



## RESEARCH ARTICLE

# Assessment of the carbon abatement and removal opportunities of the Arabian Gulf Countries

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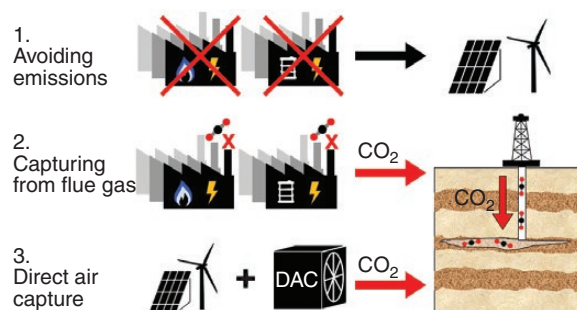
## Abstract

The Arabian Gulf Countries (AGC) are strongly reliant on the economic export of fossil fuels, while being vulnerable to climate change that is resulting in temperature increase, air pollution and sea-level rise, and threatening the health of the population and ecosystem. In agreement with the Paris Accords, most of the AGC have published short-term goals to reduce their carbon emissions in the coming decades. In relation to these goals, this study explores the potential CO<sub>2</sub> reduction, avoidance and removal in the region, by comparing a business-as-usual (BAU) scenario to three decarbonization scenarios for the power sector. In 2018, the total greenhouse gas (GHG) emissions in the AGC were ~1333 MtCO<sub>2</sub>/yr and are expected to rise to 1568 MtCO<sub>2</sub>/yr in 2030 following a BAU scenario, which is likely to be reduced to 1522 MtCO<sub>2</sub>/yr in 2030 by following the countries' planning. Countries issued plans for the coming decades that focus on increasing the share of renewable energy in their grid mix. The three decarbonization scenarios presented in this study focus on supply-side technological solutions. The retirement of the oldest natural-gas and oil power plants could lead to a total emissions reduction of ~75 MtCO<sub>2</sub>/yr, without accounting for the embodied carbon emissions associated with renewable energy. In addition, the implementation of point-source capture at power plants expected to retire in >10 years' time could avoid emissions of ~240 MtCO<sub>2</sub>/yr, provided the CO<sub>2</sub> is permanently sequestered in appropriate geological formations. The region also shows high-quality solar resources and large CO<sub>2</sub>-storage potential that could couple to direct air-capture plants to offset difficult-to-avoid emissions. This last scenario has the potential to ultimately result in net negative emissions.

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## Graphical Abstract



**Keywords:** carbon capture; CCUS; direct air capture

## Introduction

The Arabian Gulf Countries (AGC), including Bahrain, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE), produce 25% of the world's oil [1]. In addition, fossil fuels represent the majority of their revenue sources, between 53% and 100% of the total revenue from exportations [2]. In view of the Paris Agreement as well as the popularity of Environment, Social & Governance norms and fossil-fuel divestment strategies, fiscal and energy sustainability in the region is a challenge.

Reliance on fossil energies in the AGC started when the discovery of oil in Iran in 1908 motivated geologists and mining engineers from around the world to go to the region in search of oil [3]. As can be seen from the timeline of oil and gas discoveries in the AGC (Fig. 1), oil and gas were first discovered in Iraq in 1923 and 1927, respectively. However, the countries did not make use of natural gas until it was first exported in 1963 from Bahrain [3]. Today, Qatar, on its own, represents 12% of the world's natural-gas reserves [4].

The dependence of the region on oil and natural gas resulted in the production of ~1134 million metric tons of CO<sub>2</sub> (MtCO<sub>2</sub>) in 2017 [5].

Fig. 2 showcases the evolution of the total CO<sub>2</sub> emissions in the AGC, increasing in most of the countries until the mid-2010s, from 359 MtCO<sub>2</sub>-eq in 1990 to 1274 MtCO<sub>2</sub>-eq in 2015 [6, 7]. Today, the emissions of most of the countries are either constant or decreasing, with the exception of Iraq. Iraq has had the largest increase in CO<sub>2</sub> emissions in recent years and the lowest CO<sub>2</sub> emissions per capita in the AGC, at ~5.3 tCO<sub>2</sub>/cap in 2018 as opposed to 14–38 tCO<sub>2</sub>/cap in the other AGC [5–7]. This is largely due to the fact that the country is not meeting the population's power demand due to political issues, while the population continues to increase [5]. The recent plateau in GHG emissions in Saudi Arabia is explained by an increase in energy efficiency and a decrease in the carbon intensity of the energy supply [8], while the population is still increasing [5].

The AGC are currently trying to reduce their CO<sub>2</sub> emissions to improve the environment, public health and economy. The majority of the countries in the AGC

showed positive steps towards a brighter and a more sustainable future. Saudi Arabia, the UAE, Oman, Kuwait, Qatar, and Bahrain have committed to and ratified the Paris Agreement [9]. Furthermore, the AGC identified sustainability in the energy sector as a national priority driven by increments in energy demand, economic diversification, a cleaner environment and the rise in opportunities to invest in viable renewable energy sources [10]. Due to the location, topography and climate of the AGC, the countries are vulnerable to climate change [11]. The region shows many signs of an ongoing climate change and the current trend leads to the expectation of more extreme conditions in the upcoming years. One of the major issues caused by climate change is the extreme weather. Countries across the AGC continue to face an increase in the average annual temperatures and frequency of dust storms, and a decrease in the average annual rainfall [12]. Another issue related to climate change, which is directly related to the weather conditions, is public health. Due to the increase in dust storms, the level of air pollution rises and causes respiratory diseases. Furthermore, the increase in temperatures leads to thermal extremes and food-borne diseases. The level of air pollution in the AGC in 2019 was 44–91 µg/m<sup>3</sup>, several times above the recommended level by the World Health Organization of 10 µg/m<sup>3</sup> [13]. The long-term effect of this high level of air pollution is known to create major health problems such as lung cancer, chronic respiratory illnesses, strokes and heart attacks [11]. Another major concern in the AGC is the rise in sea levels that would cause flooding, agriculture soil contamination and the disruption of natural habitats. In addition, most upstream and downstream oil and gas facilities, petrochemical factories, oil and gas export terminals, power plants (including natural gas, oil and nuclear) and water-generating facilities in the AGC are located offshore and in coastal areas [14]. The rise in sea levels might thus compromise most of these infrastructures. The last climate-change-related issue in the region is water scarcity. Most AGC have been struggling to fulfil the demand on water in their country for hundreds of years. The rise in sea levels poses the threat of seawater

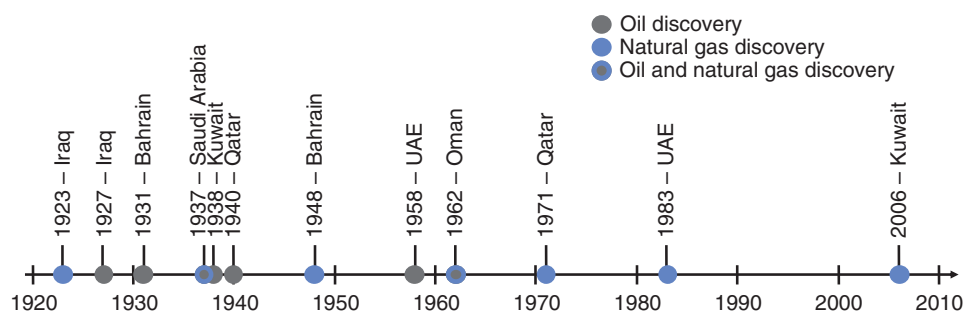


Fig. 1: Oil and natural-gas discovery timeline in the AGC [3]

