Share out of World's Population (8 billion) (%)	Land Area (km^2)	Population Density (pe/km^2)	Oil Production in 2019 (≈ million bbl/d)	Oil Production in 2017 (bb1/d/million people)	Oil Consumption (bbl/d)
Bahrain	1.78	0.022	765	2,332	0.064	36,000	58,000
Kuwait	4.38	0.055	17,818	246	2.99	721,575	500,000
Oman	5.33	0.067	309,500	17	1.02	217,178	176,000
Qatar	2.98	0.037	11,586	257	1.99	500,000	280,000
Saudi Arabia	35.85	0.451	2,149,690	17	12.4	324,866	3,237,000
UAE	10.08	0.126	83,600	121	3.77	335,103	901,000
Total	≈ **60.4**	≈ **0.76**	**2,572,959**	≈ **23.5**	≈ **22.23**	**2,134,722**	**5,152,000**

According to the United Nations Population's Prospects, the population of the GCC countries is expected to peak at 68 million in 2048 and then decline thereafter [44]. Therefore, the population of the GCC countries is expected to shrink by 12.6% (i.e. to 52.5 million) by the end of this century. By 2100, Saudi Arabia and the UAE will experience the largest population's contraction amongst the GCC countries, with declines of 19.2% and 9%, respectively. Bahrain and Oman will also see population's declines of 7.7% and 0.3%, respectively. Meanwhile, Qatar and Kuwait will see their population increase by 9.6% and 1%, respectively [44]. The main reason for the potential shrinking of the overall population in the GCC countries over the following decades can be attributed to the low fertility rates and the declining expatriate population.

All GCC countries are totally dependent on fossil energy sources, domestically, industrially, economically, commercially, and transportation-wise. Total oil production in the GCC countries, in 2019, was about 22.2 million barrels per day, resulting in approximately 2.13 million barrels per day per a million people of the total GCC's population (Table 3). Oil consumption by the GCC countries combined, with a total population of about 60 million (Table 3), is around 5.15 million barrels per day (Table 3), and it constitutes about 5.8% of the daily global production of oil, which was in 2021 about 88.4 million barrels per day [15]. Compared to other countries of the world (in terms of the population in 2020 and daily oil consumption for 2021), India, for example, with a total population of 1.38 billion, consumed about 4.67 million bbl/d; Japan, with a population of 126.5 million, consumed 3.27 million bbl/d; Russia, with a population of about 146 million, consumed 3.24 million bbl/d; and Germany, with a population of about 84 million, consumed 2.05 million bbl/d [9, 15].

Considering the 2020 population [9] and daily oil consumption [15], the figures above indicate that the GCC countries, which make up only 0.76% (less than 1%) of the world's population (Table 3), consume ≈5.8% of the world's total daily oil consumption.

Oil consumption in the GCC countries is ≈0.09 barrels per capita per day (bbl/ca/d), while in the United States (as the first industrialized country in the world) it is 0.06 bbl/ca/d, and in China (the world's second industrialized country) ≈0.01 bbl/ca/d. This means that oil consumption, per capita per day, in the United States and China does not exceed 66.7% and 11.1%, respectively, of the amount of oil consumed in the GCC countries. These figures reflect the high rates of oil consumption in the GCC countries as a whole and the per capita share by each country, despite its small population, being non-industrial and not industrially productive, compared to other large, industrial, and productive countries, worldwide.

Renewable energy sources and technologies (REST) in the GCC countries

Based on the fact that many global governments view Renewable Energy Sources and Technologies – REST – as a way to address the growing and multidimensional threats of climate change, the countries of the traditional or conventional (fossil) energy in the Gulf region are embracing REST faster than before, although their efforts are still rather slow and modest. However, by leading efforts in the UAE and Saudi Arabia, the GCC states have shown some progress towards supporting global efforts regarding the energy transition [45]. Although there have been some developments in the renewable energy sector in the GCC countries in the form of current and future projects, there are no efforts that support strategic policy development plans [46–48].

IRENA's Director-General, Francesco La Camera, said at the International Energy Forum in Riyadh, KSA, *"It is perfectly possible to generate sufficient cheap, reliable energy from renewable sources. Not only is it possible, but it is also our best option, as it would bring higher socio-economic benefits than business as usual, and it would allow us to effectively address climate change"* [45]. However, it is believed that a gradual shift from total reliance on fossil energy to REST will be effectively beneficial to the GCC countries, because:

1) REST is the most practical and available climate solution: Rapid deployment of REST in the GCC region could reduce CO_2 emissions by 136 million tons [45] to keep the world well below 2°C of warming thermal.
2) REST is the most competitive form of power generation: Today, renewable energy is the most cost-competitive source of new energy generation in the GCC, replacing conventional energy sources as an answer to increasing domestic energy demand in the region [45]. The UAE, in particular, has taken effective steps, implementing a solar energy project to operate in 2022, as the largest of its kind, worldwide [49]. The project is part of the Dubai Clean Energy Strategy 2050, which aims to provide 75% of the energy needs in the UAE using clean renewable energy by 2050, by utilizing photovoltaic panels [49–51]. The project has already produced power in the range of 13 to 950 megawatt (MW) during its first to fourth phases in the period of 2013–2020, and is scheduled to generate 900 MW in 2021 [51]. Recently, the project's 900-MW Phase 5 received one of the lowest bids for a solar PV project in the world at a rate of 1.7 US Cent

per kilowatt-hour (kWh) [45]. This project will: i) eliminate more than 2.4 million metric tons of CO_2 emissions annually, which is equivalent to removing 470,000 cars from the roads; ii) provide electricity to about 160,000 households across the UAE; iii) offer one of the most cost-competitive solar tariffs of 4.97 UAE's Fils (or 0.14 US Cents) per kWh (where Arab Emirates Dirham (AED) = 100 Fils, and AED = 0.27 USD); and vi) increase Abu Dhabi's solar energy capacity to approximately 3.2 GW [49].

3) REST creates jobs: The long-term policy objectives seen in the GCC countries, including private business, education and training, investment in local skills, capacity building, and human resources, as well as green economy for sustainable development [52] can facilitate an increase in the number of jobs in the REST sector. By 2030, REST could create more than 207,000 jobs in the Gulf region, with solar energy technologies accounting for 184,230 jobs [45].
4) The GCC region has great potential for REST – not just solar: An analysis of the suitability of solar PV technology in the GCC region reveals strong potential for deployment across all GCC countries, with Oman, Saudi Arabia, and the UAE being considered as leaders. For example, Oman is a country with the best solar energy resources in the world, with an average annual solar radiation of 2,200–2,500 kilowatt/meter square (kW/m^2) [53, 54]. Moreover, some regions in Kuwait, Oman, and Saudi Arabia are potentially good for wind resources [55]. Other REST, such as biomass [48, 56] and geothermal energy [57, 58], may have additional but still unexplored potential to be implemented in the GCC countries. Based on the targets set in 2018, which, if met, could lead to the production of around 72 GW of renewable energy capacity in the GCC countries by 2030 [45].
5) REST saves water: The increasing demand for water, due to population growth and development, has pushed countries into more severe water stress [40, 59, 60]. According to the World Resources Institute (WRI), 12 of the 17 water-challenged countries on the Earth, which experience the world's greatest water stress, are located in the Middle East and North Africa (MENA) region, including all six countries of the Gulf Cooperation Council [40, 61]. If the GCC countries were to achieve their renewable energy targets, this would result in an overall reduction of 17% in water consumption and 12% in energy consumption. The WEF Nexus' approach is considered one of the most practical and viable approaches to save water (W), reduce energy (E) consumption, and secure availability of food (F) in the GCC countries [40]. For the Gulf region as well as for other parts of the world, the WEF Nexus' approach has been extensively and comprehensively investigated, strongly endorsed, and deeply discussed [40].

