IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 2, 2021, accepted August 13, 2021, date of publication August 17, 2021, date of current version August 26, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3105378

Electricity Generation in Saudi Arabia: Tracing Opportunities and Challenges to Reducing Greenhouse Gas Emissions

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This work was supported by the Deanship of Scientific Research (DSR) at King Fahd University of Petroleum & Minerals (KFUPM) under Project DF201005.

ABSTRACT The electrical energy demand of the Kingdom of Saudi Arabia (KSA) has been observing a surging growth due to high population growth and urbanization rate. The generation mostly comes from the burning of petroleum products. The electricity sector emits more than one-third of the national greenhouse gas (GHG) of the country. Thus, it is essential to reduce the GHG from the electricity generation sector to maintain sustainability. This article mainly concentrates on the existing electricity generation and focuses on the Kingdom's GHG emissions mitigation initiatives. Although the use of natural gas and the number of cogeneration plants have been increased in electricity generation, the country has also been focusing on other initiatives, including the adaptation of combined cycle power plants, carbon capture, utilization, and sequestration (CCUS), renewable and alternative energy sources, and various utility-scale energy efficiency measures. The ambitious and inspirational renewable energy (RE) targets of the *Saudi Vision 2030* will significantly facilitate GHG emission avoidance, which will support the Kingdom to meet its Nationally Determined Contributions. This article recommends various mitigation measures, including the usage of the efficient internal combustion engine, poly-generation, combined heat and power (CHP) systems, deployment of renewable resources in the distribution and microgrid systems, bio-mass engine, and ocean thermal energy conversion plants. The decision-makers and the researchers will find the discussions and recommendations helpful in determining suitable and appropriate mitigation initiatives and technologies.

INDEX TERMS Carbon capture, climate change mitigation, electricity generation, greenhouse gas emissions, Kingdom of Saudi Arabia, renewable energy, review.

I. INTRODUCTION

One of the grand challenges of the planet earth is the assurance of affordable, reliable, and sustainable energy supply to everyone considering the population and industrial growth, global warming and climate change, fossil fuel reserve, and energy security issues. In this regard, the electricity networks of the individual countries are the most reliable mediums for energy supply. Due to reliability and ease of transportation, the world has been observing a surging growth trend of

The associate editor coordinating the review of this manuscript and approving it for publication was Zhiyi Li.

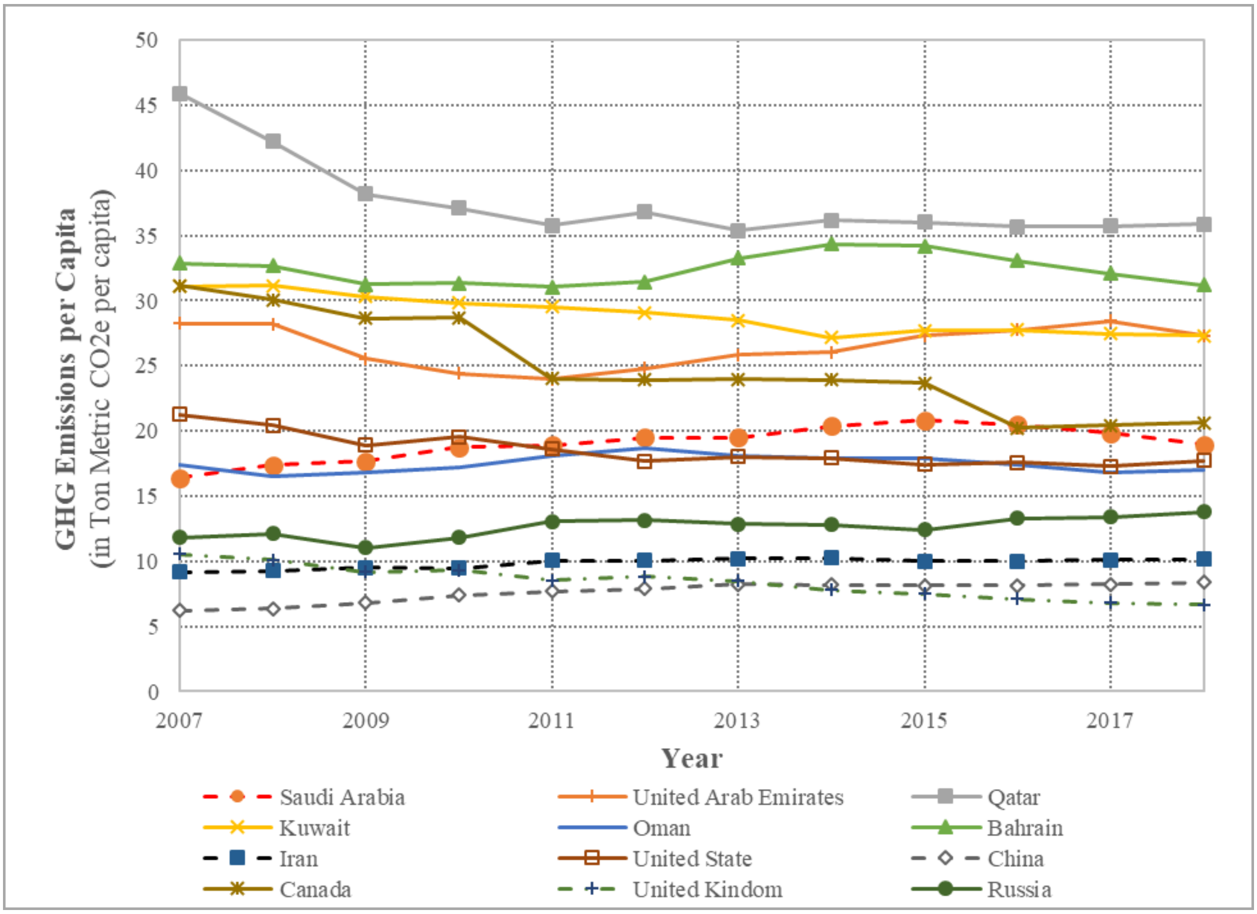

FIGURE 1. Greenhouse gas emissions per capita of different countries [12].

different energy resources integration into such networks. From 1990 to 2019, world total electricity production rose from 11.88 trillion kilowatt-hours (kWh) to 26.91 trillion kWh with an overall growth rate of 126.5% [1]. This increasing generation trend accounts for a large proportion of global GHG emissions, where almost two-thirds of the generation comes from fossil fuel-based power plants. The remaining one-third of electricity is produced from low-carbon sources such as renewable and nuclear energy resources [2]–[6]. Therefore, electricity generation is one of the key players in implementing the GHG mitigation strategies as the burning of fossil fuels in the power plants releases an immense amount of carbon dioxide (CO_2) and other GHG into the atmosphere.

Saudi Arabia is one of the leading CO_2 emitters where the major emissions sectors are the industry, electricity, road transportation, heat, household, service, and agriculture [7], [8]. It is one of the top-ranked electrical energy-consuming countries globally. It has been observing the increasing trends of electrical energy demand for the last couple of decades due to massive industrialization, population growth, and rise in living standards [9]–[11]. Figure 1 and Figure 2 show the per capita GHG emissions and electrical energy consumption of the Gulf Cooperation Council (GCC) countries, along with other countries from 2007 to 2018 [12], [13]. As can be seen, Saudi Arabia is neither the top GHG emitting country nor the top-most electricity-consuming one amongst the GCC countries. However, per capita GHG emissions and electrical energy consumption of the country are much higher than many countries. The current per capita electrical energy consumption of the country is almost three-fold compared to the world average [14]. Figure 3 illustrates the population and gross domestic product (GDP) growths and per capita energy consumption and CO_2 emissions of the country for the last thirteen years [15]–[19]. The population has risen from 25.18 million in 2007 to 34.27 million people in 2019 [15]. The GDP has risen approximately 45.637% from 2007 to 2019 [18]. In 2019, the country consumed 8.4 MWh per capita electrical energy, whereas the number was 7.022 MWh in 2007 [20]. Consequently, the CO_2 emissions have been increased from 394.68 million tons in 2007 to 559.6 million tons in 2019 [17].

A good number of studies investigated electricity production and GHG emission mitigation techniques focusing on the electricity generation sector for various countries [21]–[27]. Considering the KSA perspective, a few relevant studies