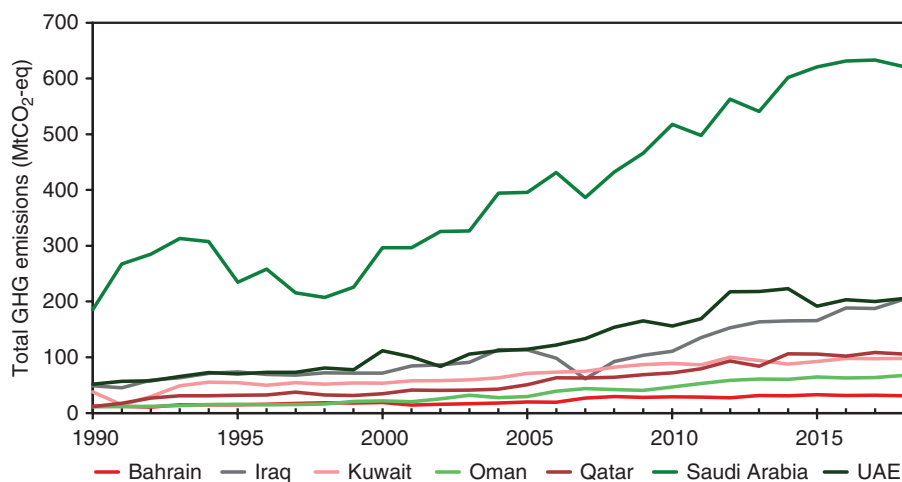


Fig 2: Total GHG emissions per country from 1990 to 2018 in the AGC (data obtained from [6, 7])

intrusion into groundwater reservoirs, compromising further the water scarcity in the region [15].

Most of the AGC developed visions with clear goals to fight climate change in the next decades. The previously mentioned drivers—increase in energy demand, economic diversification, cleaner environment and the rise in opportunities to invest in viable renewable energy sources—are key parts of countries' visions for the next 10–30 years. Saudi Arabia is working on increasing the production of renewable energy by 2030. The production should increase gradually to 12.85 gigawatts by 2023 [16]. Qatar has the goal of producing 200 MW of renewable energy by 2020, to be raised to 500 MW at a later time [17]. Bahrain aims to shift 5% of the energy consumption to renewables by 2025 and 10% in 2035, with a goal to rely mostly on clean energy by 2050 [18, 19]. The use of clean and renewable energy should be raised to 50% of the energy used in the UAE by 2050 [20]. Moreover, Oman is targeting to increase the percentage of renewable-energy usage to 39% by 2040 [21]. Lastly, Kuwait aims to improve its climate sustainability and increase the use of renewable energy by 15% in 2035 [12].

The power sector in the region represents both a challenge and an opportunity. Today the sector largely relies on fossil fuels. Natural gas generates 69% of the electricity in the region, oil 30.5% and renewable energy 0.5% [22]. Therefore, as shown in Fig. 3, the electricity and heat sector is a major contributor to the annual CO<sub>2</sub> emissions

in the region with 516 MtCO<sub>2</sub>/yr, which represents 46% of each country's total emissions [22].

On the other hand, the power sector represents a great potential for deep decarbonization. Multiple opportunities exist for low-carbon energy technologies such as solar photovoltaic (PV) and wind that could replace the aging power plants of the fleet when they retire in the next decade. Newly built fossil-fuelled power plants could implement carbon-capture retrofit. In order to have an impact on climate mitigation, the captured CO<sub>2</sub> should be sequestered in appropriate geologic formations, for instance depleted oil and gas reservoirs, that are very abundant in the region.

Some GHG emissions, in particular from the industrial and transportation sectors, are more difficult to avoid than emissions from fossil-fuelled power plants for various reasons. In the AGC, 250 and 236 MtCO<sub>2</sub>-eq are emitted by the industrial and the transportation sectors, respectively, representing on average 19% and 18% of the total emissions of these countries, respectively [22]. Even industrial emissions can be reduced by producing electricity and part of the heat with renewable sources; some industrial emissions are the production of CO<sub>2</sub> as a by-product of chemical reactions. For example, in a refinery, the reaction of long-chain hydrocarbons in the fluid catalytic cracker results in water and CO<sub>2</sub> as byproducts [23]. Avoiding the production of CO<sub>2</sub> would require a complete redesign of the process, which

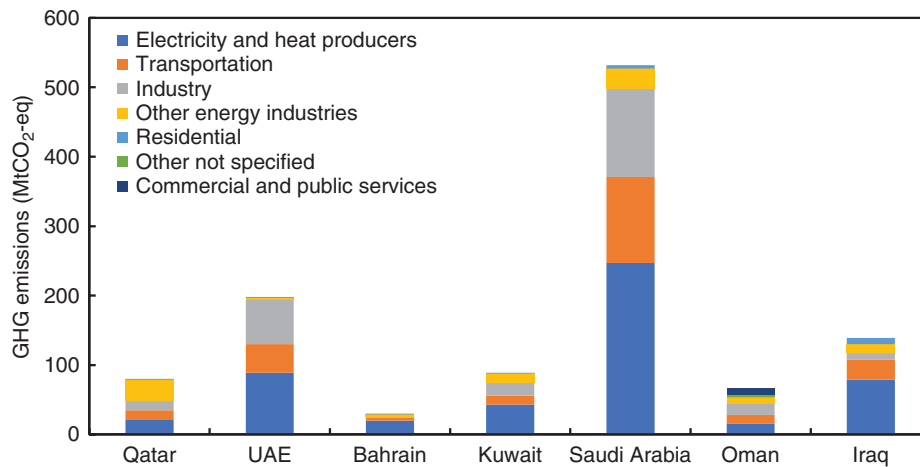


Fig. 3: CO<sub>2</sub> emissions by sector in the AGC in 2017 (data obtained from [22])

might take years, if even feasible. With current processes, capturing CO<sub>2</sub> at the source is likely only economically achievable for higher purity and higher volume streams of industrial facilities [24]. The transportation sector sets another challenge for CO<sub>2</sub> capture, as each of these emissions sources are small but numerous and highly spread out. Current solutions for reducing the emission from this sector are the electrification of modes of transportation and the use of hydrogen to replace fossil fuels or the implementation of carbon capture for heavy-duty vehicles [25–27]. Reducing subsidies or establishing caps on the use of internal-combustion-engine vehicles can also help in transitioning towards cleaner energy sources. These options are not explored in the current study, which focuses solely on the power sector.