Climate change impacts

According to the Intergovernmental Panel on Climate Change [62], global average temperature and sea level are expected to rise 1.3–5.8°C and 18–58 cm, respectively, during the year 2100 [63–65]. As a result, the expected climate change will have many negative impacts on the Eastern Mediterranean region, which will affect the countries of the Gulf Cooperation Council. These impacts include increasing water scarcity; increasing salinity of soils and surface water and groundwater; increasing frequency of extreme weather events (such as heat waves, wildfires, hurricanes, floods, droughts, storm intensity, rapid spread of diseases, health impacts, etc.); food insecurity; degradation and loss of biodiversity; desertification; elimination of forests; and induced migration [40, 63, 66–80]. The impacts of climate change will greatly affect the water resources in the GCC countries, which mostly depend on seawater desalination [40]. The daily capacity of desalination plants in the Gulf region exceeds 11 million cubic meters per day (MCM/d), which is half of the daily global production of fresh water, using desalination technologies [81]. There is a real "boom" in the desalination industries working in the GCC countries. The Gulf countries' majority now depends largely on desalinated water for the consumption of their populations: in the UAE, 42% of drinking water comes from desalination plants, in Saudi Arabia 70%, in Oman 86%, and in Kuwait 90% [82, 83]. This mechanism can also be successfully used for hydrogen energy [84], whereas desalinated water and hydrogen can be produced from seawater using solar energy. As renewables are intermittent, energy storage plays a pivotal role in the energy transition. Hydrogen technology is known to be the most promising and leading choice in the green energy transition, future-wise [85].

Results and discussions

Greenhouse gas (GHG) emissions and various energy sources (fossil and renewables)

The concentration of CO_2 has increased in particular as a result of the industrial revolution and the exponential growth in industrial activities around the world. Deforestation, agriculture, and the use of fossil fuels in transportation and other services are the main sources of carbon dioxide emissions. According to the most recent data from the Global Carbon Atlas, the top five countries that have collectively produced the most CO_2 since the industrial revolution are the USA, China, Russia, Germany, and the United Kingdom (UK). In 2020, the largest

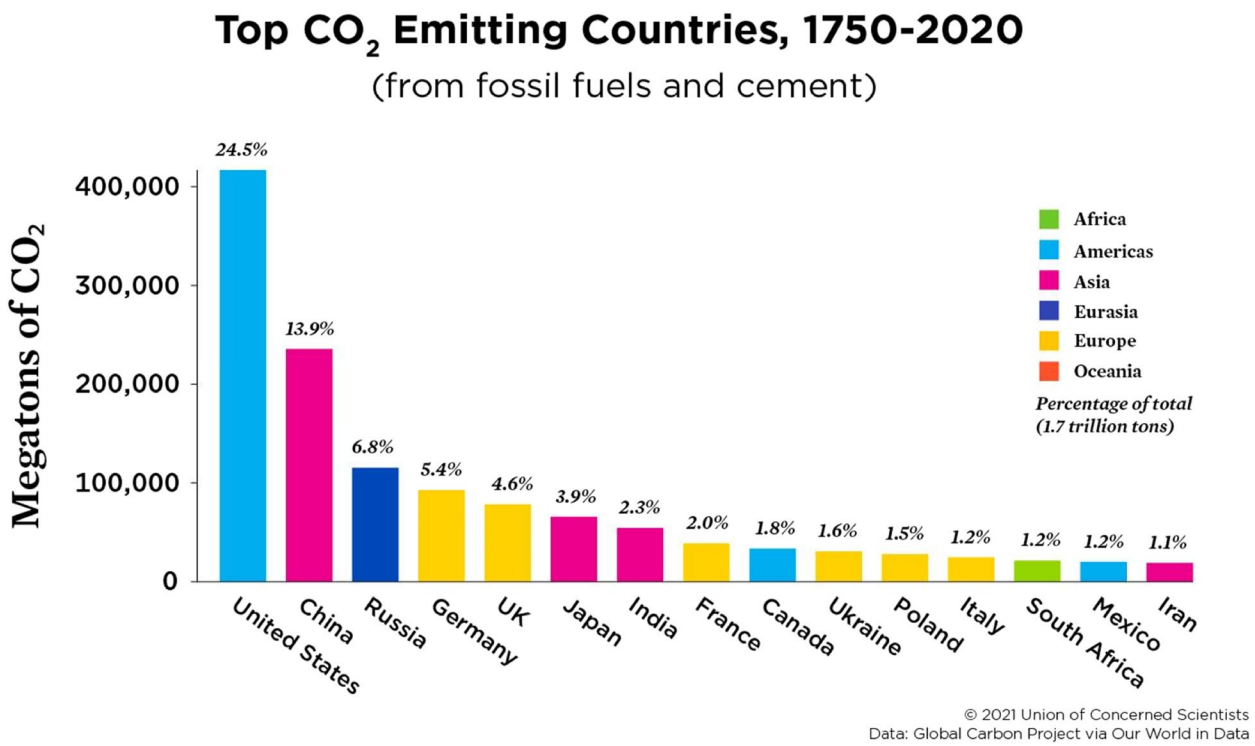

Fig. 3 Top CO2 emitting countries from year 1750 to year 2020 [86]

emitters of CO_2 were China, the USA, India, Russia, and Japan [86–88] (Fig. 3).

Despite the fact of being one of the world's largest producers and exporters of fossil fuels, the GCC's total greenhouse gas (GHG) emissions are very low (only 2.4%), compared to other regions and countries around the world. However, the GCC countries are amongst the countries with the highest per capita emissions of GHG (particularly CO_2) [66, 86, 89–91] (Fig. 4).

Accordingly, being one of the largest producers and exporters of oil and natural gas, as well as having the highest rates of per capita GHG emissions, there is no doubt that the GCC countries must share the responsibility with the rest of the world to combat the climate change impacts mentioned above. Therefore, the GCC countries must take the lead in diversifying energy sources, by reducing their dependence on fossil fuels and, thus, introducing more environmentally friendly energy sources in their use, such as REST. This, over time, will gradually replace polluting fossil energy sources with REST, as clean, green, and environmentally friendly energy sources.

Table 4 shows that the world's reliance on coal for electricity generation will drop dramatically by approximately 75% over the next 20–25 years or so (2017–2040). Meanwhile, the use of natural gas to generate electricity will remain the same (Table 4); not to mention the effects of the ongoing Russian-Ukrainian war on the energy crisis in Europe in particular [92–98].

The outlook for nuclear power have diminished since last 2017 projections, but China continues to lead the gradual rise in production [100], overtaking the United States by 2030 to become the largest producer of nuclear-based electricity by 2040 (Table 4). China is on track to lead the world in deploying nuclear power technology by 2030. China, if successful, will take global leadership in nuclear technology development, industrial capacity, and nuclear power production and management. The impacts of nuclear energy will be strategic and wide-ranging, affecting nuclear safety, nuclear security, non-proliferation, energy production, international trade, and climate change mitigation and adaptation measures.