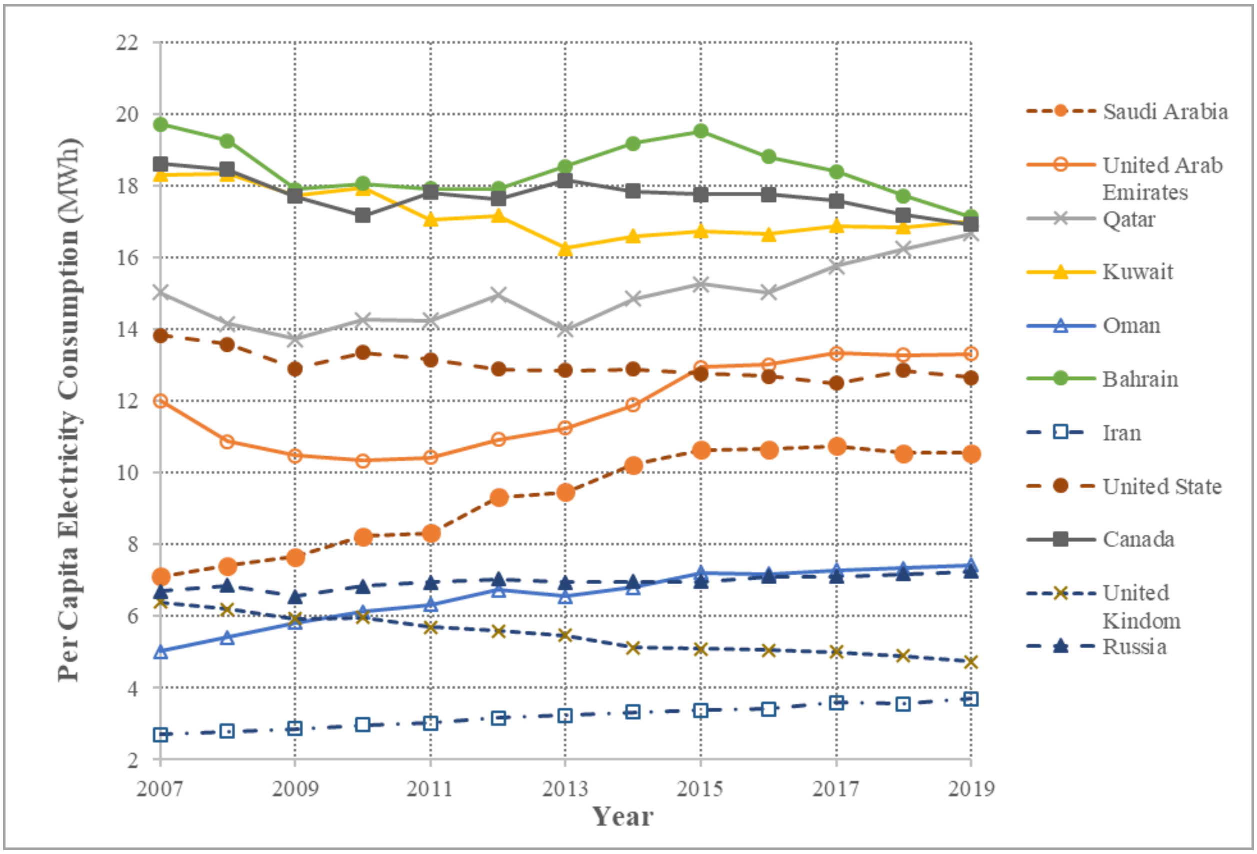

FIGURE 2. Energy (electricity) consumption per capita of different countries [13].

investigated GHG emissions reduction strategies from different sectors [28]–[30]. For instance, Samargandi [28] investigated the complex effect of economic growth and assessed whether technological innovation reduced CO_2 emissions by encouraging different energy efficiency measures. Ref. [29] provided an overview of the Saudi strategies related to GHG reduction and Carbon Capture and Storage (CCS).

Rahman *et al.* [30] analyzed the energy consumptions and GHG emissions in the road transportation sector. They also discussed potential mitigation initiatives for emission reduction. However, no significant effort was noticed in the existing literature that discussed the GHG emission reduction and mitigation initiatives in the electricity generation sector of Saudi Arabia. To reduce the GHG emissions from the sector, the country has taken several initiatives, including CCUS, replacing traditional single-cycle power plants with combined cycle and cogeneration power plants [31], [32]. In addition, the *Saudi Vision 2030* planned to install 58.7 gigawatts (GW) of renewable energy resources, mainly in the form of electricity [33]. However, a few more initiatives can be taken in the electricity sector for GHG reduction, such as the development of poly-generation, CHP, microgrids, waste to energy, and biomass plants [34]–[36]. The mentioned notes motivate the authors to critically review and analyze taken initiatives for GHG emissions reduction from electricity generation in Saudi Arabia. To make effective decisions on GHG emission reduction and mitigation initiatives, this study (i) discusses the electricity generation dynamics, (ii) investigates the taken GHG emission mitigation strategies and initiatives along with the challenges, and (iii) recommends promising strategies for GHG reduction from the electricity generation sector.

The rest of the paper is organized as follows: Section II presents the GHG emission and electricity generation dynamics of the country. Major GHG mitigation technologies and initiatives taken by the country are elaborated in Section III. The fourth section summarizes GHG emissions and avoidance. The fifth section briefly discusses the challenges associated with the GHG emissions mitigation initiatives. Section VI summarizes the key observations and recommendations for effective mitigation of GHG emissions from the electricity generation sector in Saudi Arabia. Finally, the concluding remarks of the article are presented in Section VII.

II. GHG EMISSION AND ELECTRICITY GENERATION DYNAMICS OF SAUDI ARABIA

This section briefly presents the GHG emission and electricity generation dynamics of Saudi Arabia.

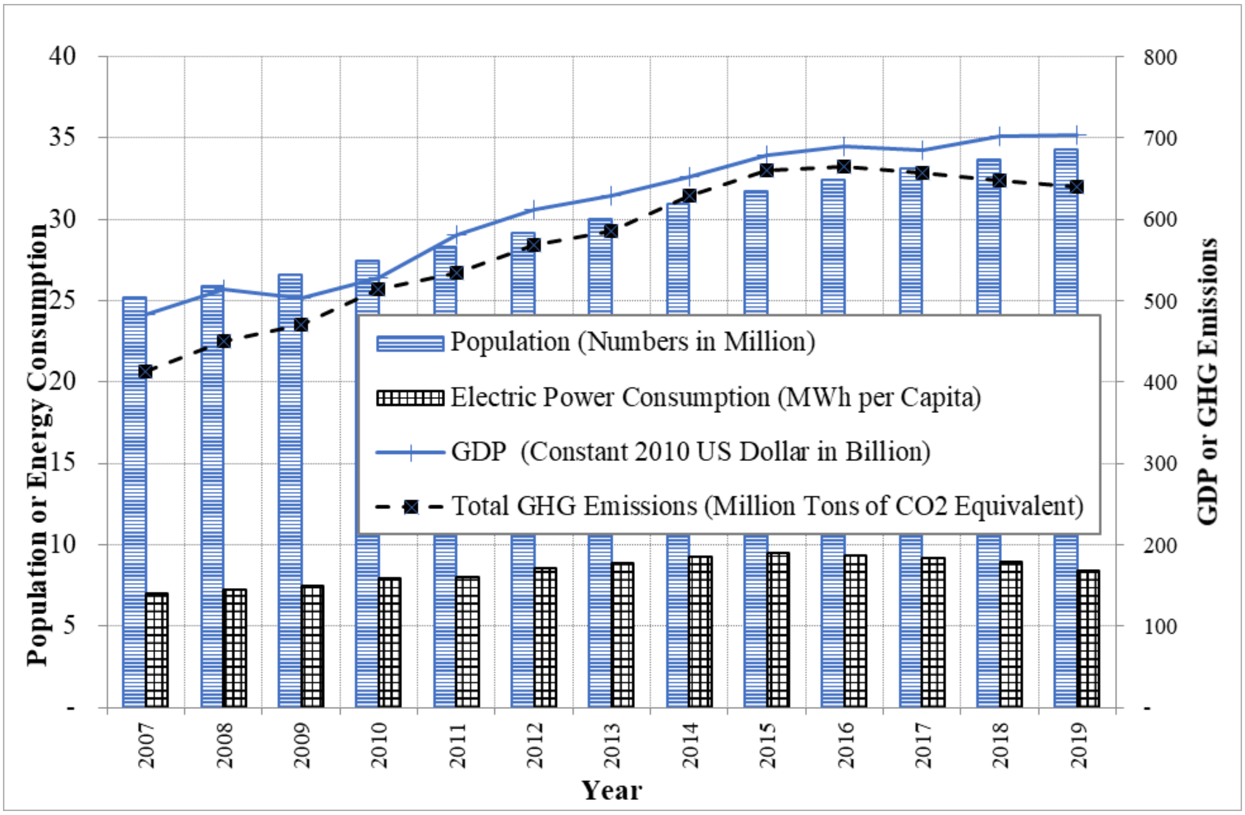

FIGURE 3. Population, energy consumption, GDP, and CO2 emissions of Saudi Arabia from 2007 to 2019 [15]–[19].

A. GHG EMISSION DYNAMICS

The KSA was listed as one of the leading CO_2 emitters and was responsible for around 1.8% of the global emissions in 2017 [7]. The annual CO_2 emission of the country was reported to be 559.6 million tons in 2019, which is a sharp increase from 394.68 million tons recorded in 2007, as presented in Figure 4 [17].

The CO_2 emission has been increased almost 11% within the last ten years. A similar scenario has been observed for CH_4 and NO_x emissions as well. CH_4 emission has increased from 41.88 million tons of CO_2 equivalents (CO_2e) in 2007 to 44.97 million tons CO_2e in 2019. The total CO_2 emissions from the electricity sector are the most significant contributor to total GHG emissions in the country that has been increased by 22% from 2012 to 2017 due to steady growth in almost every sector. The major sectors of CO_2 emissions were industries (38%), electricity, heat, and others (38%), road transport (23%), and household, service, and agriculture (1%) in 2017 [8]. The previous statistics show that electricity generation is one of the significant CO_2 and CH_4 emission sectors in Saudi Arabia. Thus, the country has been working to reduce GHG emissions by phasing out fossil fuel subsidies in line with Saudi Vision 2030. It has already announced to mitigate its yearly emissions up to 130 metric tons of carbon dioxide by 2030 [37].

