Regional Strategies for PV-Based Sustainable Energy in GCC and Europe

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Abstract: This study analyzes the feasibility of the production of solar power as a sustainable solution to the climate and energy crisis, focusing on two areas in particular: the Gulf Cooperation Council countries and Europe. Focused attention goes to emerging economies in analyzing how solar power can aid in reducing carbon dioxide emissions and attaining sustainable development. Comparative analysis is performed for the GCC region and Europe on the basis of unique solar system design ability and the performance of photovoltaic (PV) systems, taking into account realistic environmental and working parameters. In this comparative design research, mathematical equations were applied to determine the number of required solar panels to achieve determined energy efficiency in both regions. A novel mathematical modeling approach was designed and presented as new equations to achieve a correct estimate of the quantity of PV panels required from the energy requirement and a parameter called the Power Generation Factor (PGF). The practical design approach employed in the present work synchronizes the technical aspects of electrical system design with broader sustainable development goals, particularly for developing nations. By creating new mathematical equations for estimating how many PV panels would be necessary based on desired energy yields and incorporating the PGF, the study underscores the photovoltaic efficiency and panel requirement disparity between the GCC and European regions. These disparities owe to differences in solar energy generation and electricity generation factors between regions. The suggested approach is scalable and can be applied to other areas with comparable energy requirements, making it a tough and adaptable planning instrument for sustainable energy infrastructure deployment.

Keywords: Solar, Carbon Dioxide, PV, GCC, Europe.

INTRODUCTION

The impact of carbon dioxide emissions on human lives all over the world. The subsequent carbon dioxide emissions contribute to global warming and extreme weather events. This suggests that the utilization of fossil fuels to generate energy significantly impacts human lives and contributes to climate change and air pollution. It is well established that approximately 40% of carbon dioxide (CO_2) emissions due to energy production stem from the combustion of fossil fuels to generate electricity [1, 2].

The world is currently striving to become carbon neutral. "Net zero" refers to a decrease in carbon dioxide emissions to a finite amount of residual emissions that can be sequestered and absorbed by nature in the long term, and other means of emissions reduction that leave no traces behind in the atmosphere [3]. Becoming a net-zero world is one of the most ambitious endeavors of humanity ever. It requires a fundamental shift in how we produce, transport, and consume. The energy sector is already responsible for about three-quarters of greenhouse gas emissions and is the key to averting the most destructive effects of climate change. Renewable energy, such as solar, could significantly reduce carbon dioxide emissions.

Energy resources can be classified as conventional and unconventional, where conventional resources are depleting at a very rapid pace. Due to this, the world has transitioned and produced environmentally friendly and sustainable renewable energy resources. One of the solutions that has been found appropriate on these lines [4] is solar energy. Once installed on rooftops, solar panels produce a clean source of electricity using natural sunlight. Solar panels also act as mini solar power plants and reduce transmission and distribution losses.

Solar power is low-emission, environmentally friendly, and maintenance-free compared to other sources of renewable energy. The photovoltaic (PV) solar panels are also highly stable due to their environmental insensitivity to rain and wind, using well-established and available maintenance methods [5]. The PV solar panels are also designed with long-term guarantees and are offered for installation in various capacities and locations based on needs. They also offer pollution-free power generation, which is a perfect solution for renewable energy production [5].

GULF COOPERATION COUNCIL (GCC) COUNTRIES CO_2 EMISSIONS

The Arabian Gulf region, and particularly the Gulf Cooperation Council (GCC) countries, is one of the largest sources of carbon dioxide emissions globally, primarily due to its reliance on fossil fuels for both consumption and production of energy. The high per capita consumption of energy in the region and its status as a prominent producer of oil and gas are the

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reasons for its widespread carbon footprint. These can be formulated based on four main parameters. These include: dependence on fossil fuels, as this factor relies heavily on oil and gas for electricity generation, transportation, and industrial processes, which leads to excessive carbon dioxide emissions. Second, high per capita emissions, as the majority of GCC nations possess some of the highest per capita carbon dioxide emissions globally, which reflects their excessive energy consumption patterns. Third, rapid growth and development. Rapid economic and demographic expansion in the region demands greater energy production and consumption, which further boosts emissions. Industrial activities are the final factor, and industries such as steel production and water desalination also contribute significantly to the region's carbon footprint.