One option for capturing difficult-to-avoid emissions that cannot be retrofitted is direct air capture (DAC). Several technologies are being deployed on a commercial scale today. The Swiss company Climeworks has installed 14 plants worldwide and their technology is based on solid sorbents, whereas the technology developed by the Canadian company Carbon Engineering is based on liquid alkali metal oxide sorbents, commonly referred as liquid solvents. Both technologies need heat (80% of the energy) and electricity (20% of the energy) to operate. Thermal energy is used for the regeneration of the capture agent: 100°C is required for sorbent regeneration and 900°C for regeneration of solvents [28–30]. In order to optimize the carbon-capture potential of DAC, the energy has to be sourced from low-carbon energy sources, such as concentrated solar power (CSP) for the heat, and photovoltaic (PV) and wind turbines for the electricity. The heat provided by CSP is likely to be more suitable for regenerating solid sorbent, as this technology requires lower-grade heat. Some technologies in the early stage of development only require electricity for capturing CO<sub>2</sub> [29] and might be a future alternative where the access to low-carbon heat generation is reduced. As point-source capture, DAC also needs to be associated with reliable geologic sequestration in order to effectively remove carbon from the atmosphere and result in negative emissions.

The process of capturing (from point source or DAC) and storing or utilizing CO<sub>2</sub> is commonly called carbon-capture utilization and storage (CCUS). The carbon-capture and storage (CCS) approach injects CO<sub>2</sub> into the ground for long-term storage (>>1000 years) and its goal is solely to mitigate climate change. The carbon-capture and utilization (CCU) approach uses CO<sub>2</sub> as a resource to create a valuable product (enhanced oil recovery, building materials, fertilizers, etc.) but the CO<sub>2</sub> is usually re-emitted into the atmosphere at the end of the lifetime of the product [31–34].

This work investigates the current energy production and related carbon emissions in the AGC, and then explores four scenarios: a business-as-usual (BAU) scenario and three decarbonization solutions (D1, D2 and D3) focused on supply-side technologies in the power sector. In scenario D1, the aging fossil-fuelled power plants, expected to retire during the next decade, could be replaced by low-carbon energy power plants such as PV and wind. In addition, in scenario D2, the younger fossil-fuelled power plants could implement point-source capture in order to offset most of their emissions. Finally, in scenario D3, the difficult-to-avoid emissions, in particular from the industrial and transportation sectors, could be balanced by developing DAC powered by low-carbon energy sources. In order to have a positive impact on climate mitigation, the captured CO<sub>2</sub> should be sequestered in appropriate geologic reservoirs for CO<sub>2</sub> storage. The optimization of these options depends on the geographical distribution of the low-carbon sources of energy, the population centres and the CO<sub>2</sub>-sequestration sites. Local maps picturing the fossil-fuelled power plants, the low-carbon energy opportunities and the geological formations suitable for CO<sub>2</sub> storage are shown to outline the best opportunities in the region.

## 1 Methods and project approach

This study investigates the current stage of energy generation and consumption in the AGC and offers various



scenarios for the future. The current energy needs are analysed by considering the current state of the fossil-fuelled power plants in the region. Projections of energy consumption were made for a BAU case. Three alternative scenarios present solutions to decarbonize the power sector, while taking into account the aging of the fossil-fuelled power plants proposed for reducing carbon emissions.

### 1.1 BAU scenario

The calculations of the CO<sub>2</sub> emissions for the next decade (2020–30) under a BAU scenario are based on the Kaya equation (Equation 1) applied to each country. This equation depends on multiple variables such as the intensity of carbon in energy, GDP, population and energy intensity of the economy [35]:

$$Em_{GHG} = \frac{Em_{GHG}}{E} \times \frac{E}{GDP} \times \frac{GDP}{Pop} \times Pop = I \times E_{int} \times g \times Pop \quad (1)$$

where  $Em_{GHG}$  is the total GHG emissions,  $E$  is the energy generation,  $Pop$  is the population,  $I$  is the carbon intensity,  $E_{int}$  is the energy intensity and  $g$  is the GDP per capita.

In the BAU scenario, the energy sources are used with constant energy efficiencies; the last available data for carbon intensity [36] are thus considered constant in the future. Past data and future trends are available in the literature for the population (until 2030), the GDP (until 2025) and the GDP per capita (until 2025) [5, 37]. The 2020–25 trends for the GDP and the GDP per capita were extended until 2030 using a linear regression. A regression with a power function on 1990–2018 data was used to fit the energy generation versus the GDP [38], in order to estimate the energy generation for the years 2019–30 from GDP estimates over the same time period. The details of these calculations are provided in the [Supplementary Data \(see the online Supplementary Data\)](#). The total emissions of each country for the years 2019–30 were estimated using the Kaya equation (Equation 1).

### 1.2 Decarbonization scenarios for the power sector

The current stage of power generation by fossil fuels was investigated using the Enerdata database, which provides information per unit of production including the net capacity, the commission year and in some cases the planned decommission year of currently operating natural-gas and oil power plants [39]. In the cases in which no decommission dates are given, a lifetime of 40 years is assumed to estimate the retirement year of the power-generating unit [40]. Providing information at the unit level increases the accuracy of the analysis as a power-generating facility might build units and then retire them at different times. For our analysis, the units were grouped by bracket of decommissioning year: 2020–30, 2030–50, >2050 and unknown (in the few cases for which both commissioning and decommissioning years are unknown).

The CO<sub>2</sub> emissions in MtCO<sub>2</sub>/yr are estimated for the natural-gas and oil power units using the following equation:

$$E = A \times C \times EF \times M \quad (2)$$

where  $C$  is the net capacity of each unit in gigawatts (GW),  $EF$  is the emission factors in kgCO<sub>2</sub>/mmbtu,  $M$  equates to 90% and is the share of the year during which electricity is produced [41–44] and  $A$  equates to 0.02989 and is a coefficient that accounts for the changes in units. The emission factors of natural gas and oil equate to 53.1 and 73.2 kgCO<sub>2</sub>/mmbtu, respectively [45]. Equation 2 is used to calculate the CO<sub>2</sub>-emissions reduction from scenario D1 and from applying the countries' visions and the CO<sub>2</sub> emissions avoided with scenario D2.

Scenario D1 applies to power units of oil and natural-gas power plants that would retire before or in 2030. In this scenario, the retiring power units would be replaced by renewable sources of energy. The embedded emissions of these renewable sources are not taken into account in this study. At the decommission of fossil-fuel-based power plants, newly built renewable-energy resources are expected to maintain the power generation at the same level, while the GHG emissions are reaching near-zero.

Scenario D2 applies to power units of oil and natural-gas power plants that are expected to retire between 2030 and 2060. Under this scenario, point-source-capture technologies would be implemented at the power-unit exhausts. Point-source-capture technologies commonly avoid the emission of ~90% of the CO<sub>2</sub> in the exhaust. Therefore, for the calculations of the point-source-capture potential, a multiplication factor of 0.9 was added to Equation 2. The emissions of compression, transport and injection in the subsurface or utilization of the CO<sub>2</sub> are not considered in this study.