Related to this, the ongoing Russian-Ukrainian war may prompt some European countries to rethink the use of nuclear energy to generate electricity, despite its potential risks [101–103]. *"The war is prompting countries like Belgium to delay nuclear phase-outs to be less dependent on Russia, but for countries like Germany, Russia's missile attacks on nuclear plants reaffirm concerns about safety"* [102]. However, Germany, being a leading country in Europe, in terms of population and industrial capacity and development, has closed its last three nuclear power plants in April 2023, marking the end of the country's nuclear era that has spanned more

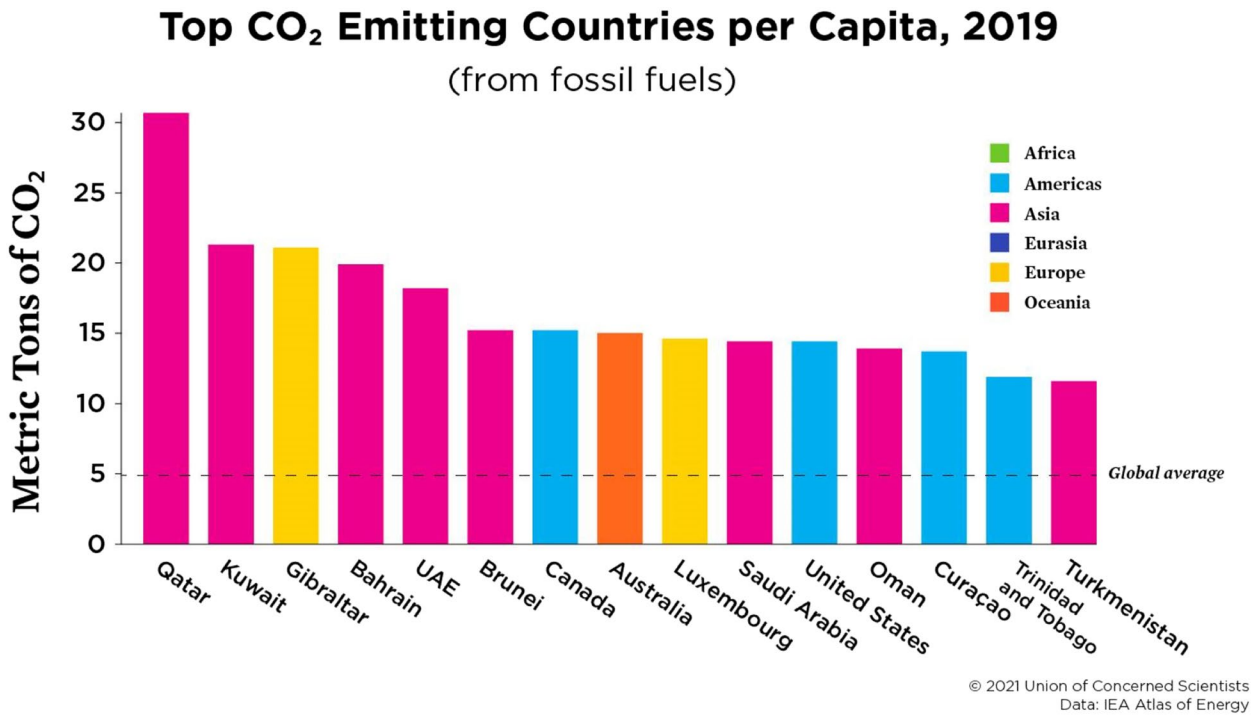

Fig. 4 Top CO2 emitting countries per capita, 2019 [86]

Table 4 Global average annual power (electricity) generated from various kinds of fossil and renewable energy sources for the periods of 2010–2016 and that projected for the period 2017–2040 [99]

2010–2016		2017–2040	
Energy Source	**Power Generated (GW)**	**Energy Sources**	**Power Generated (GW)**
Coal	65	**Coal**	17
Natural Gas	48	**Natural Gas**	48
Nuclear	2	**Nuclear**	4
Solar PV	39	**Solar PV**	74
Wind	45	**Wind**	50
Other Renewables	44	**Other Renewables**	36

than six decades [104]. This is due to the fact that there are those who want to end reliance on nuclear technology because they see it as unsustainable, dangerous, and distractive from accelerating REST in Germany. Regardless of the repercussions of the Russian-Ukrainian war and even before it began in February 2022, the world was expected to double its dependence on nuclear energy until 2040 (Table 4). For instance, in the process of building a nuclear power plant, the UK said in its latest climate strategy that nuclear power has a *"crucial role in creating secure, affordable, and clean energy"* [104].

Also, the power generated from REST (solar photovoltaic) will increase dramatically by almost 200% (Table 4). PV capacity globally will jump from 39 to 74 GW, and wind capacity will jump from 40 to 45 GW (Table 4). Overall, REST will receive two-thirds of global investment in power plants by 2040 as they are already becoming, for many countries around the world, low-cost and environmentally friendly sources of energy [99].

According to the International Energy Outlook [105], greenhouse gas emissions in the Middle East (including the GCC countries) will grow by 2.3% annually, reaching 201 billion tons in 2030. This relatively low growth in GHG emissions can most likely be attributed to the increase in natural gas consumption at the expense of oil consumption for electricity generation and seawater desalination. However, the annual increase of GHG emissions in the Middle East (2.3%) is not much compared to GHG emissions in China, which will rise from 3.5 trillion tons to more than 7 trillion tons over the period of 2007–2030. This means that China's GHG emissions will double in just 23 years. Accordingly, China needs to take serious steps and firm actions by developing long-term strategies and plans to reduce greenhouse gas emissions. *"A holistic assessment of such dimensions of low-carbon technologies,*

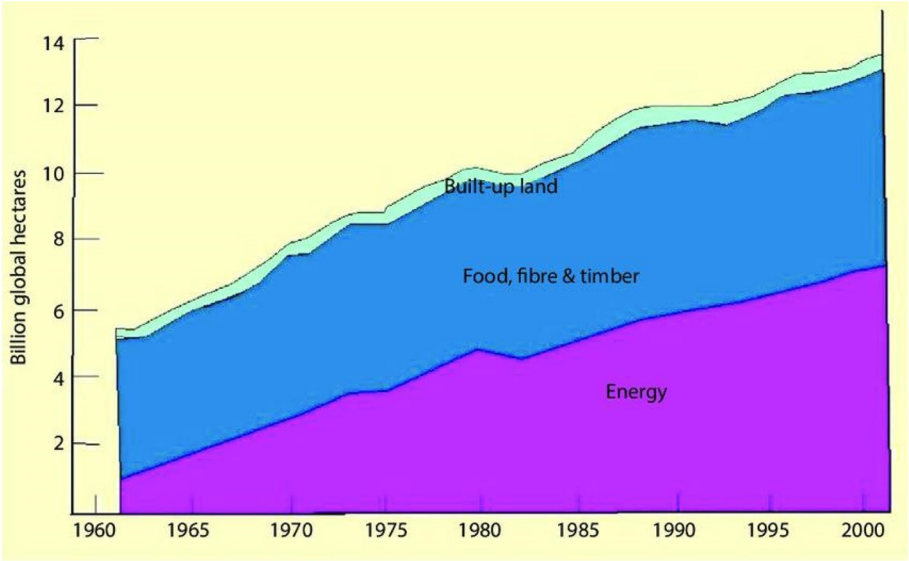

Fig. 5 Humanity's (global) ecological footprint (EFP) in billion global hectares (bgha) over a period of 40 years (1961–2001) [110, 111]

as employment, environment, ecology, health impacts and public acceptance, would improve the assessment on technology potential, cost effectiveness and spatial layout, which would also help to promote the synergies between carbon emission reduction and sustainable development" [106]. Globally, the 2030 target to reduce greenhouse gas emissions is expected to rise from 40% (the initial target) to around 50–55% as part of the Green Deal [107]. However, there is still uncertainty about how the deal will play out and who will foot the bill.