B. ELECTRICITY GENERATION DYNAMICS

The Saudi Electricity Company (SEC) is the leading entity for generation, transmission, and distribution of electricity in the Kingdom. Over the past decade, electricity consumption has been rising about 7% to 8% annually, driven by population growth, rapid industrialization driven by petrochemical city development, higher air conditioning demand in the summer months, and low electricity tariffs. Between 2010 and 2019, summer peak demand rose 36% from 45.66 GW to 62.08 GW. The generation jumped from 190.54 terawatts per hour (TW/h) in 2007 to 342.62 TW/h in 2019, reflecting an overall 80% growth. The Kingdom's total electricity production capacity includes the generation accessible from the water desalination plants and SEC's power plants operated by significant consumer companies, such as Saudi Aramco and Saudi Basic Industries Corporation. Figure 5 shows the electricity production by different entities. From 2007 to 2019, the actual generating capacity of the SEC reached 193.02 terawatt-hours (TWh) from 165.32 TWh. On the other hand, the generation capacity available from the Saline Water Conversion Corporation (SWCC) and major subscribers decreased the electricity generation from 20.85 TWh in 2007 to 7.88 TWh in 2019. On the contrary, electricity demand in the residential sector is the highest and responsible for 45.82% of total electricity consumption, with the

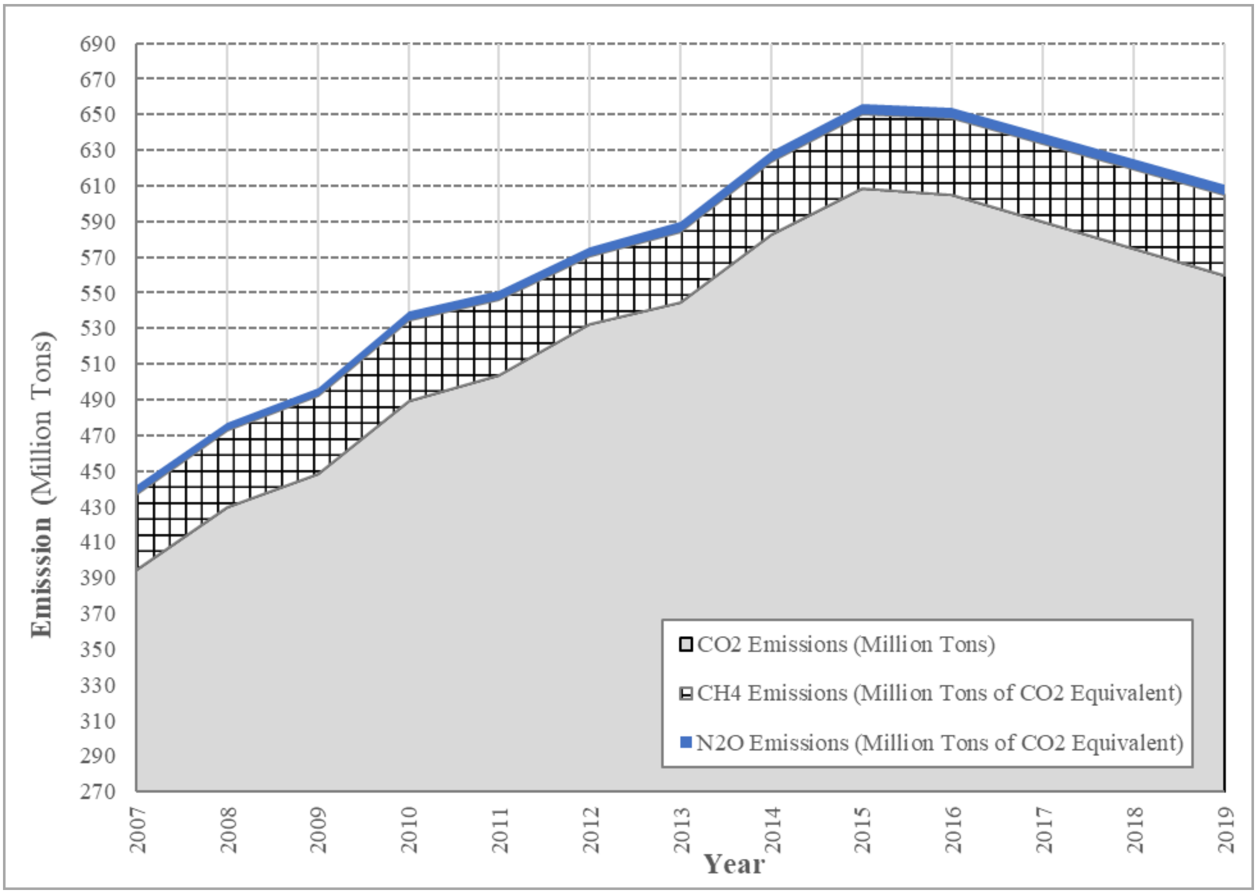

FIGURE 4. GHG emissions from the energy sector of Saudi Arabia [17].

remainder divided between the industrial, the commercial industry, and government agencies (17.68%, 16.74%, and 16.69%, respectively) in 2019 as depicted in Figure 6 [38].

III. GHG MITIGATION TECHNOLOGIES AND INITIATIVES

The quantity of CO_2 emitted by a fossil fuel power plant depends mainly on the used fuel type, plant size, and installed technology type. For example, using an intergovernmental panel on climate change default emission factors, a 500 megawatt (MW) lignite-fired power plant with an efficiency of 40% produces approximately 455 tons of CO_2 per hour. Simultaneously, bituminous coal generates 426 tons of CO_2 per hour by burning with the same capacity and efficiency [41]. Besides, natural gas, diesel, and coal-based power plants produce 0.566 kg, 0.76 kg, and 0.90 kg of CO_2 per kWh, respectively [42]. This section illustrates different initiatives taken to reduce and mitigate GHG emissions in the Kingdom of Saudi Arabia.

A. ADOPTION OF GENERATION TECHNOLOGIES

The heat from the plant exhaust stream is collected and converted into usable thermal energy by cogeneration or CHP system, poly-generation, and combined cycle power plants. The advantages of combined cycle and cogeneration techniques are the consumption of less fuel for electricity generation. In addition, such technologies improve energy production and reduce the energy intensity of power plants. Thus, they add value to hydrocarbon supply and protect the environment by reducing greenhouse gas emissions. Therefore, Saudi Arabia adopted the following technologies for the reduction of GHG emissions.

1) COMBINED CYCLE POWER PLANT

Combined cycle technology is a leading approach to increasing performance and dramatically reducing pollution and waste per unit of electricity production. The combined-cycle power plant is the perfect conventional plant in terms of performance and environmental effect. The SEC has increased combined cycle-based electricity production from 8.3% in 2010 to 31.0% in 2019, while the use of the single-cycle dropped from 50% in 2010 to 22% in 2019. As a result, there were 59,258 MWh of clean energy derived from the combined cycle. The company is now executing projects to increase the combined-cycle-based generation capacity by more than 4.2 GW in the Al-Qassim, Duba, Waad Al-Shamal, Taibah, Hail, Northern Al-Qassim, and Power Plants 13 and 14 power generation projects. Among its power plants, the Waad Al-Shamal, a combined cycled

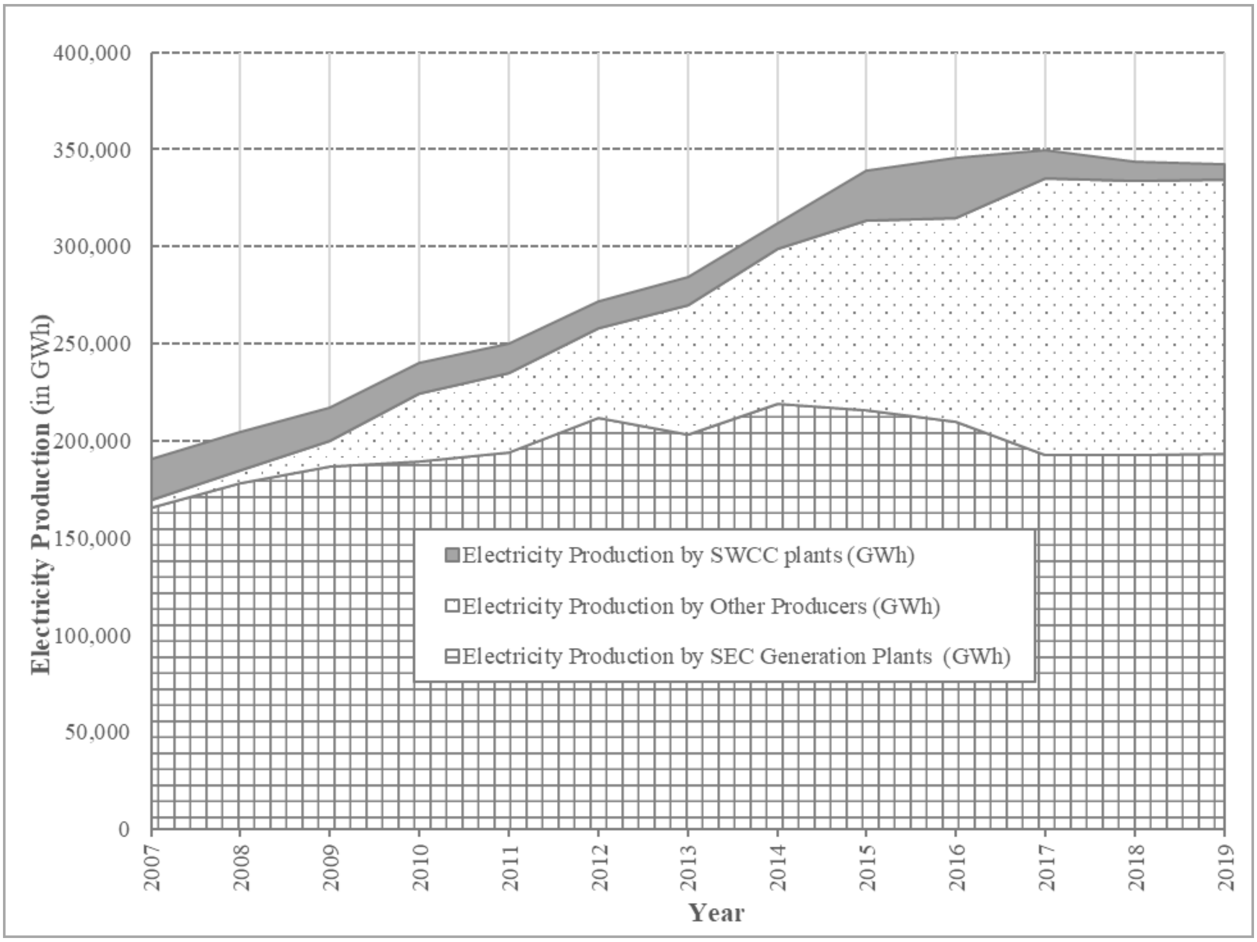

FIGURE 5. Electricity production in Saudi Arabia [39].