Scenario D3 featuring DAC (sorbent- or solvent-based technologies) is not quantified in this study because of its energy intensity and its high cost. Reducing (scenario D1) or avoiding (scenario D2) GHG emissions on a large scale is likely to be favoured over DAC in the short term. Also, the implementation of scenarios D1 and D2 would be associated with the large-scale deployment of low-carbon renewable sources of energy for D1 and of geologic storage of CO<sub>2</sub> for D2. These are key infrastructures for ensuring the efficiency of D3. Having this infrastructure already in place would help the deployment of D3.

### 1.3 Siting decarbonization scenarios

Synergies between the CO<sub>2</sub> sources, the low-carbon energy sources and the CO<sub>2</sub> sinks are geographically investigated using ArcGIS® 10.7.1 [46]. Current and potential sources of energy are mapped along with oil fields under operation [47] and geologic formations [48–51] potentially suitable for CO<sub>2</sub> sequestration. The low-carbon sources of energy—CSP, PV and onshore wind—are shown on converted lands [52], which are lands already disrupted by human activities. Offshore wind is shown within the exclusive economic zone of the studied countries and outside marine protected areas [53, 54]. Carbon-dioxide removal requires the

long-term (>1000 years) sequestration of CO<sub>2</sub> in geologic reservoirs. The presence of oil and gas reservoirs is a good indicator of high-quality reservoirs for CO<sub>2</sub> sequestration. Prospective basins for oil and gas in the Arabian Peninsula were mapped along with the location of operating oil and gas fields [47]. Less developed but promising storage technologies involve basalts and ultramafic rocks that are also displayed in the mapping work [48–50, 55]. The ‘buffer’ and ‘intersect’ tools of the analysis toolbox of the ArcGIS® software were used to perform sensitivity analyses. The goal here is to outline fossil-fuelled power plants within 100 km from sedimentary reservoirs and the proximity of potential low-carbon sources of energy to any type of geologic sequestration opportunity.

## 2 Results and discussion

Here we present the current stage of the power sector (natural-gas- and oil-fuelled power plants) in the AGC. From this current stage, we discuss the evolution of the power sector in the AGC if no modifications are made to the current energy mix and consumers’ behaviour (BAU scenario). Then, we propose different options for the deep decarbonization of the power sector in the AGC: either replacing the fossil-fuelled power plants with low-carbon energy sources or retrofitting the power-plant exhausts with carbon-capture technologies. Also, we discuss opportunities for direct air carbon capture and storage (DACCS) in the region. In the long run, this could lead to carbon neutrality or negative emissions, as large resources for CO<sub>2</sub> sequestration are available locally.

### 2.1 BAU scenario

A BAU scenario was developed to assess the outcome of the AGC continuing to generate and consume energy without changing tendencies with a growing population and GDP until 2030. The BAU scenario aims to set a baseline for comparison of projected CO<sub>2</sub> emissions with deep

decarbonization scenarios. The population is expected to grow from 99 million to 116 million people [5] and the GDP from \$1566 billion to \$2523 billion [37] between 2020 and 2030. All the countries in the AGC will also face an increment in their CO<sub>2</sub> emissions per capita if they follow a BAU scenario for their energy sector (Fig. 4). In 2018, the total GHG emissions from the AGC is 1333 MtCO<sub>2</sub>-eq/yr [6, 7], which are expected to rise to 1568 MtCO<sub>2</sub>-eq/yr in 2030 under a BAU scenario. In Saudi Arabia, despite GHG emissions per capita in 2018 going back to pre-2010 levels, the total GHG emissions of the country are expected to increase in the coming decade due to an expected growth in population [56].

### 2.2 Scenario D1: energy switch to low-carbon energy

There are 765 natural-gas power-plant units across all the AGC, 656 of which are currently operational, with a net capacity of 156.6 GW; the others are under construction, stopped, frozen or cancelled. On the other hand, there are 797 oil power-plant units across all the AGC, 741 of which are currently operational, with a net capacity of 66.7 GW. The records show that Qatar does not have any oil power plants [39]. Those generating units vary in age and net capacity. In order to understand when a transition towards low-carbon energies is likely to take place, the decommissioning year was used when available, otherwise a 40-year lifetime was assumed [40]. Fig. 5 showcases the net capacities of projected retirement of fossil-fuelled power units by age brackets of 10 years and by country.

There are 202 natural-gas units and 320 oil generating units expected to retire between 2020 and 2030 within the AGC representing a net capacity of 25.5 and 20.9 GW, respectively. Replacing retiring natural-gas and oil power units with renewable energy sources could reduce the CO<sub>2</sub> emissions by 36.4 and 41.1 MtCO<sub>2</sub>/yr, respectively. This potential does not account for the embedded carbon emissions of solar panels

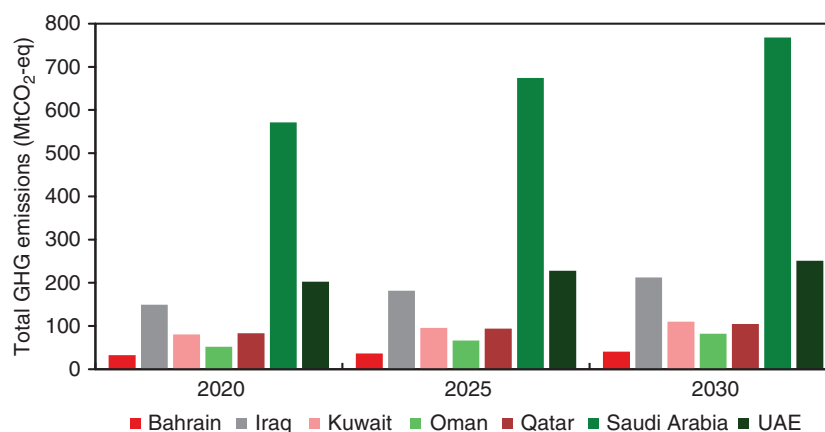


Fig. 4: Total GHG in the AGC for the upcoming decade under a BAU scenario

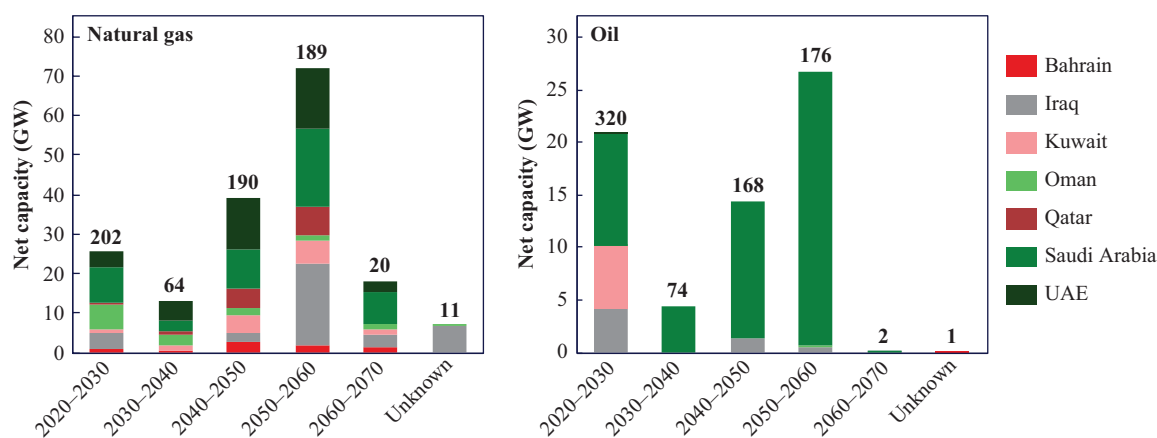


Fig. 5: Net capacity of natural-gas and oil power-plant units by country and age of potential decommissioning. Numbers above the bars represent the total number of units in the decommissioning age bracket. Note that the units decommissioning between 2060 and 2070 are currently under construction and not considered in the calculations (data obtained from [39]).

and their transportation to the solar farm. Life-cycle analyses for different energy systems in the world have shown that solar PV systems emit  $\sim 56$  gCO<sub>2</sub>-eq/kWh [57]. Also, the additional energy generation caused by an increasing energy demand, outlined under the BAU scenario, could also be met by developing renewable and low-carbon sources of energy.