EUROPEAN COUNTRIES CO_2 EMISSIONS

European economy greenhouse gas emissions during the second quarter of 2024 were pegged at 790 million tonnes of CO_2 equivalent, a decrease of 2.6% compared to the same quarter of 2023. While Europe's total greenhouse gas emissions related to production and consumption amounted to 3.6 billion tons of carbon dioxide equivalent in the year 2022, European consumption as a point of final demand was responsible for 4.8 billion tons of global emissions. Europeans are the fourth largest source of greenhouse gas emissions in the world. All these facts can be stated based on four main points. These include European emissions, where the European countries emitted the equivalent of 3.6 billion tons of carbon dioxide equivalent in 2022 and were responsible for 7% of global emissions. European consumption of products and services then led to 4.8 billion tons of global greenhouse gas emissions. The third reason is that Europe is the largest emitter of greenhouse gases and the fourth largest emitter of greenhouse gases in the world after China, the United States of America, and India. The fourth driver is the reduction of carbon dioxide emissions, which should encompass the second quarter of 2024. The European economies also saw a 2.6% drop in greenhouse gas emissions compared to the same quarter in 2023, according to the European Commission. It is interesting to note that the residential sector and the electricity and gas supply sector witnessed the largest decrease in emissions in the second quarter of 2024 when compared to the second quarter of 2023.

LITERATURE REVIEW

Several researches are carried out on the renewable energy and Carbon Dioxide emission reduction and reaching Net-Zero. Quant and Abu Zahra [6] presented a comprehensive analysis of the renewable energy sources and the incorporation of geothermal energy into carbon dioxide emission processes. The study analyzed how this energy sources can lead to net-negative or zero carbon dioxide emissions.

Bieth [7] conducted a panel data regression to study the relationship between gross domestic product (GDP), human development index (HDI), and carbon dioxide emissions in six ASEAN countries and Japan. The study found that GDP positively but not significantly impacted carbon dioxide emissions, and HDI positively but not significantly impacted it.

García-Alfonso and González-Díaz [8] focused on Tenerife, evaluating the possibility of electric vehicles mitigating passenger car and power generation emissions. The island power generation system highlighted the necessity to improve charging strategies and increase energy storage capacity in order to achieve significant fuel savings.

Onofrei *et al*. [9] examined the relationship between carbon dioxide emissions and economic growth in the 27 member states of the European Union using a panel data set from 2000-2017. Through the qualitative sequential methodology followed by the research work, it confirmed the existence of a long-run cointegration between carbon dioxide emissions and economic growth. The result showed the existence of a statistically significant effect of economic growth on carbon dioxide emissions.

Li *et al*. [10] considered China and examined the relationship between carbon dioxide emissions, economic growth, industrial structure, and R&D investment during the period 2000-2018. Using machine learning algorithms, the authors forecasted carbon dioxide emissions during 2016-2018.

Inoue and Yamada [11] evaluated the energy cost of a high ratio of renewable energy and roughly zero carbon emissions, focusing particularly on the stability of the power grid in Japan. The study developed an optimum power generation model by area, targeting an 85% reduction in carbon dioxide emissions from the power grid by 2050.

Ghodki [12] focused on solar panels, which are the most important element in solar electricity generation. They suggested an automatic dust collecting system with the help of a robotic arm. The study concluded that the patented device, due to its scalability and ease of operation, offers a competitive option among other cleaning systems with excellent operational, electrical, and economic parameters.

Jaiganesh *et al*.'s [13] study highlighted the importance of renewable energy sources, such as solar energy, in reducing coal and water utilization for electricity production. The efficiency of the panel can be improved by 15 to 20% using different cleaning techniques such as manual cleaning, vacuuming, and electrostatic precipitator cleaning.

Elsheniti *et al*. [14] developed a one-dimensional model in 2020 that was designed to predict the temperature of a photovoltaic panel relative to a phase change material (PCM). The model provides results as satisfactory as those of computational fluid modeling (CFM) with a significant reduction in computational time. In addition, the effect of varying the thickness of the PCM for the following days of simulation was investigated.