power plant of the SEC with a capacity of 1,390 MW, started its operation in 2018. These ventures will save approximately 60 million barrels of oil a year and decrease carbon dioxide emissions by about 25.8 million tons a year. Besides, the Rabigh 2 independent power production project is considered a milestone in the Kingdom's electricity sector due to be the first combined-cycle technology project for electricity generation with a total thermal efficiency of 58.8%. The capacity of the project is 2,060 MW [31].

2) COGENERATION

Cogeneration is the production of heat and electricity from the same source simultaneously. Compared to traditional power plants, cogeneration offers greater efficiency, resulting in a substantial decrease in fuel usage. Recent research on cogeneration has concentrated on new designs of fossil fuel cogeneration plants as an energy source [43]. The current traditional gas turbine cogeneration plant in Ras-Tanura, Saudi Arabia, will investigate the possibility of integrating various concentrated solar power technologies with gas turbine cogeneration plants. The plant can generate 150 MWe of electricity and thermal content to produce a steam flow rate of 81.44 kg/s at 45.88 bars and 394 °C [44]. In 2006, Tihama Uthmaniya and Tihama Shedqum Cogeneration Gas Turbine Power Plants were installed with a design capacity of 305 MWe each. Saudi Aramco has added 1.318 MW of additional power capacity to facilities by implementation a range of cogeneration projects, including the expansion of capabilities at Wasit and Shaybah plants. The Fadhili Plant Cogeneration Company located in the Eastern region of the KSA provides 1,520 MW of electricity via an effective cogeneration scheme [32].

B. RENEWABLE AND ALTERNATIVE SOURCES FOR ELECTRICITY GENERATION

Low-carbon and low-cost renewable and sustainable energy resources are expected to dominate future energy generation. According to Energy Information Administration (EIA) projection, nearly half of world electricity will be produced from renewable energy resources by 2050 [45]. More than 170 cities in the United States of America (USA) [46] and more than 80 cities in Europe [47] have already been committed to power their communities with 100% clean and renewable energy by 2050. In line with the global trends,

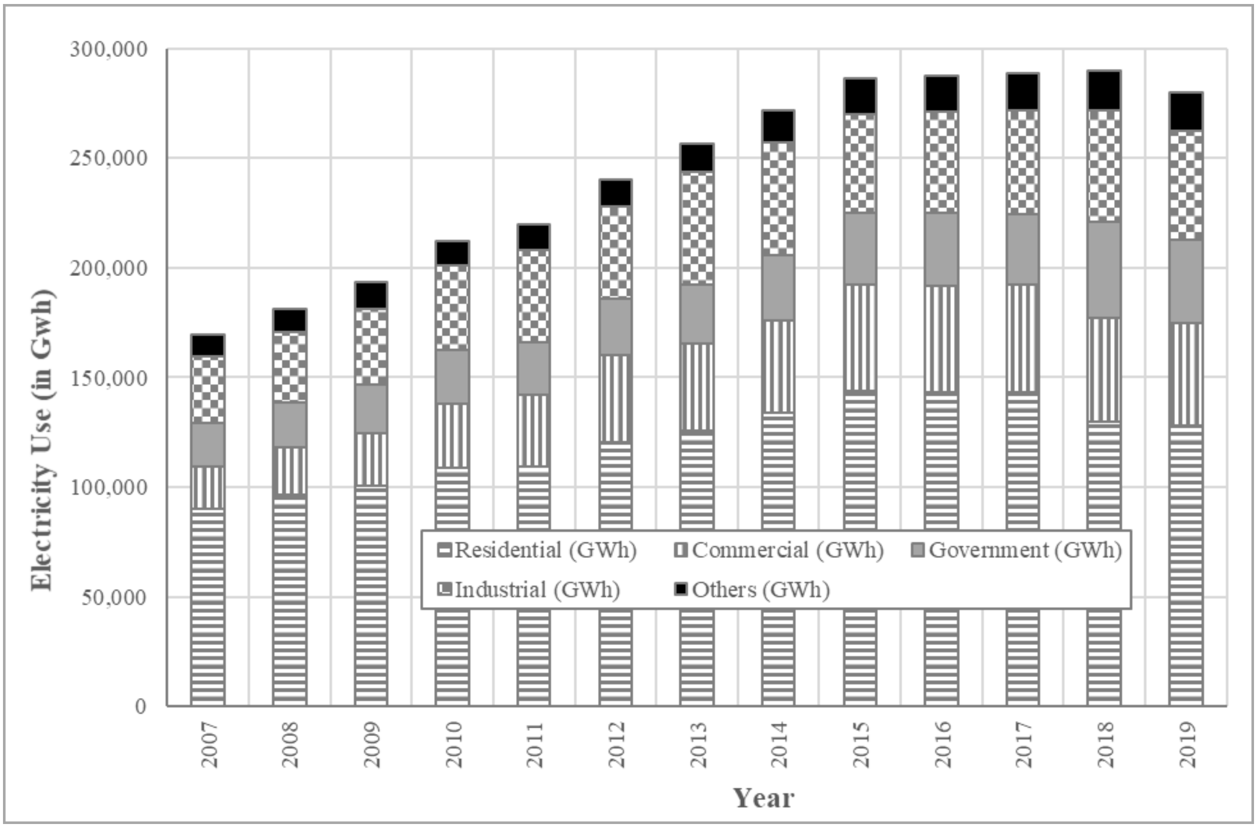

FIGURE 6. Electricity consumptions in Saudi Arabia [40].

Saudi Vision 2030 sets the ambitious goal for generating 58.7 GW of power from renewable energy resources. As a midterm goal, the country planned to build 27.3 GW renewable energy generation by 2023 [48]. Besides, KSA planned to build high-ambitious 100% renewable energy-powered NEOM and Red Sea projects [49], [50]. The location of planned renewable projects across the country has already been identified as listed in Table 1 [51]. Most of the planned renewables will be generated as electricity through the deployment of various technologies such as photovoltaic (PV), concentrated solar power (CSP), and wind power as they seem to be more suited for the weather and geographical conditions of the Kingdom. Concisely, the country is heading towards developing and implementing sustainable energy policies, diversifying the electricity generation mix, upgrading the electricity grid, implementing smart grid technology and electricity market, and linking national and regional electricity networks for energy trading. In addition to the planned projects, the renewable energy installed capacity of the country has been increasing gradually as per the recent reports and statistics of different international entities, including the International Renewable Energy Agency (IRENA) and Renewable Energy Policy Network for the 21st Century (REN21) [52]–[55].

TABLE 1. Renewable energy resources projects deployment plan [51].

Type	Locations
Solar PV	Sakaka, Al Masa'a, Madinah, Mahd Al-Dhab, South Yanbu, Mastoorah, Rabigh, South Jeddah, Al-Faisalia, Al-Laith, Dhahban, Haden, Bisha, Tabarjal, Qurayyat, Rafha, Qaisumah, Unaizah, Henakiyah, Dhurma, Tuwaiq, Sudair, Malham, Ghilanah, Al-Haeer, Al-Quwaiiyah, Al-Kharj, Layla, Wadi Al-Dawasir, Farasan, Jazan, Sharorah.
Wind	Dumat Al-Jandal, Waad Al-Shammal, Sourah, Al-Ras, Yanbu, Al-Ghat, Shaqra, Tuwaiq, Duwadimi, Starah, Wadi Al-Dawasir.
CSP	Tabarjal, Tabuk, Al-Kahafa, Khushaybi

Figure 7 shows the gradual development of renewable energy installations from the year 2010 to 2020. The renewable installations were about 2 MW in 2010 and increased slowly until 2017. However, the RE installations have been accelerated significantly from the year 2018 due to the *Saudi Vision 2030*, and it reached about 413 MW of installation capacity in 2020. Besides, several small-scale PV plants were deployed through public-private partnerships across the country. Among different types of available renewable resources, harvesting of solar and wind energies have been observed, and their installation capacities are around 394 MW (∼99% of total installation) and 3 MW (∼ 1% of total installation), respectively in 2019 [52]. Figure 8 shows the RE generations in the country from the year 2010 to 2018 according to the IRENA report [56], [57]. The percentage of electricity share from renewable energy has been raised from 0% in 2009 to 0.5% in 2019. The rapid growth of renewable electricity generation was observed from the year 2018, and the total renewable energy generation was about 219 GWh, where 214 GWh was generated from solar energy and 5 GWh from wind energy [56]. This section briefly discusses the different RE resources potential and planned projects across the country.