The role of natural gas in the transition stage and beyond has yet to be clarified, as natural gas will have to be decarbonized, and biohydrogen gas will have to be assimilated. Regarding the GCC countries, it is believed that they must adapt some models based on long-term strategies to achieve a low-carbon future, by relying on less fossil energy sources that must be replaced by REST, gradually and efficiently. This can be achieved through interventions in the built environment, deployment of REST, technology investments, gradual integration into global knowledge-intensive industries, and reduction of large ecological and carbon footprints [108]. This is in addition to artificial intelligence's (AI) utilization in REST. For generation of renewable energies to play a larger role in the global energy mix, AI may be a key to achieving higher efficiencies [109].

Ecological and carbon footprints (EFP and CFP) in the GCC countries

The total ecological footprint (EFP) of the activities of a selected population is measured in terms of global hectares (gha). A global hectare is one hectare (ha) of biologically productive area with an annual productivity equal to the global average (1 ha = 0.01 km^2 = 10,000 m^2). The ecological footprint is a measure of human demand on the Earth's ecosystems and a measure of a unit's impact on its habitat based on consumption and pollution.

The biosphere currently contains approximately 11.2 billion global hectares (bgha) of biologically productive space, which is approximately a quarter of the Planet's surface area (Fig. 5). The biologically produced area of 11.2 bgha includes 2.3 bgha from the oceans and inland waters, and 8.8 bgha from the land. The land portion (8.8 bgha) consists of 1.5 bgha of crop-land, 3.5 bgha of pasture (grazing-land), 3.6 bgha of forest-land, and 0.2 bgha of built-up land [110, 111].

Currently, most Arab countries face environmental debts [59, 112]. In global terms as defined by the Organization for Economic Cooperation and Development (OECD), environmental debt refers to the build-up of past environmental impacts of natural resources' depletion and environmental degradation, owed to future generations and measured by costs required to restore the environmental damage that is economically and technically restorable [113, 114]. In more elaborating terms, environmental debt refers to the debt accrued by richer countries due to their plundering of poorer countries through exploitation of their resources, degradation of their natural habitats, free control and/or occupation of ecological spaces of local populations, in order to be used for waste disposal, resulting in heavy burden on the environment and public health [115, 116]. Within the definition of environmental debt, two aspects are understood:

1) Environmental damage caused over time to ecosystems by one country in another, occurring beyond national jurisdiction and through production and consumption patterns, in violation of international standards, laws, regulations, and treaties; and 2) Additional exploitation or further use of ecosystems by a country at the expense of equitable rights to other countries' ecosystems, which usually occurs in violation of international law and treaties.

Compared to the situation some 62 years ago (in 1961), the average EFP in the Arab region has increased by more than 57%. This ranges from 1.2 to 2.1 global hectares per capita (gha/ca) [112]. To understand this sharp jump in EFP in the Arab region in general and in the GCC countries in particular, it can be said that there are two main catalysts behind this dramatic jump, which are: 1) The 3.5-fold population growth, which has led to a significant escalation in aggregate consumption; and 2) As a result of rapid development, rising incomes, and changing lifestyles, the Gulf States witnessed sharp increases in the resources consumed and the services used, including energy, water, food, fiber, wood, transportation, space cooling, seawater desalination, etc. This has been at the expense of the environment (in terms of EFPs) and public health.

Due to the hot and dry climatic conditions prevailing in the Gulf region, as well as the high rates of water consumption, large amounts of energy are consumed for space cooling and seawater desalination [40]. These factors, when combined with inefficient consumption and lack of rational management of natural resources, have led to a rise in EFPs per capita. As shown in Fig. 6, Qatar has the highest per capita ecological footprint (EFP/ca) in the world, measuring 11.68 gha/ca, followed by Kuwait (9.72 gha/ca) and the UAE (8.44 gha/ca). These EFP rates are higher than many developed and developing countries [112, 117–120].

Figure 6 shows that the value of EFPs of Qatar, Kuwait, and the UAE combined (29.84 gha/ca) is more than that of all of the top ten African countries combined (24.25 gha/ca). Meanwhile, the total population of the three Arab Gulf countries (Qatar, Kuwait, and UAE) is 17.44 million (Table 3; above), and the total population of the ten African countries is about 224 million [121], including two Arab countries in North Africa, namely Egypt (population ≈103 million) and Tunisia (population ≈12 million) [121]. These results indicate, statistically, that the total per capita of EFP in the three Gulf countries combined is 1.23 times more (i.e. 29.84/24.25 = 123%) than that of the ten largest African countries combined, while the population of the three Gulf countries combined is less than 8% (i.e. 17.44 million/224 million) of that of the ten African countries combined.

To make a comparison, these results also indicate that the average citizen in Qatar (as an Arab country in the Gulf region) has the highest EFP in the world (11.68 gha/ca) – 9 times more than that of the average citizen in Morocco (1.32 gha/ca) [112, 122], which is an Arab country in North Africa. This is despite the fact that the Moroccan EFP has increased, during the period 1990–2010, from 1 to 1.47 gha/ca [123]. On the other hand, biocapacity, which represents productive surface area per capita, has decreased by 25% since 1960 to 2020, as it has declined from 1.14 to 0.86 gha/ca [123]. However, these Morocco's EFP and biocapacity levels are lower than the global average levels, as they are globally 2.84 gha/ca and 1.68 gha/ca for ecological footprint and biocapacity, respectively. The biocapacity (or biological capacity) of an ecosystem is an estimate of its production of certain biological substances, such as natural resources, and its absorption and leaching of others, such as carbon dioxide and other greenhouse gas emissions from the atmosphere [124, 125].

In addition, the EFPs of three citizens in Qatar, Kuwait, and the United Arab Emirates (29.84 gha/ca) exceed the EFP of the Moroccan citizen (1.32 gha/ca) by about 23 times (i.e. 29.84/1.32). To put this into perspective, if all human-beings were to live as citizens living anywhere in the Arab region, 1.2 Planet Earths would be required. On the other hand, if all of human-beings living on the Planet Earth were to live as Qataris, for example, it would need 6.6 Planet Earths to satisfy their standards of living, including food, water, and energy consumption, as well as other needs. Thus, more carbon dioxide emissions will be emitted into the atmosphere. Conversely, if everyone were to live as Moroccans with an EFP of 1.32 gha/ca, the world's population would only need three-quarters (75%) of the Planet Earth [112].

Literally, measures of the GCC countries are much larger than that of the global averages, if the ecological footprint – EFP – and carbon footprint – CFP – of the GCC countries are compared with the other part of the planet (Fig. 7). A carbon footprint is defined as the total greenhouse gas emissions generated by an individual, event, organization, service, place or product, expressed in carbon dioxide equivalent (CO_2e) [126].

The world population has changed and will continue to change significantly over the period 1970–2050 (over an 80-year period). This is from 3.7 billion in 1970 to 9.6 billion (Fig. 8), or 9.8 billion in 2050, and to 11.2 billion in 2100, according to the United Nations [128].