The AGC has the best resources in the world for solar energy and some opportunities for wind farms, and this decarbonization scenario would benefit from the high market penetration of renewable energy in the region. Numerous renewable-energy projects are operating or under construction in the region [58] and the countries' visions detailed below show that renewable energies are developing in the area, with clear goals of increasing the share of renewable energy in the grid mix. Most studies are looking into the possibility of 100% low-carbon energy in the region (including a share of nuclear energy) [59, 60]. Despite its large potential, a regional interconnection grid and a significant overload, which could facilitate the integration of intermittent renewable energy, the region is not a leader for the development of renewable energy [58]. Scenario D1 explores the impact of phasing out the oldest fossil-fuelled power plants in the decade 2020–30, with the ultimate goal of completely decarbonizing the power sector.

The land area necessary for producing a given amount of energy is much larger for these renewable sources than for fossil-fuelled power plants of the same capacity. Due to the intermittency of renewable energy, additional infrastructure and space are also needed for energy storage. Desertic areas are home to unique ecosystems and, even if land use change in these areas would have a minimal impact on the carbon cycle, a careful deployment of these technologies is thus necessary to avoid disrupting natural ecosystems and competing with other human interests. Fig. 6 depicts the opportunities for PV and wind on converted lands that are already disrupted by human activity, but are not used for human settlements and food production. Opportunities are also shown for offshore wind

within the exclusive economic zones of the AGC. In addition to zones with low wind speeds that might technically be unsuitable for developing wind farms, the Persian Gulf and the Red Sea are places of high maritime traffic, which might reduce further possible locations for offshore wind development.

### 2.3 Scenario D2: carbon-capture retrofit at power plants

The 443 natural-gas units and 418 oil units likely to retire between 2030 and 2060, shown in Fig. 5, have a net capacity of 124.2 and 45.6 GW, respectively. Being unlikely to retire within the next 10 years, these units could avoid part of their carbon emissions by investing in point-source-capture technologies. Solvent-based carbon-capture retrofit technologies for fossil-fuel power plants exist today (e.g. Fluor technology at the Bellingham (Massachusetts, USA) cogeneration plant from 1991 to 2005, Petra Nova at the WA Parish Generating Station (Texas, USA) since 2017 and CCS project at the Boundary Dam Power Station (Saskatchewan, Canada) since 2014) [62–65] and have the ability to capture 90% of the CO<sub>2</sub> present in the exhaust stream. This has the potential to avoid the emission of 159.5 and 80.8 MtCO<sub>2</sub>/yr from the natural-gas and oil power units, respectively. These estimates are in the same order of magnitude as the results presented by Mansouri *et al.*, whose study features several scenarios of solar PV and CCS deployment in Saudi Arabia that result in reduced and avoided emissions in the range of 136–235 MtCO<sub>2</sub> in 2025 [57].

The cost of capture and compression at natural-gas power plants in the USA is slightly above \$60/tCO<sub>2</sub> [66, 67]. Although the study asserts that the process needs more time and government support to be cost-efficient, it suggests that it can be implemented today. With government support and involvement of the large energy companies in the AGC, retrofitting fossil-fuel power plants with carbon capture could be developed in the region.

In order to effectively avoid CO<sub>2</sub> emissions in the atmosphere, the captured CO<sub>2</sub> needs to be sequestered in appropriate geologic formations. In the region, the large resources for CO<sub>2</sub> sequestration in depleted oil and gas reservoirs are an attractive opportunity. In addition, oil companies are using CO<sub>2</sub> for enhanced oil recovery (CO<sub>2</sub>-EOR). This process is less efficient in effectively avoiding CO<sub>2</sub> emissions but could motivate energy companies in the AGC to implement point-source capture, as the sales of CO<sub>2</sub> to oil companies would generate revenues and lower the overall cost of capture. Currently, most CCUS routes in the AGC include CO<sub>2</sub>-EOR as their storage/utilization option [68–72]. Another EOR technology that could be commercially more viable is the Miraah Solar Project in Oman that produces steam from solar energy for EOR [73]. The use of solar energy instead of natural gas to produce steam reduces the GHG emissions and the CO<sub>2</sub>-EOR infrastructure can be used for dedicated storage once the oil and gas extraction stops.

The efficiency of point-source capture and storage depends on the location of the power plant, as the process of transporting the CO<sub>2</sub> from the capture location to the storage site emits CO<sub>2</sub>. Co-location of the entire CCUS process increases the net removal potential of the system. Also, for the same amount of CO<sub>2</sub> captured, the total cost can differ upon the transportation distances (location of the closest injection site), the means of transportation and the injection costs.

As stated above, closely locating the capture and sequestration steps would optimize the amounts of CO<sub>2</sub> effectively avoided for the same amount of CO<sub>2</sub> captured. Fig. 6 pictures the fossil-fuelled power plants that are expected to retire in >10 years, along with geologic formations. The most mature technology today injects CO<sub>2</sub> into

sedimentary formations, either for enhanced oil recovery (CO<sub>2</sub>-EOR) in oil reservoirs or for dedicated storage via saline aquifers and depleted oil and gas reservoirs. The locations of oil fields are shown in Fig. 6. The presence of oil fields is a good indicator of suitable geological formations for CO<sub>2</sub> sequestration; they efficiently trapped oil and gas for millions of years, provided that their depth is >800 m. This depth ensures that the CO<sub>2</sub> is pressurized to >74 bars and remains in a supercritical state. As explained above, basalts and ultramafic rocks can be envisioned as alternatives for CO<sub>2</sub> sequestration once the technology reaches a commercial scale. Northern Oman hosts the Samail ophiolite, which is the largest outcrop of peridotite in the world. Carbon mineralization is already happening naturally in these ultramafic rocks. Engineering-system models show that injecting CO<sub>2</sub> at depth in peridotite formations could enhance the rate of mineralization by 16 000 times, thus creating a significant sink for CO<sub>2</sub> [74].