In 2023, Qamber [15] conducted a study focusing on reducing the energy consumption in buildings, with a particular emphasis on using energy-efficient appliances. In this study, a new technique called Adaptive Neuro-Fuzzy Inference System (ANFIS) was applied in the design of solar panels needed. This technique uses curve fitting in developing country-specific models researched. These models are tailored based on the daily units of each country's energy consumption.

Khalid *et al*. [16] addressed in their paper the example of photovoltaic panels, which is a rapidly increasing field of energy integration. While photovoltaic systems are friendly to the environment and efficient in energy because of their widespread installation, they also present problems that may negatively impact their efficiency and performance. Moreover, the paper outlines the future needs related to these cleaning systems. A full collection of published articles in this field is included in the research, providing a complete explanation of the successes achieved to date.

RESULTS AND DISCUSSION

A rooftop solar photovoltaic system is a system installed on a roof, leveraging the direct exposure to sunlight. It is considered one of the most environmentally friendly roofs since it offers electricity generation for edifices. It is green in that it produces clean energy that is free from pollution to the environment.

Photovoltaic (PV) energy research is of extreme importance towards sustainability, as outlined in this paragraph. Photovoltaic solar energy is a primary technology employed for generating renewable electricity and is critical to achieving net-zero emission plans. It is thus of key importance in advancing the motive of sustainability. Transitioning to a circular photovoltaic economy can potentially reduce the environmental impact of solar energy considerably by reducing waste and depletion of resources, contributing towards the achievement of a lower environmental footprint. Investment in circular PV technologies and strategies has large economic potential through new market creation and induced innovation. From a socioeconomic perspective, a circular PV energy system has the ability to provide social returns by promoting good management of resources and local economies via repair and remanufacturing operations.

The Panel Generation Factor (PGF) is solar panel setting which is a highly significant measure used in an effort to forecast the energy yield of a photovoltaic (PV) system. This is essentially talking of the level of electricity that will be generated by a solar panel in a given location and under given conditions. Therefore, the PGF helps to determine the size and number of solar panels required for an application and consider parameters like location, weather, and panel efficiency. Besides, it seeks to determine a generalized expression(s) of its approximation. Furthermore, the results achieved for both under study regions (GCC and Europe) and are shown in Tables (**1** and **2**), respectively.

For the considered regions (GCC and Europe), the Panel Generation Factor (PGF) resulting from PV and help to calculate panel size are as follows:

PGF (GCC) = 5.84

PGF (Europe) = 2.93

Assumed that energy needed (kWh per Day) with step 200kWh per Day for 200kWh per Day to 2000kWh per day.

Total Panels Energy Needed (kWh/Day) = Assumed Needed Energy * (Factor=3) (1)

The equation "Overall Panels Energy Required (kWh/Day)" indicates that the system demands three times the assumed energy demand, apparently to account for system inefficiencies and factors like weather variations reducing energy generated by panels. Safety or Efficiency Factor of Panel is therefore assumed to be 3. The factor is important, considering solar systems incur losses on wiring, inverters, and panel efficiency. Also, effective sun hours can be less than the average, and weather conditions like cloudy days, rain, or snow (in the snowing countries) reducing production.

The cumulative kWp of panel capacity is directly proportional to the total panels energy required and inversely proportional to the panel generation factor (PGF). Therefore, this relationship is as follows:

Cumulative kWp of Panel Capacity (kWp) = Total Panels Energy Required (kWh/Day) ÷ PGF (2)

For the design purpose, it had to calculate the number of PV panel required. This has to calculate the total kWp of panel capacity (kWp) which is directly proportional to the required number of PV panel. By the same analogy, the required number of PV panel is directly proportional to the Modules Factor which is 9.0909091, the relationship is:

No. of PV Panel Required = Cumulative kWp of Panel Capacity (kWp) * (Modules Factor=9.0909091 Panel per kWp) (3)

The Modules Factor is assumed as 9.0909091 Panel per kWp.