On the other hand, carbon dioxide emissions were 14.9 Giga-tons (Gt) in 1970 and are expected to reach 80

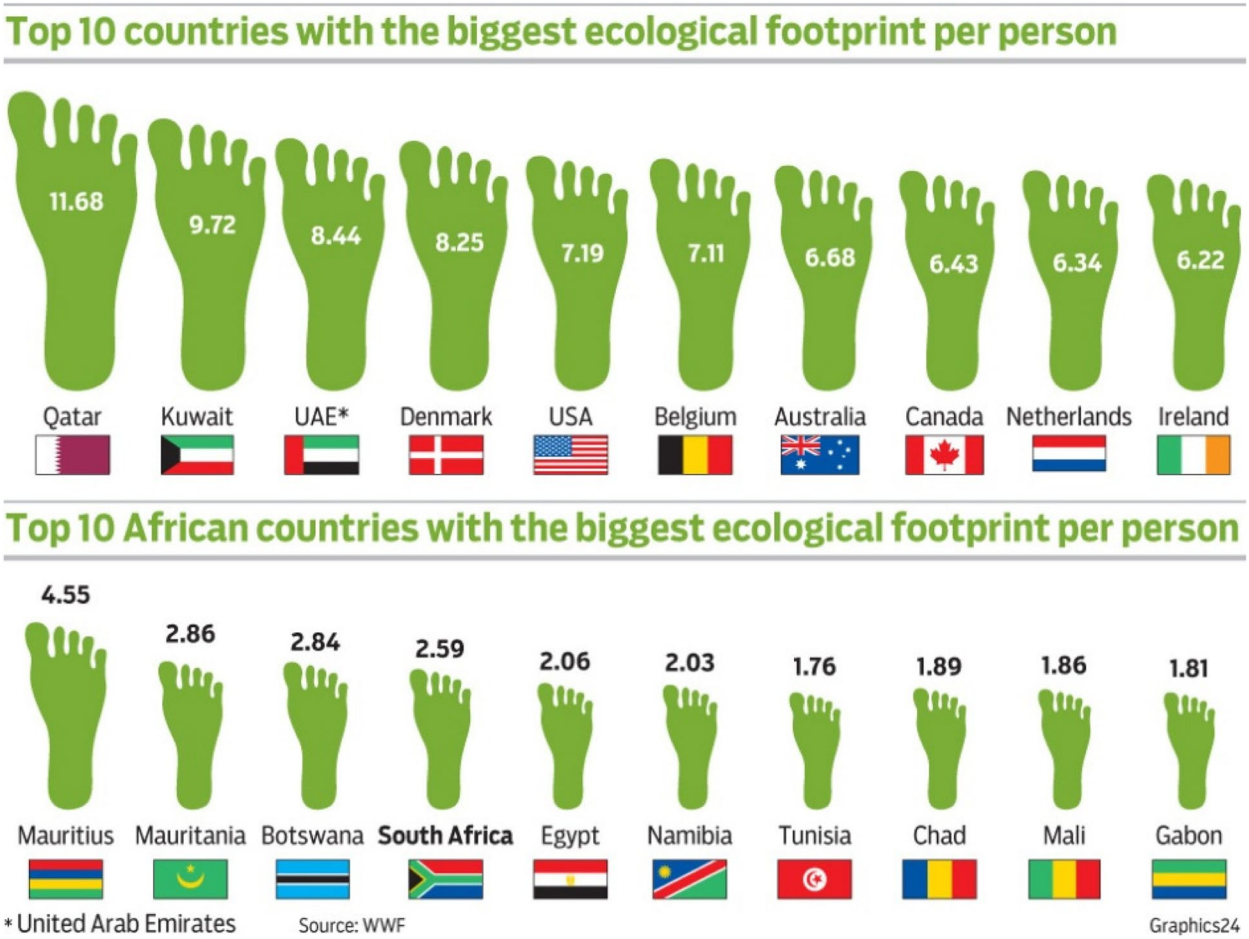

Fig. 6 Countries with biggest ecological footprint (EFP): Upper Raw: The world's Top 10 countries with the biggest EFP; Lower Raw: The African top 10 countries with the biggest EFP [120]

Gt in 2050 (Fig. 8). This means that over a time period of 80 years, the world population will increase 2.6-fold, while CO_2 emissions will increase 5.4-fold. In more detail, during the period of 1970–2010 (40 years), the global population consumed the natural resources of one Planet Earth (Fig. 8), and during the period of 2010–2013 (4 years) the global population consumed the natural resources of 1.5 Planet Earths (Fig. 8). Meanwhile, during the period of 2010–2050 (40 years) the natural resources of three Planet Earths are expected to be consumed by the global population (Fig. 8). All of this has happened in the past 50 years (1970–2020) and will continue to happen in the next 30 years (2020–2050), but at faster rates of population's growth and natural resources' consumption, leading to the rise of per capita EFP and CFP levels, as demonstrated in Figs. 6, 7, and 8.

Higher levels of EFP and ECP for each individual and for the entire community indicate greater energy consumption and greater reliance on vehicles and newer technologies, leading to less activity and, therefore, less healthy individuals and communities. This refers to higher rates of energy consumption to meet the demands of urbanization, industrialization, and modern life, as well as faster growing economic sectors, such as transportation, construction, manufacturing, tourism, catering services, and so on. For example, the number of vehicles in the GCC countries jumped from around 18 million in 2008 to more than 23 million in 2015 [130]. This reflects an increase of about 28% over a 7-year period. The data shows that the average car ownership in Dubai, UAE, is approximately one for every two residents (or 540 vehicles per 1,000 residents), while in major cities (such as New York, London, Singapore, and Hong Kong), there are 305, 213, 101 and 63 vehicles per 1,000 residents, respectively [131]. According to official figures, the number of vehicles in Dubai in 2006 was about 740,000, but this doubled to 1.4 million at the end of 2014. Adding to the density of vehicles in Dubai, about 450,000 vehicles from other emirates enter Dubai, on average, every day [131].

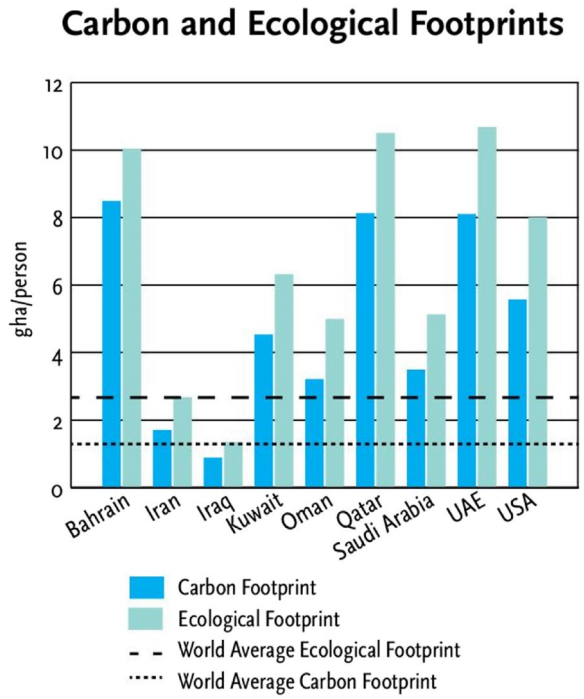

Fig. 7 Data of the carbon footprint (CFP in blue) and the ecological footprint (EFP in green) for the GCC countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and UAE), as well as for Iran, Iraq, and USA, compared with the world's averages of CFP and EFP in 2007 [117, 127]

Accordingly, the rapid economic growth in the GCC countries has had negative impacts on the wellbeing of the environment and public health, resulting in higher rates of obesity, cardiovascular and cancer diseases and, thus, higher mortality rates [116, 132–134]. Growth and progress in the GCC countries over the past three decades has led to improvements in infant mortality, life expectancy, and fertility rates [135]. However, despite these improvements, the region suffers from the type of health problems that are prevalent in higher-income societies, where large proportions of the population are sedentary. Increasing obesity in children, adolescents, and adults, high blood pressure, and higher rates of diabetes are health problems that the GCC countries have developed during the last few decades [132]. For instance, the GCC countries are amongst the regions with the highest prevalence of diabetes, worldwide [136]. The International Diabetes Federation (IDF) has reported high prevalence rates of over 20% for diabetes and over 15% for prediabetes in most of the GCC countries. These are amongst the highest rates worldwide [137].