1) SOLAR ENERGY

The Kingdom has been assessing the potential of solar energy by setting up 46 weather stations throughout the country for several years as the plan of installation of modern and cost-effective solar power plants to meet the increasing electricity demand and diversify the domestic energy mix. The daily average of direct normal irradiance (DNI), global horizontal irradiance (GHI), and diffuse horizontal irradiance (DHI) are around 6200 Wh/m^2, 5000 Wh/m^2, and 2000 Wh/m^2, respectively. The mentioned indicators (GHI, DNI, and DHI) illustrate the vast potential of solar energy systems (both PV and CSP) all over the Kingdom [58], [59]. In 2017, the Ministry of Energy launched Renewable Energy Project Development Office (REPDO), which works with the energy sector stakeholders to offer unified leadership in RE project tendering and development mainly.

The lion share of the targeted solar power plants (40 GW of PV and 2.7 GW of CSP) will be developed under the supervision of REPDO [48]. During the first phase (Round 1) of the RE project development strategy; REDPO awarded the Sakaka 300 MW PV power plant to ACWA Power Company. The plant has been developed in the northern part of the Kingdom and connected to the national utility grid in 2019 [60]–[62]. REPDO embarked on the second phase (Round 2) of the RE project development and invited expressions of interest for seven additional solar PV Independent Power Producers (IPP) with a potential 1.52GW capacity. The projects include Madinah Solar PV IPP (50 MW), Rafha Solar PV IPP (45 MW), Qurayyat Solar PV IPP (200 MW), Al Faisaliah Solar PV IPP (600 MW), Rabigh Solar PV IPP (300 MW), Jeddah Solar PV IPP (300 MW), and Mahd AlDahab Solar PV IPP (20 MW). In 2020, the REPDO issued the Request for Proposals (RFP) for the third phase (Round 3) in two categories. It consists of four PV solar projects with a total capacity of 1,200 MW. Project sites are in the central area of the Kingdom include (i) Category A projects: Wadi Ad Dawasir 120 MW Solar PV IPP and the Layla 80 MW Solar PV IPP, and (ii) Category B projects: Ar Rass 700 MW Solar PV IPP and Saad 300 MW Solar PV IPP.

The SEC completed the first phase of the Layla Al-Aflaj solar power plant project of 10 MW and the Waad Al-Shamal of CSP 50 MW capacity in 2019 and connected to the utility grid. The project was conducted in collaboration with King Abdulaziz City for Science and Technology (KACST) and Saudi Technology Development and Investment Company (TAQNIA) [63]. In partnership with Saudi Aramco, the company also established a 500-kilowatt (kW) solar power plant in Farasan Island, Jazan, which generates around 860 GWh of energy annually. In addition, five solar-powered systems have been installed in various company buildings that produce about 8,550,000 kWh of energy per year [31].

2) WIND ENERGY

Wind energy is one of the prominent and leading renewable energy resources globally as it produces safe power with less pollution. Though the technology has a few detrimental environmental effects, such as killing birds and technical challenges for grid integration; however, the benefits outweigh the challenges [64]. Therefore, wind power can substantially contribute to fulfilling the Kingdom's energy demand as the country has long coastlines and vast isolated desert areas [65]. The country evaluated the potential of wind energy by constructing ten weather stations across the Kingdom. The average annual wind speed was more than 5 m/s at the height of 40 meters. The nation has even higher wind speeds at 60 meters, 80 meters, 98 meters, and 100 meters. Observations of wind speed from some selected locations also show strong potential for wind energy systems in many parts of the Kingdom [59].

Based on the field investigations, Saudi Arabia aims to become one of the largest wind energy markets in the next five decades [65], [66]. The *Saudi Vision 2030* already planned to generate 16 GW of electricity from the wind turbine [48]. The REPDO, under the Ministry of Energy, sponsored the Dumat Al Jandal 400 MW Project in 2017 to generate electricity [67]. The entity also initiated a few more wind energy projects, including Midyan Wind, a 400 MW onshore power plant in 2017 [62], and Yanbu Wind, an 850 MW plant in 2019 [68]. In addition, Saudi Aramco, with the support of General Electric (GE), installed a 2.75MW of wind power plants in Turaif in 2017 [69]. Furthermore, in collaboration with KACTS and TAQNIA, the SEC commissioned a 2.75 MW of capacity wind turbine in Huraymila in 2019 [63]. Besides, the CG Holdings Belgium NV Systems and Avantha Group Company have concluded a contract to install wind technologies to supply 400 MW of energy in Saudi Arabia [70], [71]. Another wind project is expected to generate roughly 1.4 TWh of average annual energy [71].

3) HYDROPOWER

Hydropower is one of the most significant renewable energy resources globally that generated around 16.8% of the world's total electricity and 37.5% of all renewable electricity in 2020 [72]. As the leading desalination water producing and consuming country globally, Saudi Arabia uses the water of the desalination plants to produce electrical energy. Total water production reached 2,558 million cubic meters in 2019 [73]. The total electricity production from the desalination plants of the licensed companies, including the SWCC, reached 151 TWh in 2017, about 99 TWh in 2012, as depicted

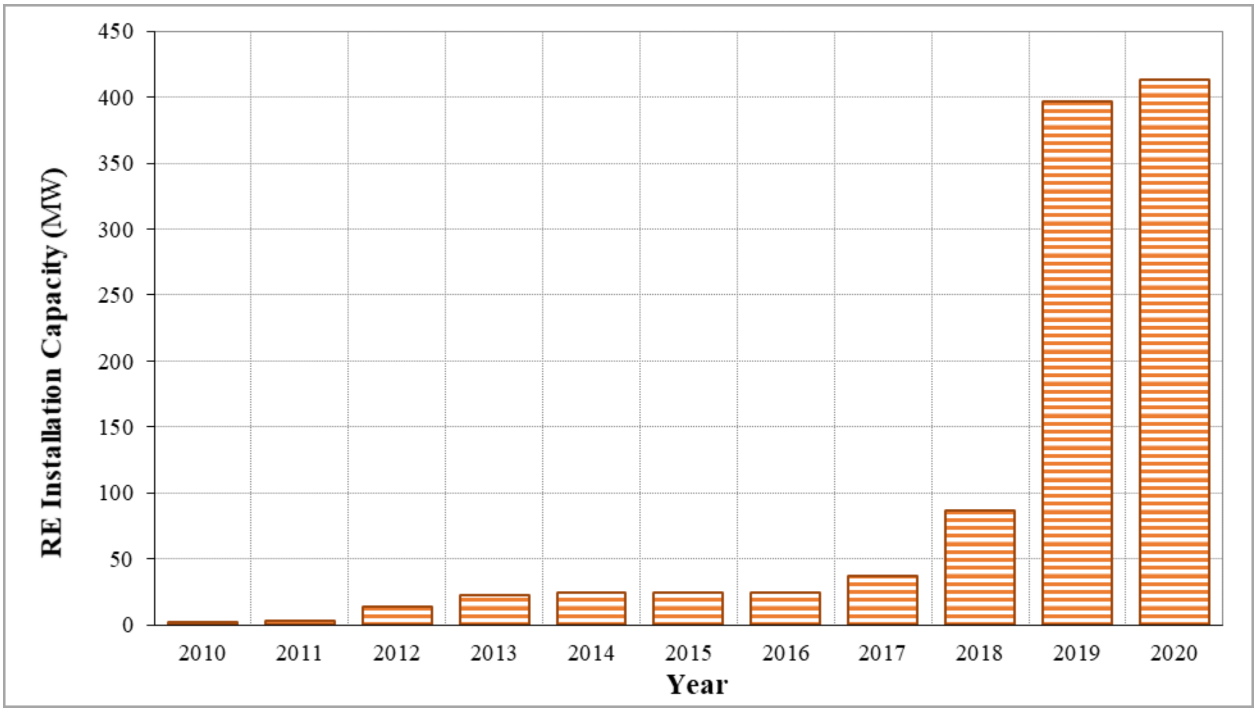

FIGURE 7. Renewable energy installation capacity (MW) in Saudi Arabia [52].

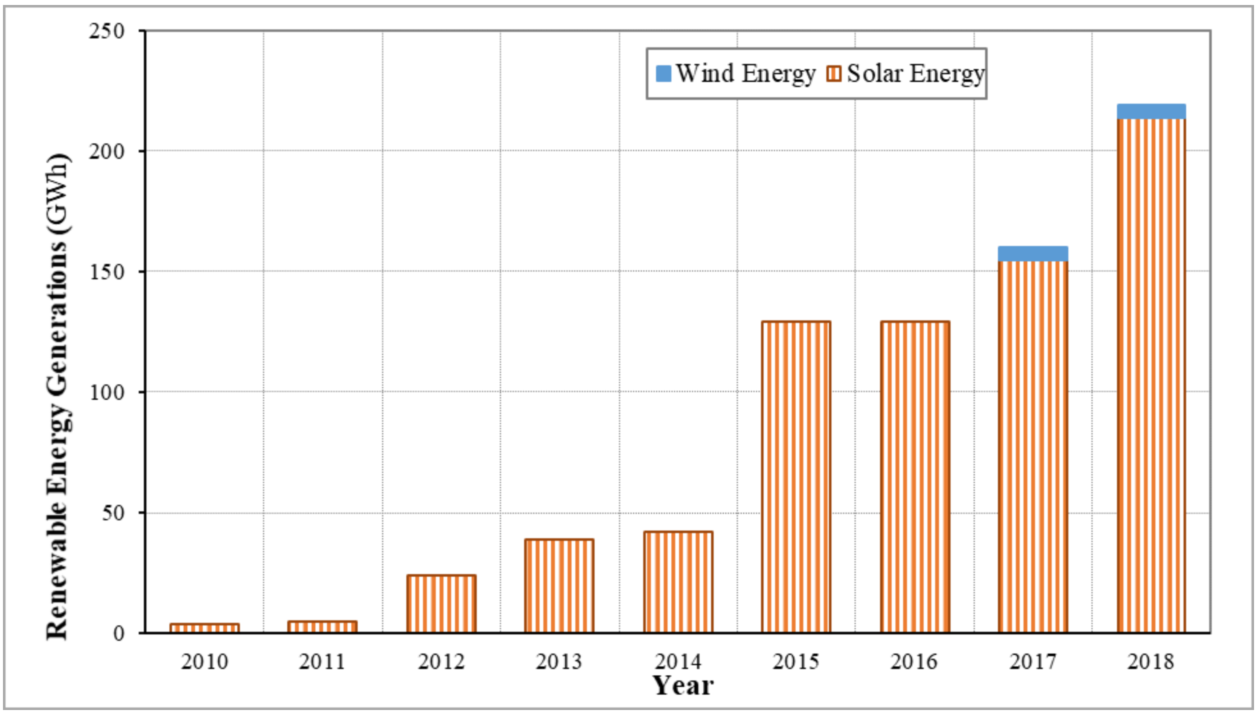

FIGURE 8. Renewable energy generation in GWh [56], [57].