Fig. 6 shows that natural-gas and oil power plants are mostly located on the shore and a good correlation exists between the location of the fossil-fuelled power plants and sedimentary basins. Of the operating units set to retire between 2030 and 2060 located within 100 km of sedimentary basins, 437 are natural-gas generating units and 188 are oil power units that generate 121 and 13 GW, respectively. Point-source-capture implementation at these natural-gas and oil generating units could capture 155.6 and 23.2 MtCO<sub>2</sub>, respectively. The amount of net avoided CO<sub>2</sub> would be slightly lower, as CO<sub>2</sub> is emitted at all steps of the CCUS process in particular when longer transportation distances are needed.

Most of the power plants located on the shore of the Red Sea, far away from sedimentary reservoirs, are

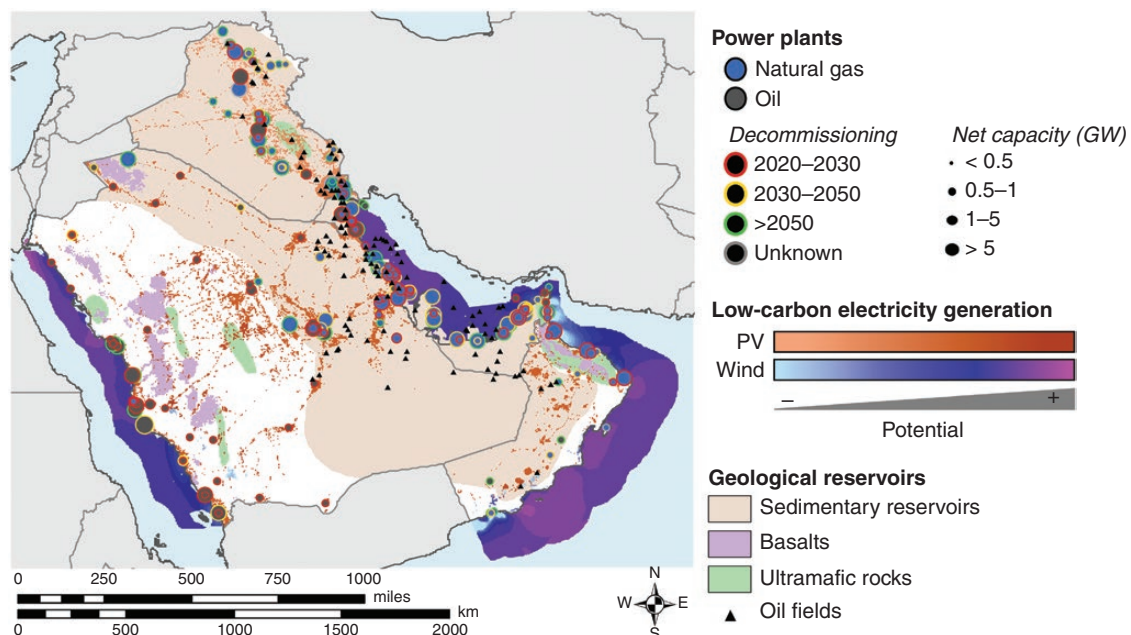


Fig. 6: Current stage of the oil and natural-gas power plants in the AGC and options for low carbon emissions, either by switching to low-carbon energy or by implementing point-source carbon capture and storage [39, 47–49, 51–55, 61]



oil power plants. They are supplied by the east-west crude-oil pipeline that crosses Saudi Arabia. The pipeline connects the city of Abqaiq to the city of Yanbu with 4.8 million barrels per day. The pipeline has a length of 1260 km and a diameter of 122 cm [76]. The lack of sedimentary basins and the many oil power plants on the west coast mean that only 20% of the net capacity of oil power plants retiring between 2030 and 2060 is closely located to sedimentary basins, as opposed to 78% of the net capacity for natural-gas power plants. The west coast may have suitable basins for CO<sub>2</sub> storage that were not assessed by Pitman *et al.* in 2012 [51, 72] and that were not taken into account in the present study. This discrepancy shows the need for local detailed studies of the subsurface to determine what locations are suitable for CO<sub>2</sub> injection. This knowledge might already exist, as the Arabian Peninsula has been explored by oil and gas companies for decades (Fig. 1). Oil companies are potential buyers of captured CO<sub>2</sub> for usage at CO<sub>2</sub>-EOR operations. As the sedimentary basin deepens towards the north-east side of the Arabian Peninsula, more oil fields are located in this area and are thus well co-located with fossil-fuelled power plants.

CCUS projects already exist or are under development in the UAE and Saudi Arabia [75]. The Uthmaniyah CO<sub>2</sub>-EOR demonstration project started in 2015 and is the first project in the region. About 0.8 MtCO<sub>2</sub>/yr from the Hawiyah NGL recovery plant is compressed and dehydrated, before being sent through a pipeline for CO<sub>2</sub>-EOR. The SABIC CCU Project captures ~0.5 MtCO<sub>2</sub>/yr from an ethylene glycol plant. Then CO<sub>2</sub> is compressed and purified before being sent via a pipeline to a chemical plant producing enhanced methanol chemicals and urea fertilizers. The first phase of the Abu Dhabi CCS project started in November 2016 and has captured ~0.8 MtCO<sub>2</sub>/yr from an iron and steel plant that uses the direct reduced iron process from which CO<sub>2</sub> is a by-product. The CO<sub>2</sub> is then transported via a pipeline for EOR at oil fields owned by the Abu Dhabi National Oil Company. The second phase of the project is planned to start in 2025 and aims to capture 1.9–2.3 MtCO<sub>2</sub>/yr from a gas processing plant and use the captured CO<sub>2</sub> for EOR in the same field as phase 1 of the project [75].

As current CCUS projects in the AGC indicate, the most economical way of implementing CCUS today, on power plants or industrial streams, seems to be the association of point-source carbon capture with the utilization of CO<sub>2</sub> for various industrial purposes. One of the potentially biggest consumers of CO<sub>2</sub> is the oil industry that needs it for EOR processes. Tsai *et al.* [70] argue that CO<sub>2</sub> capture at a steel plant and the use of that CO<sub>2</sub> for EOR is one of the most economical routes. A case study explores different scenarios for CCUS implementation at Qatari power plants with utilization for EOR [71]. Under optimization scenarios allowing for domestic CO<sub>2</sub> credit trading, the cost of reaching a CO<sub>2</sub>-emission cap value of 70% of the annual emissions of each power plant totals ~\$145M/yr [71].

A common explanation for the slow deployment of CCUS is the capital cost for building the infrastructure. In Saudi Arabia, stakeholders expressed the need for government subsidies for the first large-scale demonstration projects, due to the high capital cost of CCUS and the technical uncertainties. They show a similar level of support for incentivizing CCUS at the same level as renewable energies and the perspective of revenues generated by additional oil production favours the use of captured CO<sub>2</sub> for EOR rather than dedicated storage [72]. EOR uses CO<sub>2</sub> to extract more oil from partially depleted oil reservoirs. Using CO<sub>2</sub> for EOR results in the extraction of oil and the release of CO<sub>2</sub> into the atmosphere when the combustion takes place. This is thus less efficient than dedicated storage for carbon-dioxide removal. In a decarbonized economy, the wells used for CO<sub>2</sub>-EOR could be repurposed for dedicated storage in depleted oil reservoirs.