In the GCC countries, the largely inefficient combustion of fossil fuels, accelerated momentum of urbanization, higher oil revenues, and economic growth have significant impacts on air quality, as these issues have contributed negatively to environmental degradation as a result of increased emissions of greenhouse gases into the atmosphere [138]. In 2011, Kuwait, Saudi Arabia, and the United Arab Emirates were amongst the ten countries with the worst air pollution in the world [112, 139]. *"The Gulf region is one of the most polluted in the world due to its addiction to oil and gas. Qatar leads in exposure to harmful $PM_{2.5}$ particles, followed by Saudi Arabia, Egypt, Bahrain, Iraq and Kuwait,"* said Julien Jreissati, a campaigner at Greenpeace Middle East and North Africa (MENA) [140]. Although the GCC countries cannot give up their high rates of oil consumption, they are trying to increase investment in green economies to reduce greenhouse gas emissions [141].

Particulate matter of 2.5 microns or smaller ($PM_{2.5}$) is one of the deadly elements behind air pollution that results in terrifying rates of illness and even mortality amongst all ages of people living in the proximity of polluted areas [116, 142]. It is estimated that air pollution was responsible for 176,000 premature deaths in 2013 in the Arab region (including the GCC countries), and a loss of more than 2% of regional GDP [143–145]. *"In the six Gulf countries, ambient air pollution was responsible for 13,000 premature deaths in 2017. That's a huge increase from 10,000 deaths in 2010,"* said Lauri Myllyvirta, senior analyst at Greenpeace Air Pollution Unit, with reference to the Global Burden of Disease [146].

Municipal solid waste (MSW) in the GCC countries

The world generated 2.01 billion tons of municipal solid waste (MSW) annually, with at least 33% of that – very conservatively – not being managed in an environmentally safe way. Worldwide, the average waste generated is 0.74 kg per capita per day (kg/ca/d) but it ranges widely, from 0.11 to 4.54 kg/ca/d [147].

Regarding the GCC countries, the rise of EFP and CFP in the GCC countries indicates high rates of consumption of energy, water, and food, as well as due-services by individuals, households, and enterprises, which has led to a rapid increase in generating greater amounts of all kinds of waste, including MSW (Fig. 9), demolition waste, and electronic and electrical waste.

The MSW generated in 2012 in the Arab countries (including the GCC countries) amounted to 150 million tons and is estimated to exceed 200 million tons annually by 2020 [112], where MSW represents the second largest stream after construction waste [149]. With an average per capita production of more than 1.5 kg of MSW per day (kg/ca/d), the GCC countries are ranked amongst the top 10 waste-producing countries worldwide. In 2017, the United Arab Emirates recorded the highest waste rate per capita per day at 2.1 kg, followed by Saudi Arabia, Qatar, and Bahrain at 1.7 kg/ca/d for each, and finally

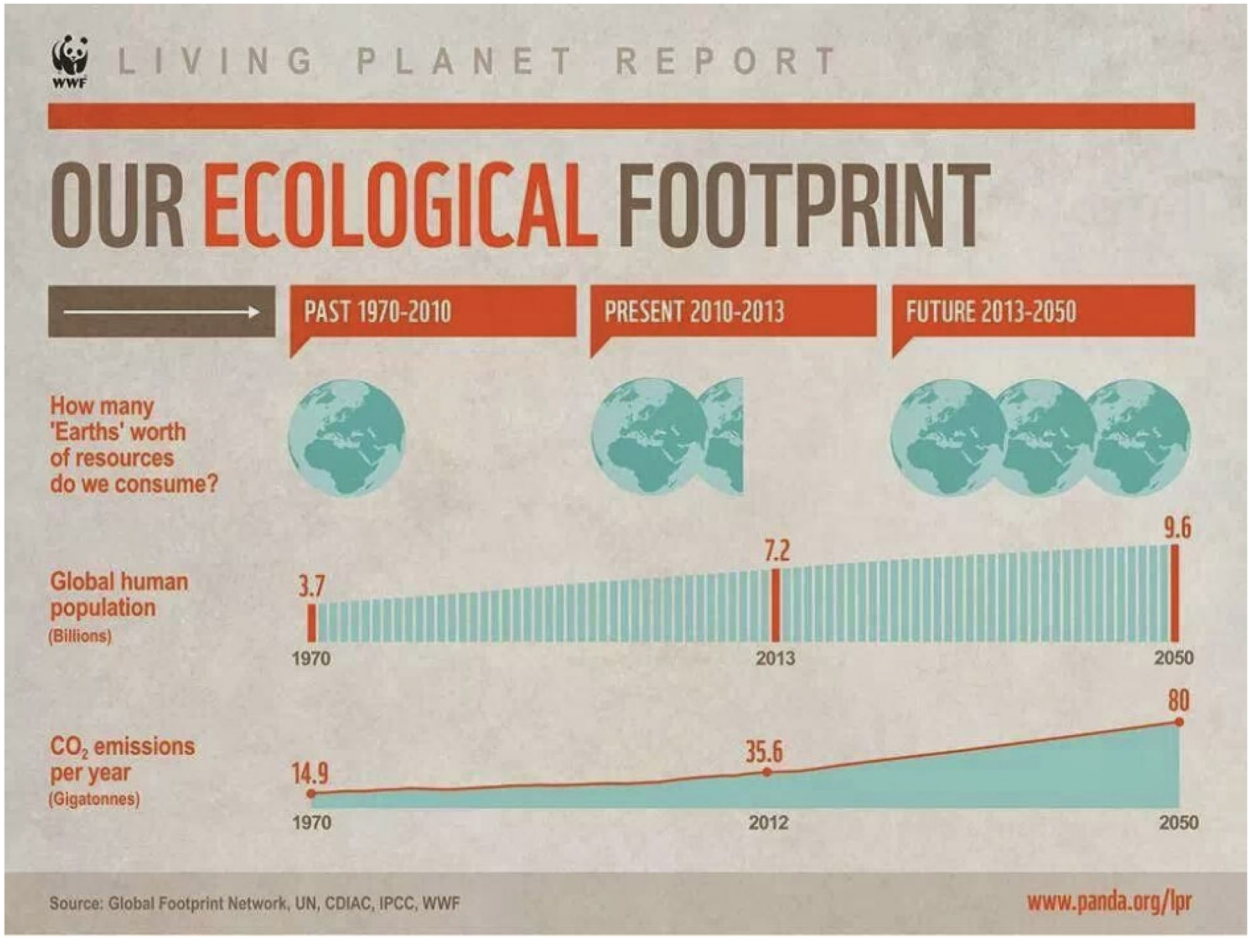

Fig. 8 The world's ecological footprint (EFP) over a period of 80 years (1970–2050) [129]