in Figure 9 [74]. The desalination plant located in Ras Al Khair, one of the largest hydroelectricity producers, supplied about 45 million MW/h in 2017, about 23 million MW/h in 2012 [75].

4) WASTE TO ENERGY

Waste sources, which are substantial in quantity and could be used for renewable energy, consist mainly of municipal solid waste (MSW), byproducts of wastewater treatment plants,

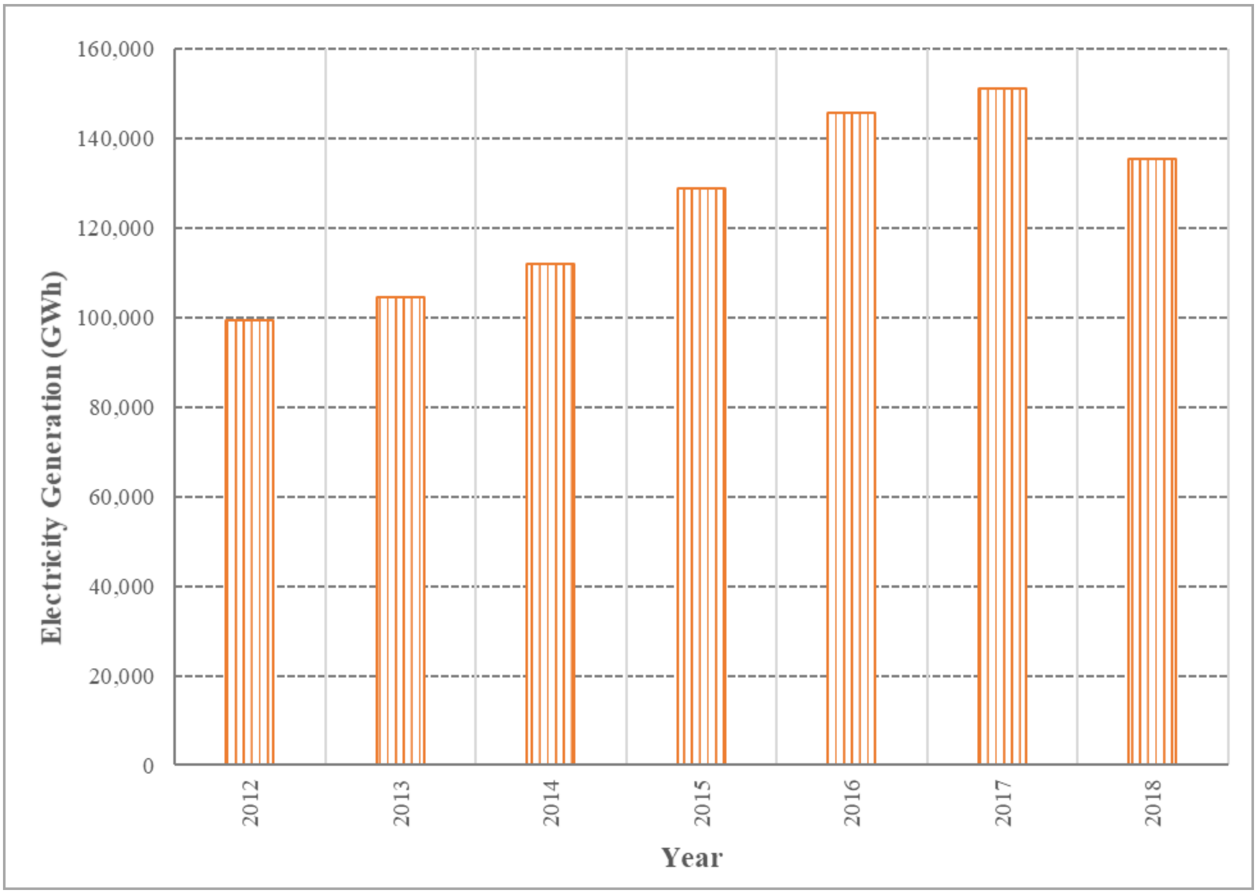

FIGURE 9. Total generated hydroelectricity in Saudi Arabia [74].

and industrial and agricultural organic wastes [76]. The Kingdom generated 15.3 million tons of MSW in 2014, and the volume is projected to be doubled by 2033. In addition, a substantial amount of industrial and agricultural wastes is also produced annually. In general, the MSW activities in the country are limited to collecting and storing the wastes in open landfill sites that may cause environmental and public health issues [77]. However, the waste-to-energy (WTE) schemes of the country can serve a dual purpose: minimizing waste to be handled or processed and generating usable energy in a climate-friendly way. Modern WTE technologies, such as incineration based on refuse derived fuel, anaerobic digestion, pyrolysis, and gasification, can transform waste management into energy [78]–[81]. Thus, the decision-makers considered the wastes as the possible renewable sources for energy generation and targeted to produce 3 GW power by 2040 [75], [82]. The Kingdom has set up a $300 million facility that can process approximately 180 tons of wastes to produce 6 MW of electricity and 950 m^3 distill water per day [75]. Besides, the Reuse Wastewater Project seeks to increase the reuse of treated water to preserve water supplies by rehabilitating treated water pump stations and setting up distribution networks, among several initiatives [48]. Major industries like Saudi Aramco are also taking many industrial waste management and water treatment initiatives that assist in GHG emission reduction in the electricity generation sector [83].

5) NUCLEAR ENERGY

Nuclear power plants use nuclear reactions to produce electricity and thermal energy and desalinate water. This zero-emission energy source generates energy without emitting harmful byproducts like fossil fuels. In 2010, the Kingdom established the King Abdullah City for Atomic and Renewable Energy (K· A· CARE) to incorporate a balanced combination of nuclear and renewable energy to reduce net CO_2 emissions. The country also launched the Saudi National Atomic Energy Project (SNAEP) to enable peaceful atomic energy into the national energy mix and economic diversification as per the *Saudi Vision 2030*. The SNAEP has four core components large nuclear plant, fuel cycle, small module reactor, and regulator. The country already planned to construct two large nuclear power reactors for electricity generation and several small reactors for water desalination. The government set a target for 17 GW electricity production from atomic resources by 2040 to provide 15% of the power demand [48], [84], [85].

6) GEOTHERMAL ENERGY

Geothermal energy is produced from natural underground heat. Based on available data, the KSA is one of the most geothermally active countries in the Middle East and began exploring geothermal resources in 1980. Many regions of the country, including Al-Lith, Arar, Hail, Harrat, Jizan, Madinah, Riyadh, and Tabuk, have good potential for geothermal energy [86]–[90]. For example, the Jizan province has been characterized as high heat flow and elevated geothermal gradients that host several hot and thermal springs. It was estimated that the province could generate 134×10^6 kW of electricity through the effective utilization of the available geothermal resources [88]. The Kingdom planned to install the geothermal facilities of 1 GW capacity by 2032 [91]. The country has already developed a few refreshments and swimming pools using geothermal energy in the Jizan area [90].

7) BIOENERGY

Biomass is the term used for electricity generation from plants and dairy sources [92]. Biodiesel is renewable energy derived from animal fats or vegetable oils that has enormous potential to replace the diesel derived from petroleum [93]. Dairy farmers, bakeries, and olive oil plants in Saudi Arabia may use anaerobic digestion treatment to produce a significant amount of organic waste. Besides, the restricted agricultural residue could potentially increase biomass energy. The impressive biomass energy prospects of the country can reach up to 17.8 million tons of oil equivalent by 2034 [94]. Despite having enormous potential, the use of biomass energy remains idle in KSA. According to World Bank data, traditional biomass consumption of the country was only 0.00848 % in 2012 [95].

C. OTHERS

This section discusses additional initiatives taken by the Kingdom for GHG emissions reduction in the electricity generation sector, including distributed RE projects, energy efficiency initiatives, and electricity tariffs restructuring.