Table 1: **The GCC Region Required Energy, Overall Panels Energy Required and Number of PV Panels Required**

Required Energy (kWh/Day)	Overall Panels Energy Required (kWh/Day)	No. of PV Panels Required (Modules)
200	260	405
400	520	810
600	780	1215
800	1040	1619
1000	1300	2024
1200	1560	2429
1400	1820	2834
1600	2080	3238
1800	2340	3643
2000	2600	4048

Table 2: **The European Region Required Energy, Overall Panels Energy Required and Number of PV Panels Required**

Required Energy (kWh/Day)	Overall PV Panels Energy Required (kWh/Day)	No. of PV Panels Required (Modules)
200	260	807
400	520	1614
600	780	2421
800	1040	3227
1000	1300	4034
1200	1560	4841
1400	1820	5647
1600	2080	6454
1800	2340	7261
2000	2600	8068

The PV panels per day results relationship graph illustrated in both Figures (**1** and **2**) for both areas GCC and Europe to calculated values, respectively. Based on calculated values the predicated values were also calculated. The predicted values calculated after identifying the received below model (Figures **1** and **2**) as equation (4) to the total PV Panels energy demanded (kWh/Day) for every required energy region (GCC and Europe):

$$y = -(7.19 \times 10^{-19})\, x^2 + 1.3\, x - (1.5 \times 10^{-12}) \quad (4)$$

where:

x s Required Energy (kWh/Day)

y is Overall PV Required Panels Energy (kWh/Day)

Figure (**3**) illustrates the number of PV panels as a function of three parameters for the GCC region by the mathematical model expression of equation (5), whereas Figure (**4**) illustrates the different number of PV panels as a function of three parameters for the Europe region by the mathematical model expression of equation (6).

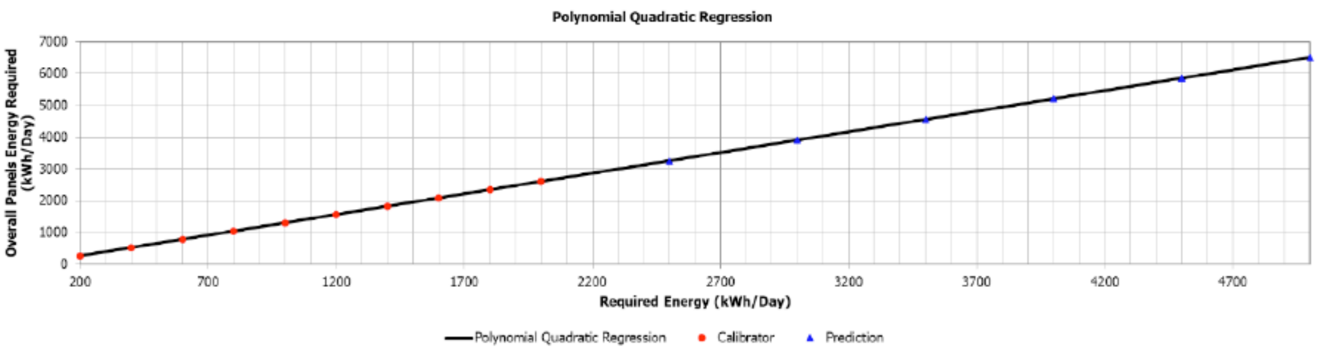

Figure 1: Overall Panels Energy Required vs Required Energy (GCC Region).