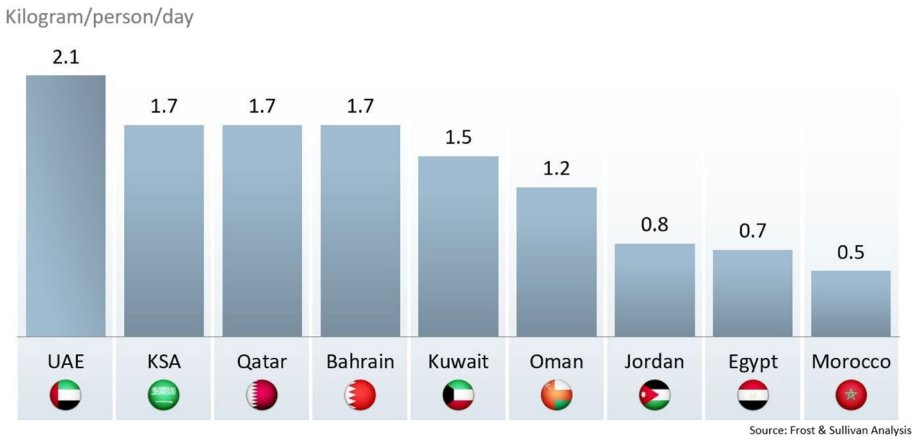

Fig. 9 Municipal solid waste's (MSW) generation (in kg/ca/d) in the GCC countries (UAE, KSA, Qatar, Bahrain, Kuwait, and Oman), as well as in other three Arab countries (Jordan, Egypt, and Morocco) for the year 2017 [148]

Kuwait and Oman at 1.5 and 1.2 kg/ca/d, respectively (Fig. 9). In comparison, some other Arab countries (i.e., Jordan, Egypt, and Morocco) produce much less municipal solid waste than the GCC countries (Fig. 9). If the per-capita MSW in the three Arab non-Gulf countries (Jordan, Egypt, and Morocco) were summed, it will result in 2 kg/ca/d in the three countries together, which is still less than that amount of MSW (2.1 kg/ca/d) produced in the UAE alone amongst the GCC countries (Fig. 9). Also, if the MSW's averages are taken into account, this means that the GCC average is 1.65 kg/ca/d, compared to 0.67 kg/ca/d in the other three Arab non-Gulf countries, as demonstrated in Fig. 9.

On the other hand, the MSW recycling's rate in the GCC countries was, as in 2012, less than 5% of the total waste generated [112]. In 2016, it increased to 11% in Kuwait, Oman, and the UAE, while it remained at 1% in Saudi Arabia and Qatar [150], whereas Oman was not mentioned. Accordingly, it is estimated that the annual cost of damages resulting from improper waste management exceeds 0.6% of the combined GDP in the Arab region [112]. In other words, the GCC countries lose about USD 6 billion annually, due to low recycling rates [151]. Some countries in the world have already developed long-term strategies to convert MSW into energy [145, 152], while the GCC countries have recently entered the field of this technology [153, 154]. This is despite the fact that municipal solid waste is a heavy burden on the economies and environments of the GCC countries, both individually and collectively. For example, the planned Al-Dhafra landfill's site in Abu Dhabi, UAE, will have an expected treatment capacity of between 600,000 and 900,000 tons of waste per year [146]. Meanwhile, most of the 50 million tons of waste produced in Saudi Arabia annually end up in landfills [146], causing massive damages to the environment and ecosystems altogether.

Sustainable development and the United Nations' Sustainable Development Goals (UN's SDGs), with respect to the GCC countries

Sustainability or sustainable development (SD) is defined as development that meets the needs of the present without compromising the ability of future's generations to meet their own needs [59, 111, 155]. This means that sustainable development requires that current economic activities do not harm the well-being of present and future's generations, so that a balance should be maintained amongst economic, social, and environmental capital [59, 111]. Sustainability can be better defined as the ability to persist or maintain a particular behavior indefinitely. This covers environmental, economic, and social sustainability (enviro-econo-social sustainability – EESS) [59, 111].

Environmental sustainability is the ability to maintain rates of harvesting of renewable natural resources (such as water) [156]; to reduce rates of air, water, soil, and noise pollution; and to manage the depletion of non-renewable resources (e.g. fossil energy sources: oil, natural gas, coal, and oil shale) in a way that will continue, indefinitely, for future generations. Economic sustainability is the ability to maintain, indefinitely, a certain level of economic production that should lead societies to prosperity, stability, and security (in terms of food, water, land, energy, etc.) [156]. Social sustainability is the ability of a social system (e.g., neighborhood, community, state, nation, geopolitical entity, etc.) to operate, indefinitely, at a specific level of social welfare, which certainly requires, as preconditions, environmental sustainability and economic sustainability. Therefore, for a society whose citizens and residents enjoy a good life (similar to the situation in all GCC countries), the society must have the three pillars of sustainability (i.e. EESS) to sustain and continue in a healthy manner of life.

The United Nations Sustainable Development Goals (UN's SDGs or SDGs) are a blue dot for achieving a better and more sustainable future for all [157, 158]. The 17 SDGs address the global challenges facing humanity, including those related to poverty, inequality, climate change, environmental degradation, peace, and justice (Fig. 10).

In order to leave no one behind, it is important that people, all over the world, need to achieve the SDGs by 2030. Although the SDGs are interrelated, the goals discussed here are just a few, with regard to the objectives of this research paper. It should be noted that after many years of hesitation, the GCC countries are moving towards achieving and implementing the UN's SDGs, although it is likely that only a few goals will be achieved by 2030, as planned by the United Nations. According to the report issued by the World Summit Organization in partnership with the Mohammed bin Rashid School of Government under the title *"Arab Region Sustainable Development Goals Index 2022,"* only three countries managed to achieve only one of the 17 goals [159]. Unfortunately, 19 out of the total 22 Arab countries have not yet achieved any of the United Nations' Sustainable Development Goals [159].

Conclusions, recommendations, and policy implications

The global oil market is undergoing fundamental changes. Oil prices have recently (in 2020/2021) reached their lowest levels in nearly two decades – most likely due to the effects of the Coronavirus (COVID-19) pandemic on global markets, as demand for fuels (oil and natural gas) had fallen dramatically. In 2022, prices recovered as

Fig. 10 United Nations' Sustainable Development Goals (UN's SDG) [157, 158]

a result of the ongoing war between Russia and Ukraine, which began on February 24, 2022. These fluctuations in fossil energy prices reflect global changes and events (particularly the COVID-19 pandemic); geopolitical instabilities (in terms of military conflicts, particularly the Russian-Ukrainian war and its regional and international impacts and consequences, as well as the conflicts in the Arab region); and the competition amongst the main global players, including producers and exporters of hydrocarbon energy resources: oil and natural gas.

The main competitors that produce hydrocarbon energy sources mainly include the GCC countries, USA, Russia, Venezuela, Canada, Iraq, and Iran, although Iran is currently banned from exporting its fuel. This is in addition to some other countries that currently produce and sell offshore natural gas from the Mediterranean Sea, as well as from other onshore and offshore regions of the world. Therefore, more and more countries are becoming players in the global oil and natural gas markets and, thus, increasingly supplying the global markets with these commodities, although the world (especially the USA, China, Europe, and India) is still and will remain thirsty for oil due to the increased demand for it as a result of the revolutionary industrialization and development activities, globally. This is happening despite the climate change and other environmental changes and their negative consequences and effects on the environment and public health, caused by greenhouse gas emissions into the atmosphere, as a result of the world's consumption of large quantities of hydrocarbons.