1) DISTRIBUTED RE PROJECTS

In February 2021, the Ministry of Energy announced the installation of small-scale solar PV systems to allow the citizens to produce electricity at their homes or establishments and connect to the national grid by launching a new program named '*Shamsi*' [96]. The program facilitates an online platform for the feasibility study (focusing on energy yield estimation) of small-scale PV systems according to the selected technology for all 13 provinces of the country. It also allows assessing revenues, savings, and payback periods based on energy generation and consumption. Besides, the program aims to expedite the necessary processes for small-scale PV systems integration into the distribution networks. The program is being operated by collaborating major energy stakeholders in the Kingdom [97]–[99]. The country also launched a regulatory framework for grid integrated small-scale solar PV systems. The capacity of each PV system per facility should be ranged from 1 kW to 2 MW. It limits the maximum aggregated capacity of each off-taker to 5 MW, and the total PV system capacity should not exceed 15% of the nameplate capacity of the substation transformer. Each distribution region of the country can add PV systems up to 3% of its previous year's peak load. Eventually, around 1.8 GW of renewable energy into the grid will be added through small-scale PV projects. Furthermore, the framework introduced net-billing schemes for the surplus electricity exported to the grid from the residential off-takers at a rate of (0.07 SAR/KWh or 1.87 ¢/kWh) [100]. Currently, around 1.60% of households in the Kingdom utilize solar energy in different forms [73].

2) SAUDI ARABIAN STANDARDS ORGANIZATION

The Saudi Arabian Standards Organization (SASO) facilitates the use of insulators in the renovation of existing buildings to minimize energy demand [101]. For instance, Enova, a supplier of energy and multi-technical facilities, has concluded the development of a groundbreaking series of energy conservation measures to ensure a 30% decrease in energy usage at SASO's plant [102]. Concisely, the organization has been maintaining a pivotal role in establishing national standards to support the use of energy-efficient products that eventually reduce the energy demand and GHG emissions.

3) NATIONAL ENERGY EFFICIENCY PROGRAM

The National Energy Efficiency Program (NEEP) of the country intends to minimize the growth of peak electricity demand. The entity has been working on the energy conservation legislation and regional and national standards and creating a new central database on energy supply and demand, energy management capability, and awareness campaigns. As a result, the country made considerable progress in developing and implementing the regulations and guidelines for building, transportation, manufacturing, urban planning, and district cooling to use and conserve resources effectively [103]. For example, the entity revised the energy efficiency standard for air conditioners to be 8.5 (three stars on the label) for window units and 9 (four stars) for split units. To comply with the developed standards and regulations, the energy-intensive industries are taking measures to increase their energy efficiency. Hence, overall energy demand and GHG emissions are being reduced.

4) ELECTRICITY TARIFF RESTRUCTURING

The electricity prices in the Kingdom were low, especially for the residential customers, until December 2017, as the government used to provide subsidies and soft loans to the electricity generation, transportation, and distribution entities [104]. However, the Saudi Council of Ministers implemented an increased electricity tariff for most of the sectors (residential, agricultural and charities, and commercial) of the country from January 1, 2018 [31], [105]. Besides, the SEC implemented a penalty system for those customers whose contractual loads exceed one megavolt-ampere in case of inefficient energy consumption since January 2018. When the monthly consumption of ineffective electricity reaches 48.4% of the productive electricity consumption, the inefficient energy usage tariff is imposed at 0.05 SAR (∼0.013¢) per additional kVArh (power factor coefficient is less than 0.90) [106]. The restructured tariff and inefficient energy consumption regulations have been enforcing the customers for efficient electricity utilization, hence, energy demand and GHG emissions reduction.

5) RESEARCH AND EDUCATIONAL PROGRAMS

The Kingdom has been investing in local expertise and technology development through various research, training, and educational programs to realize ambitious energy plans. In addition, the country has been providing incentives to the local small and medium-sized enterprises involved in technology transfer and localization. The K· A· CARE, the leading prominent entity, has been facilitating the transfer, development, and localization of a substantial amount of renewable and atomic energy technologies since 2010. The entity collaborates with other relevant stakeholders, including public and private organizations and universities [107]. The King Abdulaziz City for Science and Technology (KACST) is responsible for promoting research and innovations in collaboration with the local universities and companies. It has a dedicated Energy Research Institute that conducts research activities related to renewable energy resources and efficient utilization of energy resources. Renewable energy research of this entity covers technology development mainly related to solar heating, cooling, power, and desalination [108]. Besides, the Ministry of Education, Ministry of Energy, Industry and Mineral Resources, and Ministry of Environment, Water and Agriculture also provide financial funding through different research projects for renewable and sustainable energy usage-related technology development and deployment. The Ministry of Education recently commenced a new wing named the Research and Development Office to support research and innovation activities in the Saudi Arabian universities under various programs [109]. Besides, the major companies, including Saudi Aramco, Saudi Electricity Company, and Saudi Basic Industries Corporation, provide research support to the universities for energy technology development [110]–[112]. To utilize the available research funding, most of the leading Saudi universities established renewable energy-related research centers. For example, Solar Center at King Abdullah University of Science and Technology [113], Interdisciplinary Research Center for Renewable Energy and Power Systems at King Fahd University of Petroleum & Minerals [114], Sustainable Energy Technologies Center at King Saud University (KSU) [115], and Center of Research Excellence in Renewable Energy and Power Systems at King Abdulaziz University [116].

IV. GHG EMISSIONS AND AVOIDANCE

In this section, GHG emissions and avoidance from electricity generation and cogeneration using the fuel consumption information [38] and the Tier-1 methodology suggested by the Intergovernmental Panel on Climate Change [117] are discussed. The emissions of carbon dioxide, methane, and nitrous oxide seem similar in recent years, as depicted in Figure 10.

The carbon dioxide emissions from (i) electricity generation were 160, 177, 157, and 157 million tons, and (ii) cogeneration were 28, 31, 29, and 31 million tons in 2016, 2017, 2018, and 2019, respectively. The methane emissions from electricity generation vary between 4 and 6 thousand tons; the emissions from cogeneration vary between 2 and 4 thousand tons in those years. Total emissions from electricity generation and cogeneration were 189, 209, 187, and 189 million tons in 2016, 2017, 2018, and 2019, respectively. During the last few years, the GHG emissions were not varying significantly. The reasons include the deployment of advanced generation technologies, increased tariff for electricity usage, and various energy-efficient programs, which causes a decrease in electricity demand. Therefore, it is expected that the per capita GHG emissions from the electricity generation sector of the country will be more controlled in the future than in the previous years due to the implementation of various regulations and the deployment of advanced technologies.

Moreover, the Kingdom can avoid a substantial amount of GHG emissions if the planned renewable and nuclear energy projects are successfully deployed. The country has the advantage of long daily average hours (∼ 8.53 hours) of sunshine [118]. Therefore, it is estimated that solar energy will produce approximately 108,000 GWh considering a production ratio of 0.80. The wind energy will produce about 21,000 GWh considering a production ratio of 0.26. Nuclear power will produce approximately 142,000 GWh based on a production ratio of 0.92. The total electricity production of 271,000 GWh by renewable and nuclear energy sources will save 215.61 million tons of carbon dioxide, 6.44 thousand tons of methane, and 1.11 thousand tons of nitrous oxide based on grid emission factors of Saudi Arabia [119].

V. CHALLENGES

This section briefly discusses the significant challenges associated with GHG reduction in the electricity generation sector. First, wind and solar energy are intermittent in nature as their outputs depend on the weather condition. Such uncertainty adds complexity to maintaining the balance between energy availability and demand for a reliable electricity grid. If and until energy storage is cost-effective, the secret to its proper implementation is the *'flexibility'* in the electricity grid. Enhanced wind and solar resources forecast over various periods would promote renewable energy depending on the weather [64], [120], [121]. In addition, another challenge for Saudi Arabia is finding economical and feasible ways to reduce the impacts of high temperatures, dust, and humidity on solar panels. The PV surface temperature increases with