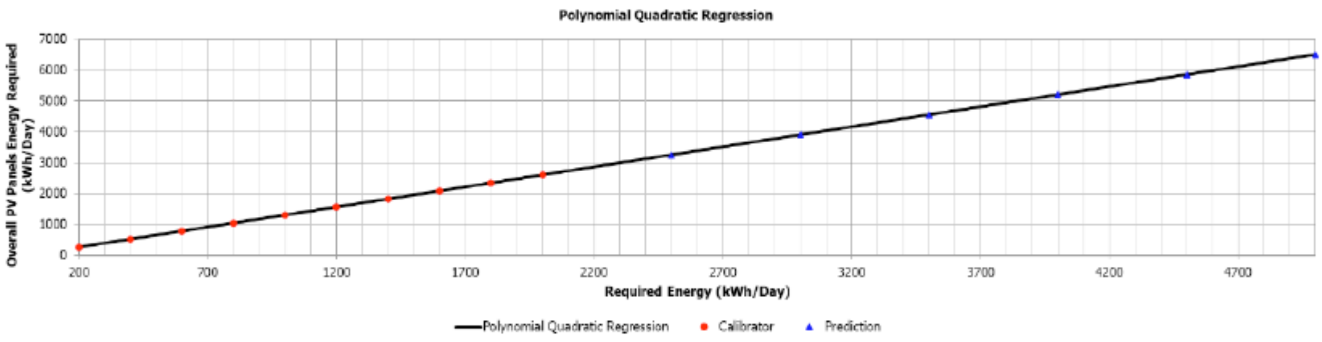

Figure 2: Overall Panels Energy Required vs Required Energy (European Region).

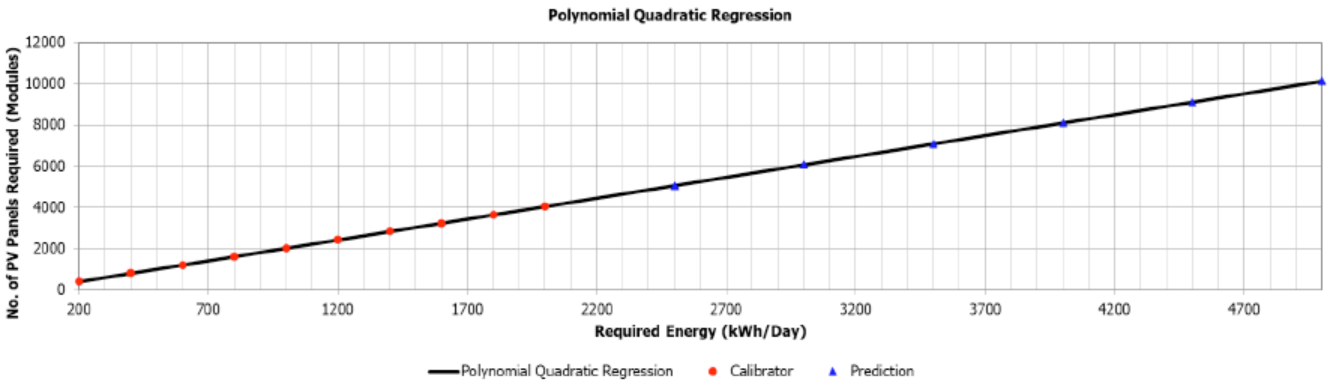

Figure 3: Required Number of PV vs Required Energy (GCC Region).

$$y = -(8.77\times 10^{-19})\, x^2 + 2.024\, x + 0.4 \quad (5)$$

where:

x is Required Energy (kWh/Day)

y is Number of PV Panels Required (Modules)

$$y = -(2.84\times 10^{-7})\, x^2 + 4.033\, x + 0.65 \quad (6)$$

where:

x is Required Energy (kWh/Day)

y is Number of PV Panels Required (Modules)

The calculate cumulative kWp of panel capacity (kWp) results for both Europe and GCC regions are provided in Table (**3**). They are divided to two Figures (**5** and **6**). Figure (**5**) is the figure which make results for the GCC region for values in Figure (**5**) which are located radially. The values are equidistant between the scale, where it is equal for all axes. Also, the grid lines are found and obtained as a reference. Likewise, Figure (**6**) is the chart that give outcomes for the Europe region for values in Figure (**6**) that are positioned radially. The values are equal distances to the scale, where it is the same in all axes. Also, the grid lines are found and obtained as a reference. Besides, the grid lines are retrieved and accessed as a guide.