However, during the past few decades, many countries of the world have expressed more concern about the well-being of the environment, in light of the dramatic environmental changes affecting the globe. Accordingly, the world has witnessed some growing concerns about the environment and ecosystems, along with the global repercussions of military conflicts and geopolitical instabilities around the world. These factors have prompted some countries to gradually shift away from the consumption of hydrocarbons, by reducing their dependence on fossil energy sources and gradually replacing them by renewable, green, clean energy alternatives. This means that more countries are increasingly relying on renewable energy sources and technologies – REST, as they are environmentally friendly, especially in light of the mounting geopolitical instabilities and military confrontations amongst countries around the world.

This situation has encouraged countries, individually and collectively (such as the European Union – EU) to legislate policies and develop plans and strategies that support reduction of their dependence on fossil energy sources, and to encourage more usage of REST instead,

and to develop further green economies. Accordingly, some European countries have already relied on nuclear energy (such as France), while others (such as Germany, Belgium, etc.) have plans to rely more and more on hybrid energy sources (fossil and REST, mainly wind, solar, and hydroelectric). Offshore clean energy (wind) hubs may become essential for efficient generation and distribution of offshore power in many European countries. In addition, offshore energy hubs may provide decarbonized energy supplies for marine transport, oil and gas extraction, and offshore farming, while also enabling the conversion and storage of decarbonized liquefied energy carriers for export.

Crude oil reserves in the GCC countries are estimated at around 527 billion barrels, constituting approximately 31% of the global reserves, while the countries of the Middle East and North Africa – MENA – have crude oil reserves estimated at 744 billion barrels, constituting approximately 43% of the world's oil reserves, as indicated in this research. The GCC countries must realize the need to reduce their dependence on fossil fuels, which requires the implementation of new, efficient, and effective reforms, plans, strategies, laws, policies, and regulations, with the aim of diversifying energy sources, economies, and financial returns. Although there are some developments in the renewable energy sector in the GCC countries in the form of current and future projects, there are no efforts to support the development of real strategic policies and plans towards further utilization of REST, due to the fact that such an approach is still fairly moderate.

However, due to the current financial situation and the unstable geopolitical situations in many regions of the world, financial wealth, in the GCC region and globally, will probably be depleted in the next few decades. Accordingly, successful sustainability requires environmental (E), economic (E), and social (S) sustainability (S) – being described as "EESS." This EESS approach requires significant and adequate implementation of sustainability aspects by the GCC countries, separately and collectively, in relation to the United Nations' Sustainable Development Goals – UNs SDGs. The pace and momentum of the GCC countries for this mechanism, initiative, or approach (i.e. EESS) towards achieving the SDGs by 2030 is a transient or intergenerational choice, as well as a challenge facing the GCC countries, given the following: Not achieved any one of the SDGs at the regional level within the GCC countries, in particular, and in the Arab region in general.

In conclusion, this paper provides insight in the form of developing energy transitional strategies, based on a decarbonization's approach and provision of advice on diversifying business models and transforming the workforce to adapt to the energy transition. This paper also provides guidance to GCC officials, policymakers, academics, and research scientists, as well as others concerned across the world, including governments, universities, research institutions, think-tanks, companies, and so forth by working through potential scenarios to help plan the GCC energy transition step by step. New low carbon technologies are being introduced to the markets all the time. Integration of future energy and fuel technologies such as solar, wind, and hydrogen is critical, although technical solutions exist. The paper could potentially suggest GCC countries/stakeholders to identify the appropriate technologies and determine return on investment and transition from one energy source to another energy source without causing a disturbance.

It is noted that current and potential future political instabilities in the MENA region and the world at large, due to superpowers' hegemony and control over natural resources (such as hydrocarbons, water resources, and minerals), as well as countries' interventions in the affairs of each other represent real limitations and challenges that may face the ambitions, plans, and strategies presented in this comprehensive research work. Therefore, it is seen that the GCC countries should take the initiative in driving the development of REST and rely more on them. Accordingly, the Gulf countries will have the ability to face any dynamic changes from the future's perspectives (such as wars, political instability, and population growth, as well as natural disasters, such as the impacts of climate change, etc.) that may affect not only the Gulf region but also the entire world. Such perspectives, if considered efficiently by the GCC countries, individually and collectively, will also enable them to achieve the UN's SDGs (or at least some of them) – faster and easier.

As final notes, regarding this research work, there is nothing to mention about research limitations, in terms of research objectives, questions, methodology, availability of data, etc. Also, it is believed that publishing this important article in this time, in particular, is an important step in the right direction. This is because COP28 (the 28th Conference of the Parties, UN Climate Change Annual Summit 2023) will take place soon in the Gulf region (in Dubai, UAE), during the period of 30 November until 12 December 2023.

Abbreviations

ADNOC	Abu Dhabi National Oil Company
AG	Arabian Gulf (also known as Persian Gulf)
AI	Artificial Intelligence
ARAMCO	Saudi Arabian Oil Company
BAPCO	Bahrain Petroleum Company
CFP	Carbon Footprint
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COP26	26^{Th} Conference of the Parties, UN Climate Change Annual

	Summit 2021
COP27	27Th Conference of the Parties, UN Climate Change Annual Summit 2022
COP28	28Th Conference of the Parties, UN Climate Change Annual Summit 2023
COVID-1	Coronavirus Disease of 2019
E	Energy
EESS	Enviro-Econo-Social Sustainability
EFP	Ecological Footprint
EFPs	Ecological Footprints
EFP/ca	Ecological Footprint per Capita
F	Food
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GECF	Gas Exporting Countries Forum
GHG	Greenhouse Gas (emissions)
IDF	International Diabetes Federation
KOC	Kuwait Oil Company
KSA	Kingdom of Saudi Arabia
MENA	Middle East and North Africa (region)
MSW	Municipal Solid Waste
OECD	Organization for Economic Cooperation and Development
OPEC	Organization of the Petroleum Exporting Countries
PDO	Petroleum Development Oman
PNZ	Partitioned Neutral Zone, Kuwait
PV	Photovoltaic (solar energy)
QNB	Qatar National Bank
QP	Qatar Petroleum
REST	Renewable Energy Sources and Technologies
R/P	Oil Reserve to Oil Production Ratio
SD	Sustainable Development
SDGs	Sustainable Development Goals (UN's SDGs)
TOTAL	French Oil Company
UAE	United Arab Emirates
UN	United Nations
USA	United States of America
W	Water
WEF Nexus	Water-Energy-Food Nexus
WRI	World Resources Institute

Units

AED	Arab Emirates Dirham
bbl	Barrel of oil
Bbbl	Billion barrel of oil
bbl/ca/d	Barrel of oil per capita per day
bbl/d	Barrel of oil per day
bb1/d/million	Barrel of oil per day per a million of people
bgha	Billion global hectares
°C	Degrees Celsius
cm	Centimeter
gha	Global hectares
gha/ca	Global hectares per capita
Gt	Giga-tons
GW	Giga-Watt
ha	Hectare
kg	Kilogram
kg/ca/d	Kilogram per capita per day
km	Kilometer
km^2	Kilometer square
kWh	Kilowatt-hour
kW/m^2	Kilowatt per meter square
m	Meter
m^2	Meter square
MCM/d	Million cubic meters per day
MW	Mega-Watt
pe/km^2	Persons per kilometer square
$PM_{2.5}$	Particulate matter of 2.5 microns or smaller in size
TCF	Trillion cubic feet
TCM	Trillion cubic meters
UAE's Fils	United Arab Emirates' Fils = 0.001 AED
UK	United Kingdom
US Cent	United States' Cent
USD	United States' Dollar

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Declarations

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