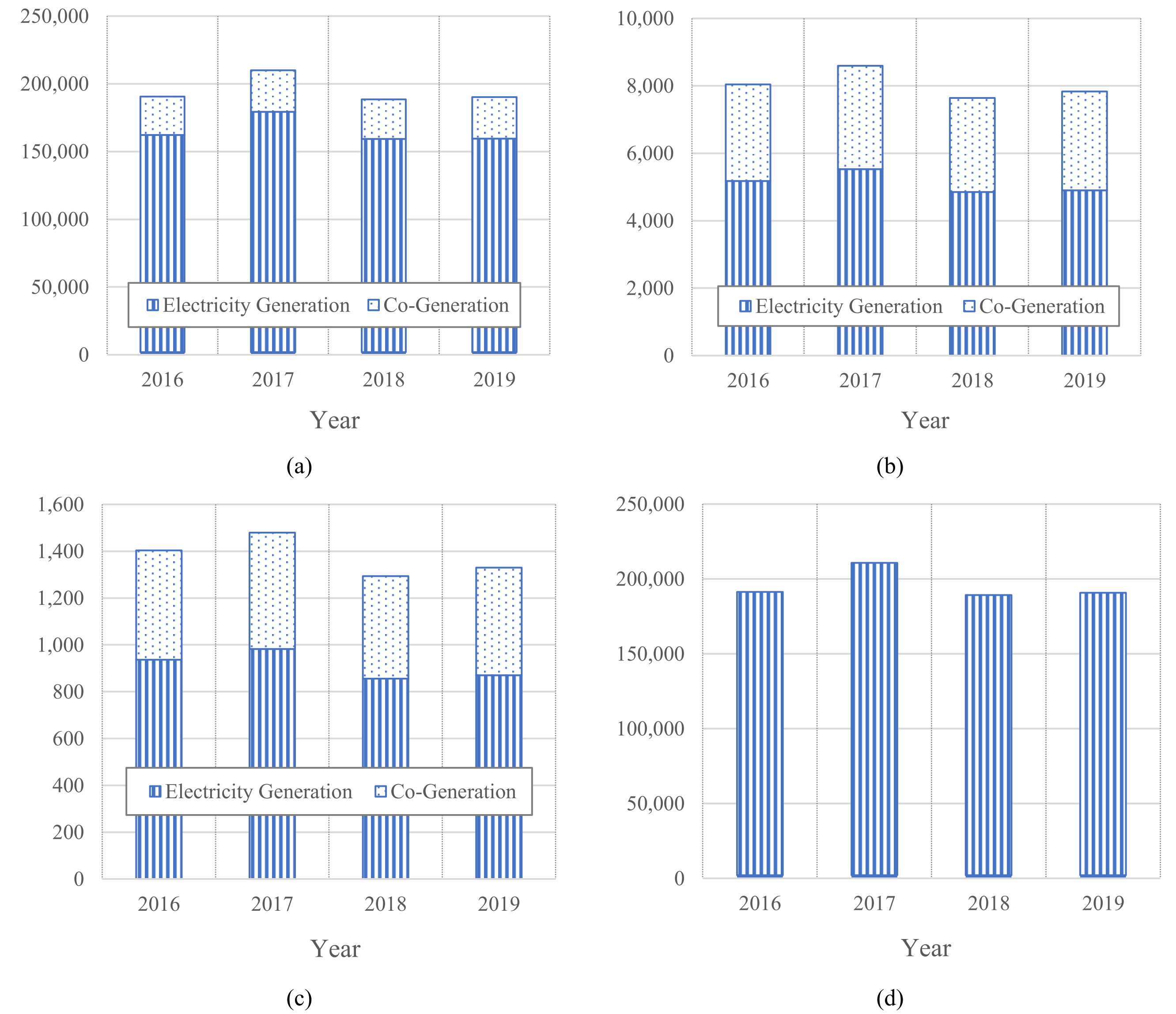

FIGURE 10. The comparison of (a) CO2 emissions (Gg), (b) methane emissions (Ton), (c) nitrous oxide emissions (Ton), and (d) CO2 equivalent emissions from the electricity generation and the cogeneration plants from 2016 to 2019 in Saudi Arabia.

a longer exposure time to high ambient temperature and sunlight. The elevated temperatures explicitly impact the power production and efficiency of the PV systems [122]. Their efficiency also decreases with the rise of relative humidity. Besides, dust on the PV module surface prevents solar irradiation from attaining the cells through the glass cover. The composition, density, and particle distribution of extracted dust can affect the current-voltage, power output, and characteristics of PV modules [123].

In Saudi Arabia, small-scale distributed PV systems face two significant challenges for distributed systems: technical and regulatory. The technical challenges for high penetration of small-scale distributed PV systems into the national utility grid include protection, voltage stability, uncontrollable variability, power quality, and harmonics [118], [124]–[132]. Most of the technical challenges arise as the distribution networks were constructed considering the possibility of extensive penetration of distributed renewable systems. In addition to the technical challenges, the regulatory issues for grid-connected distributed PV systems in Saudi Arabia lack a third-party certified workforce to design and install the PV systems, proper guidelines for grid integration, and consistent power purchasing agreement between the power producers and the utility company. For instance, the Water & Electricity Regulatory Authority (WERA) announced a net metering scheme in 2017 [118] and changed it to net billing in 2019 [129]. Therefore, such challenges should be considered for the massive rollout of grid-connected small-scale distributed renewable energy resources across the country.

Ensuring the security of nuclear power plants security, shielding reactors from natural catastrophes and external aggression, lacking of local experts, and seeking viable strategies for long-term waste disposal are the main challenges facing the nuclear industry [133]. Saudi Arabia also needs to uphold the mentioned challenges to realize its planned atomic energy projects. Besides, major challenges, including regulatory and technical requirements, fly ash disposal, and trained workforce, should be resolved before massive and sustainable waste-to-energy projects development for economic growth and GHG emission reduction [134], [135]. Feedstock unavailability, pressure on transport section, the inefficiency of conversion facility, equipment, and technology shortage, loss of biodiversity, and promote aesthetic degradation constraints can be grouped as the challenges faced by the biomass energy production supply chain [136], [137]. Furthermore, the critical challenges of the geothermal industry are the lack of local and national regulations, inadequate human resource management, and technology availability [138], [139].

VI. OBSERVATIONS AND RECOMMENDATIONS

The KSA has already implemented several initiatives to reduce and mitigate GHG emissions from the electricity generation sector, as stated earlier. This section briefly provides the observations and recommendations that can be considered for further reduction of GHG emissions from the sector. Such initiatives include the deployment of efficient combustion engines, poly-generation and cogeneration plants, various renewable energy resources, micro-grids, and ocean thermal energy conversion systems.

Poly-generation is the simultaneous generation by concatenated thermodynamic processes and the proper utilization of byproducts of useful thermal, mechanical, and electrical resources. The residual heat from electricity generation is supplied to the district heating network. Therefore, the energy efficiency of such systems is enhanced significantly. The D-Poly project proposed policy recommendations to help regenerate the prospects for large-scale industrial poly-generation projects in the industry, improve business productivity, and minimize GHG emissions [140]. The CHP systems are referred as the co-generators that use residual energy for industrial process heat or the heating of space and water in a steam turbine, combustion turbine, or combustion engine generator. They can be used in manufacturing facilities, educational institutes, and governmental facilities. The CHP systems have been deployed and assessed in different places to achieve better energy efficiency [141], [142]. Besides, the gas and steam turbines can be operated as stand-alone generators in a single cycle or as combined-cycle in a joint sequential process. The combined-cycle systems in other engines use combustion gases from one turbine to generate more electricity efficiently. The combined-cycle technology is gaining popularity as they reduce GHG emissions more than conventional technology to produce the same amount of energy [143]–[145].

A viable mitigation method for reducing GHG emissions in fossil-fuel power plants is the use of CCS technology [146]. A variety of CO_2 capture techniques, including gas-phase separation, stable adsorption, liquid absorption, gas separation membranes, and cryogenic distillation, can be used in CCS technology [147], [148]. Oil and gas plants around the globe, including Saudi Arabia, have been using CCS technology that eventually reduces GHG emissions [149], [150]. Due to sustainability and biodegradability, algae-based bioenergy has gained a lot of attention in recent decades. Algae can be considered a possible feedstock for biofuel production due to their carbohydrate and oil content [151], [152]. The use of algae to capture CO_2 from flue gases and turn it into biomass is one of the most promising approaches. In addition, algae have a lot of potential as renewable fuel sources and CO_2 capture by photosynthesis to reduce GHG emissions [153]–[155].

Energy storage systems (ESS) are the appealing solutions to mitigate the intermittency of the solar and wind based RE generation due to climatic conditions. The ESS can also provide energy during the unavailability of solar energy during the nighttime or cloudy hours. Batteries, supercapacitors, superconducting magnetic, pumped hydro, and compressed air energy storages are the most popular for mitigating the uncontrollability of the RE resources, RE power output smoothing, frequency, and reactive power control, and peak shaving [156]–[160]. Thus, the ESS technology maximizes RE resources usage and eventually electricity generation from fossil fuel-based plants, hence, the GHG emissions. Besides, as the micro-grids use renewable energy generation, energy storage and management, and smart grid technologies, thus, they minimize GHG emissions and assist in tackling the climate change issue [161]–[163]. They may also use the batteries in electric vehicles to balance output and consumption within the microgrid. Furthermore, ocean thermal energy conversion systems use the temperature difference between ocean water at various depths to power the turbines for electricity generation [164].

Internal combustion (IC) engines, such as diesel engines, are widely used in remote areas for electricity generation. They are also used for mobile power supply at construction sites and emergency power supply at buildings and power plants. A variety of fuels can be used, including petroleum diesel, liquid biomass-based fuels, biogas, natural gas, and propane. The GHG emissions significantly reduce when the IC engines gain maximum efficiency with biomass or biogas-based fuels. Different entities have already started to explore such potential as detailed in [165], [166]. However, the country can introduce advanced biomass technologies to reduce the environmental effect from the biomass wastes as attractive alternatives for power and fuel production [78]. Therefore, the adoption of the mentioned advanced fossil fuel-based technologies and the massive deployment of green power generation technologies will drastically reduce a considerable amount of GHG emissions from the electricity generation sector in the Kingdom of Saudi Arabia.

VII. CONCLUSION

This article provided a landscape of electricity generation and GHG emissions of the Kingdom of Saudi Arabia. It illustrated possible GHG emissions avoidance by adopting low emission, renewable, and nuclear energy technologies. In 2019, the overall electrical energy generation of the country was 342.62 TWh, where a small portion was generated from non-conventional sources such as solar, wind, nuclear, hydroelectric, and waste-to-energy. This article discussed the initiatives taken by the country for GHG emission reduction, including deployment of cogeneration and combined cycle power plants, renewable energy resources (solar, wind, nuclear energy, waste-to-energy, hydropower, and geothermal). It also pointed out the challenges pertinent to fossil fuel, nuclear, and renewable energy resources-based technologies. Besides, the article suggested several promising initiatives that can be considered to reduce and mitigate GHG emissions in the Kingdom. Such initiatives include adopting efficient combustion engines, poly-generation, and converting the more cogeneration and combined cycle power plants from single-stage gas turbine power plants. Furthermore, the deployment of various EES and microgrid technologies to adopt more renewable energy resources can be considered as one of the promising options for the country. As an extension of the study, the entire electricity sector (generation, transmission, distribution, and consumption) of the Kingdom can be considered along with the illustrations of various strategies and recommendations for GHG emission reduction and mitigations from the policy perspective.

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