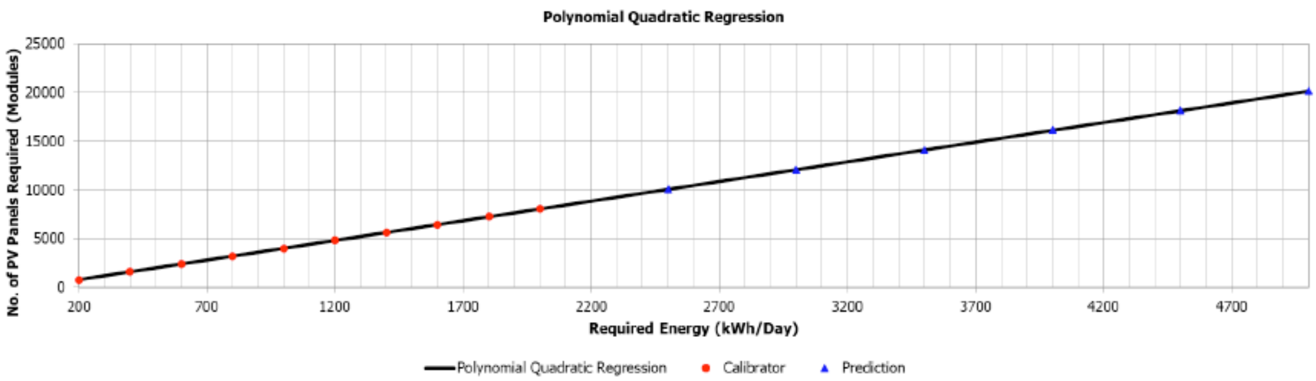

Figure 4: Required Number of PV vs Required Energy (European Region).

Table 3: GCC and Europe Regions Cumulative kWp of Panel Capacity (kWp)

Required Energy (kWh/Day)	Overall Panels Energy Required (kWh/Day)	Cumulative kWp of Panel Capacity (kWp)	
		GCC	Europe
200	260	45	89
400	520	89	178
600	780	134	266
800	1040	178	355
1000	1300	223	444
1200	1560	267	532
1400	1820	312	621
1600	2080	356	710
1800	2340	401	799
2000	2600	445	887

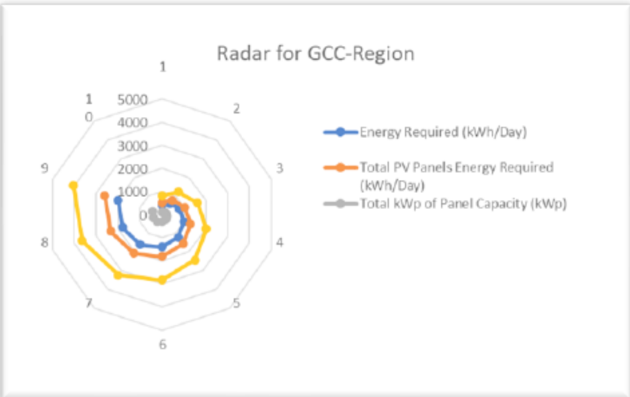

Figure 5: Radar Results of GCC Region.

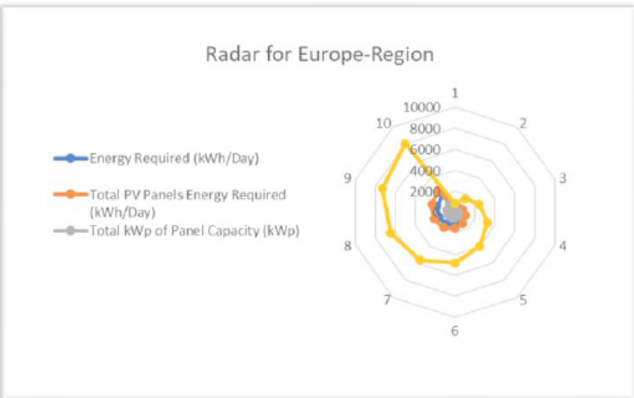

Figure 6: Radar Results of European Region.

Radar charts in Excel are used to plot multivariate comparisons. It is a graphical representation of multiple data points which can be added up to show a large amount of data within a single image. It also goes by the name spider chart or star chart. Every pictogram is used to represent the data, and the length is equal to the size of a data point.