#### 2.4 Scenario D3: siting considerations for DAC with carbon storage

The two scenarios described above for the decarbonization of the power sector propose to either replace retiring power plants with low-carbon sources of energy or to implement point-source capture on the major exhaust streams. This last option could also be relevant for large industries that have exhaust streams with high CO<sub>2</sub> concentrations. Low-volume and dilute streams in the power, industrial and transportation sectors that cannot be replaced by a low-carbon energy option are unlikely to be retrofitted by point-source carbon capture. The most economical way to capture these dilute and spread-out emissions today might be through DAC. DAC is more energy-intensive than point-source capture as the air is much more dilute in CO<sub>2</sub> (0.04%) than in combustion or process streams, typically ranging from a few percent to 100%. However, coupled with reliable geological sequestration, DAC has the potential to offset the emissions that are otherwise difficult to capture. If deployed at a 100-MtCO<sub>2</sub>/yr to a 1-GtCO<sub>2</sub>/yr scale, depending on the extent of deployment of the other deep decarbonization options, DACCS could even lead to carbon neutrality or negative emissions in the AGC.

The current DAC technologies require 80% thermal energy and 20% electrical energy [28, 29]. Other types of DAC under development today would only require an electrical energy input [77] and would thus be more geographically versatile. The literature shows that generating 100% of renewable energy to meet the energy needs is technically feasible and cost-competitive in the Middle-East and North Africa regions [59]. The AGC are thus likely to have additional renewable-energy capacity to power DAC plants. As the AGC have very high-quality solar resources, the thermal requirements could be met with CSP and the electric requirements with solar PV, and to a lesser extent onshore and offshore wind. CSP is a technology under development and is designed to create electricity from solar

heat. In our case, the heat would be used directly for the regeneration of the capture agent of the DAC plant.

The classic CSP plant design features two tanks of molten salts and concentric arrays of mirrors directed to the top of a tower where the solar radiation is focused. The molten salt from the cooler tank is circulated to the top of the tower where it is heated up. The hot molten salt is circulated downwards to the hot tank and then used to create steam that would generate electricity via a steam turbine. The molten salt is then circulated back to the cooler storage tank for a new cycle. In order to minimize the energy losses in the pipes, a new design that requires a single storage tank for the molten salt and no tower has been recently successfully tested with a 25-kW demonstrative prototype in the UAE [78, 79]. The Concentrated Solar Power on Demand (CSPonD) consists of a concentrated solar-power receiver that also acts as a thermal-energy storage tank. The hot salts are in the upper part of the tank and separated from the cold salts by an insulated divider plate. The divider plate moves down during the day and allows the cold salts to move in the upper part to be heated. To produce electricity, the hot molten salt is circulated through a heat exchanger that creates steam and then stored back in the cold section of the tank. During the night, the divider plate moves up to have a constant flow of hot molten salt and a steady production of electricity [78, 79].

The modular design of the sorbent-based DAC technology makes it possible to site DAC plants theoretically anywhere. In that context, the location of DACCS systems depends on the opportunities for low-carbon energy generation and on the proximity to CO<sub>2</sub>-sequestration sites. Opportunities for DACCS using solar and wind as

low-carbon sources of energy are shown in Fig. 7. These opportunities are restricted to converted lands, in order to minimize competition with other human interests (food production, human settlements) and to avoid further disrupting natural ecosystems, and also only locations within 100 km from sedimentary reservoirs as well as opportunities strictly co-located with basalts and ultramafic rocks, in order to outline opportunities with short transportation distances.

Given the advantages of the region and the technological readiness of the components of the system, one of the most suitable DACCS systems combines thermal energy from CSP; electrical energy from CSP, PV or wind; a sorbent-based DAC plant; and CO<sub>2</sub> sequestration in sedimentary reservoirs. When CSP is not available, opportunities for electrical DACCS are shown. In these locations, the heat could be supplied by heat pumps running on low-carbon generated electricity (PV and, to a lesser extent, wind) or, when the technology is ready, these are sites for electro-swing DAC implementation [77]. Alternative options for CO<sub>2</sub> sequestration in basalts and ultramafic rocks are also shown in Fig. 7. CO<sub>2</sub> sequestration in these rocks still needs to be developed on a commercial scale, but could present interesting storage options in particular in Oman and on the west coast of Saudi Arabia.

The AGC present large opportunities for heat and electricity generation from solar energy and have considerable resources for CO<sub>2</sub> sequestration. This makes the region a very good candidate for DACCS implementation, which could turn from a net source of anthropogenic CO<sub>2</sub> to a net sink of atmospheric CO<sub>2</sub>. DACCS is still a costly system today and its implementation now depends on factors other than technological readiness, such as local and

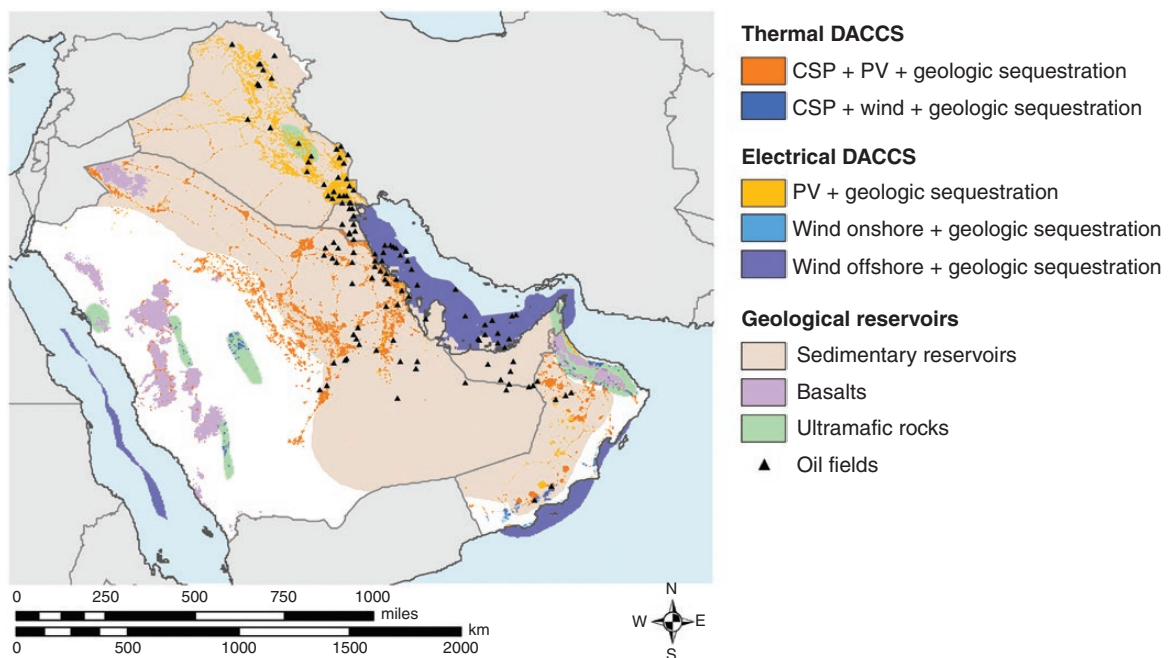


Fig. 7: Opportunities for DACCS implementation in the AGC. Note that any opportunity of CSP is also valid for PV only [22].