The quantitative disparity would be in economic terms like trade volume, investment, and GDP among the GCC and the European. Further, the quantitative data reveal the European's greenhouse gas (GHG) emissions fell by 5.1% in 2023, while GCC countries are high emitters per capita with low energy efficiency. Though the GCC is relatively more reliant on conventional energy, the European region is not so due to a combination of technologies as well as current-day carbon capture operations, such as commercial-scale application in several GCC countries. Comparison is complex because GCC reliance on fossil fuels is equivalent to high emissions but Europe's is aimed at reducing reliance. As qualitative comparisons of the GCC and European regions; three factors were considered among them: the efficiency, the costs, and CO_2 emissions. The GCC area has a leader among them because its efficiency relies very much on inefficient energy generation technologies based on oil and gas, thereby leading to high overall emissions. Then there is the European area, which has established average operating measures of efficiency, *e.g.*, the Euro Efficiency, which considers several climate zones in Europe. Photovoltaic (PV) efficiency of power generation from electricity, or sunlight-to-electricity ratio that solar panels can produce, varies with technology, panel design, and local conditions and is not a static figure for an area. Overall, GCC countries have a high-density solar resource with intense irradiation, while Germany and Italy lead the market in solar PV capacity and grid integration with consistent effort towards improving efficiency using advanced technologies and smart grid integration. There is, too, the issue of expense, though no specific variations in expenses between GCC-region and are outlined, and reliance on conventional energy and necessity to adhere to the

Paris Agreement make it a serious issue with lots of investment in energy transitions and emission reductions. The GCC average price of electricity is at approximately 2.5 cents/kWh, where Europe region average varies considerably from country to country across Europe. To European that is costly because of the phase out from coal to renewables and embracing high-technology, but gets economies with new technologies as well. For utility-scale PV in 2024 from approximately €55/MWh in Spain to approximately €100/MWh in Sweden and the UK. This depends on location, cost of capital deployed, and level of future reduction with estimates rendering a drop to €35-€60/MWh probable by 2030. Also, the CO_2 emissions (CO_2 Reduction). The whole GCC region is one of the top 14 per capita CO_2 emission countries, and colossal total emissions are largely based on electricity and water desalination energy use. While, in the European continent it had a decrease of 5.1% of overall greenhouse gas (GHG) emissions in 2023 compared to 2022. Therefore, the GCC has strategic collaboration with Europe with technology like Carbon Capture, Utilization, and Storage (CCUS). But renewable energies like solar and wind are in the economic infancy stage in the region [17, 18].

CONCLUSIONS

This study creates region-specific, high-precision models via a parameter called the Power Generation Factor (PGF). The results create a one-to-one relationship between energy demand and photovoltaic (PV) solar panels required. Moreover, the capability of developing PV system constraints for increasing energy output to a significant level was achieved from calculations performed prior to arriving at the final equations, which identify the energy output needed in both the GCC and European regions. The model approach developed in this study is scalable and flexible and can be employed in any number of regions with comparable or even dissimilar energy needs. By integrating solar power into national and regional planning proposals-more in high-emission countries such as the GCC and the European nations-the study offers a feasible path towards reducing greenhouse gas emissions. The models developed offer an achievable and adaptable framework for solar panel demand forecasting, thus making them an extremely effective tool for global energy planning and climate action plans. This study concludes in support of carbon neutrality targets by providing a clear framework for reducing CO_2 emissions through the adoption of solar power. Additionally, the findings offer actionable advice for policymakers and planners of energy, especially in fossil fuel–dependent nations such as the GCC. The study allows developing economies to capitalize on solar power, hence enhancing climate resilience and supporting access to clean power sources. This paper provides a comparative analysis of solar energy generation in the GCC and Europe under real conditions. It develops mathematical formulas and models for estimating the number of PV panels to be used and daily energy output as a function of demand and climatic parameters. It also employs a systematic approach and method that aligns solar system planning with higher sustainable development goals. By incorporating solar power into overall strategic planning, particularly in regions of high emission rates, the research here prescribes a robust strategy for curbing greenhouse gases. The adaptable models presented herein are valuable tools for estimating solar infrastructure demand, aiding considerably in energy system planning and world climate policy.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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