**Table 1:** Comparison of the countries' visions to increase the share of renewable energy (RE) in their grid mix in the next decades and the potential for RE by replacing retiring fossil-fuelled power plants by RE sources [5, 16, 17, 21, 39, 59, 80–82]

Country	Energy source installed in 2019		Countries' visions			Net capacity retiring at target year (GW)		Existing RE + scenario D1
	Total net capacity (GW)	RE share (%)	Year	Expected total net capacity at target year <sup>a</sup> (GW)	RE target according to the countries' visions	NG power plants	Oil power plants	
Bahrain	8.8	0.1%	2025	10.0	255 MW (~5%)	1.1	–	11.4%
			2035	11.3	710 MW (~10%)	1.1	–	10.0%
Iraq	34.8	7.3%	2030	43.7	10%	3.8	4.2	25.8%
Kuwait	19.8	0.5%	2030	22.3	15%	0.9	5.9	30.8%
Oman	10.6	0.1%	2030	12.7	20%	10.3	0.1	51.6%
			2040	13.8	39%			75.4%
Qatar	14.5	0.03%	2030	17.0	500 MW (~4%)	0.3	0.0	2.0%
Saudi Arabia	85.6	0.5%	2030	98.2	9.5 GW (~10%)	9.2	13.3	23.3%
UAE	35.5	5.3%	2021	36.3	27%	2.7	<0.1	12.8% <sup>b</sup>
			2050	37.8	50%	32.1	<0.1	90.2% <sup>b</sup>

<sup>a</sup>Electricity-generation evolution calculated using the same trend as the population growth of each country.

<sup>b</sup>Nuclear adds 6% of low-carbon energy since summer 2020 [80, 83].

international regulations, government incentives, stakeholders' decisions and public acceptance.

## 2.5 The countries' visions

Most of the AGC have a share of renewable energy that is <1% of the grid except for Iraq (7% hydroelectric) and the UAE (5% solar PV) [39]. All of the countries are reliant on fossil fuels (natural gas and oil) as their primary source of energy, but developed visions for a more sustainable future [16, 17, 21, 59, 80–82]. Most of these objectives are focused on the next decade and aim to increase the share of solar and wind energy in the grid mix [59]. This strategy is similar to scenario D1 described above that estimates the potential of CO<sub>2</sub>-emission reduction when replacing the net capacity of retiring fossil-fuelled power plants by renewable energy sources. Table 1 provides the amount of renewable energy installed in 2019 and compares the objectives of the countries with scenario D1. It shows that if the countries are not building new fossil-fuelled power plants, except for those that are already under construction, some of the targets might be challenging in the proposed time frame (i.e. the very short-term goal of reaching 27% clean energy by 2021 in the UAE from 5.3% clean energy installed in 2019), the majority of them seem realistic under scenario D1, and most of the countries could be more ambitious.

Natural gas and oil, the traditional resources of the region, are still expected to play a major role in the years to come with projects under construction and under development totalling to 69.2 and 25.9 GW for natural gas and oil, respectively. However, the AGC are well positioned for high-quality solar PV resources with already 2.4 GW installed principally in the UAE and Saudi Arabia, 2.6 GW under construction mostly in the UAE and Oman, and 20.7

GW distributed in all the countries. The countries plan to diversify their energy sources adding other fossil-fuel resources like coal (8.1 GW) and other low-carbon resources like nuclear (6.8 GW), wind (2.4 GW), biomass (0.6 GW) and hydro (0.3 GW) to their grid mix [39].

The total CO<sub>2</sub> emissions from the AGC are expected to rise from 1333 MtCO<sub>2</sub> in 2018 to 1568 MtCO<sub>2</sub> by 2030 under a BAU scenario. Applying the country's visions on the power sector only has the potential to decrease the total emissions of the AGC by 46.3 MtCO<sub>2</sub> in 2030, mostly by developing solar energy (as proposed under scenario D1 with a more aggressive timeline). Some projects to capture CO<sub>2</sub> at industrial facilities are operating or under consideration today, and that effort is key to developing carbon capture on a large scale. The AGC have seen their net capacity double from 2000 to 2010 and multiplied by 1.5 from 2010 to 2019, and thus they operate today with a young fleet of fossil-fuelled power plants. More than 50% of natural-gas power plants and ~40% of oil power plants are expected to retire after 2050. These power plants are particularly pertinent for point-source-capture implementation (as proposed under scenario D2), in particular if they are also located in the vicinity of suitable CO<sub>2</sub>-injection sites. In addition to the current goals, countries could be even more ambitious by setting up goals related to point-source capture (scenario D2) and/or DAC (scenario D3), which is necessary to reach carbon neutrality.

## 3 Conclusion

The AGC have demonstrated willingness to reduce their carbon emissions by publishing short-term goals and by developing CCUS projects. Iraq has the largest share of renewable energy (mostly hydropower), despite currently struggling to meet the energy demands of its population.



The region's economy depends on the extraction and exportation of fossil fuels, but the AGC are also vulnerable to climate change. The region is susceptible to many climate-related changes that threaten the health of the population and environment: temperature increase, air-pollution worsening and sea-level rise.

The current AGC GHG emissions were ~1333 MtCO<sub>2</sub>/yr in 2018, which are expected to rise to 1568 MtCO<sub>2</sub>/yr in 2030 in a BAU scenario. This increase could be limited to 1522 MtCO<sub>2</sub>/yr if the countries achieve their visions. This study analyses three scenarios to decarbonize the region's power sector in the region. The retirement of the oldest natural-gas and oil power plants (scenario D1) reduces total emissions by ~75 MtCO<sub>2</sub>/yr, without accounting for the embedded carbon emissions of the renewable energy source. If the AGC implements point-source capture at power plants that are expected to retire in >10 years' time (scenario D2), the countries will avoid ~240 MtCO<sub>2</sub>/yr provided that the CO<sub>2</sub> is permanently sequestered in appropriate geological formations. Roughly 180 MtCO<sub>2</sub>/yr of these emissions are located within 100 km of a potential sedimentary storage. The region also shows high-quality solar resources that are currently under development and could be coupled to DAC plants and geological storage in order to offset the difficult-to-avoid emissions (scenario D3).

The published data regarding the energy sector in the AGC are limited [57] and most of them are published by a third party and not the energy sectors themselves. More quantitative and granular data need to be collected by official entities and published by the energy sector, including oil and gas reservoirs, the power sector and the industrial sector. Increased transparency would help in understanding the current state of the greenhouse-gas emissions and plan for future decarbonization projects. It would also increase the public awareness on the energy transition towards a decarbonized economy for facilitating the deployment of future projects. Although currently a major exporter of fossil fuels and net emitter of CO<sub>2</sub>, the AGC can use their large CO<sub>2</sub>-storage resources, and a potentially decarbonized economy to become importers of CO<sub>2</sub> with a net negative carbon footprint.

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## Supplementary data

Supplementary data is available at *Clean Energy* online.

## Conflict of Interest

None declared.

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