Warming-Induced Increase in Power Demand and CO_2 Emissions in Qatar and the Middle East

Léna Gurriaran,[1,2,7,*] Katsumasa Tanaka,[1,3] I. Safak Bayram,[4] Yiannis Proestos,[5] Jos Lelieveld,[5,6] and Philippe Ciais[1,**]

[1]Laboratoire des Sciences du Climat et de l'Environnement (LSCE), IPSL, CEA/CNRS/UVSQ, Université Paris-Saclay, Gif-sur-Yvette 91190, France

[2]Atos, River Ouest, Bezons 95870, France

[3]Earth System Risk Analysis Section, Earth System Division, National Institute for Environmental Studies (NIES), Tsukuba, Japan

[4]Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G1 1XW, UK

[5]Climate and Atmosphere Research Center (CARE-C), The Cyprus Institute, Nicosia, Cyprus

[6]Max Planck Institute for Chemistry, Department of Atmospheric Chemistry, Mainz, 55128, Germany

[7]Lead Contact

*Correspondence: lena.gurriaran@lsce.ipsl.fr

**Correspondence: philippe.ciais@lsce.ipsl.fr

Abstract

Rising global temperatures in the Arabian Peninsula region caused by climate change have increased the demand for air conditioning, resulting in more electricity consumption and CO_2 emissions. This paper treats Qatar as a representative country for understanding the effect of future regional warming on the electricity demand and CO_2 emissions We first develop a model that relates daily electricity demand with temperature. By combining this model with temperature projections from the CMIP6 database (bias adjusted and statistically downscaled) and population and GDP projections from four shared socioeconomic pathways (SSPs), we can calculate Qatar's demand for electricity until the end of the century. The model identifies an average sensitivity of

+4.2%/°C for the electricity demand and projects an increase in electricity demand by 5 to 35% due to warming alone at the end of this century. The model suggests that under SSP1-2.6, warming-induced CO_2 emissions could be offset by carbon intensity improvements. Furthermore, under SSP5-8.5, assuming no carbon intensity improvement, future warming could add 20 to 35% of CO_2 emissions per year by the end of the century, with half of the electricity demand related to more frequent hot days. We further found that the temperature effect on power demand and CO_2 emissions is small compared to the effects from socioeconomic factors such as population, GDP, and carbon intensity.

Keywords

Electricity demand; scenarios; climate change; CO_2 emissions; Middle East

1. Introduction

1.1 Background

The scientific community agrees that fossil fuel CO_2 emissions induce global warming (IPCC, 2021). One question that remains unaddressed, however, concerns how rising temperatures will subsequently influence anthropogenic CO_2 emissions. According to the International Energy Agency (IEA, 2019), more than 40% of the global anthropogenic CO_2 emissions in 2018 originated from electricity and heat producers. However, although countries might generate the same amount of electricity, their CO_2 emissions might differ. In Middle Eastern countries, the vast majority of electricity is produced with fossil fuels. In Qatar for example, 100% of the electricity is currently produced with natural gas (IEA, 2019; Okonkwo et al.,2021). Air conditioning has been identified as consuming the most electricity in Qatar's residential sector (Alrawi et al., 2019); warmer conditions in the future will therefore raise the electricity demand unless decarbonization policies such as the installation of photovoltaics and improvements in building energy efficiency or behavioral changes counteract this response. This work studies how the frequency and intensity of hot days and regional warming in the future may influence electricity demand in Qatar and provides further feedback on electricity-related CO_2 emissions.

1.2 Literature Review

We distinguish two types of studies in the scientific literature related to how climate change relates to energy demand. The first type includes studies that examine relationships between electricity demand and climate from a local point of view, usually on a country, city, district, or household scale. Such studies establish relationships between climate variables and electricity loads and show that power demand is temperature-dependent. Scientific publications of this type tend to focus on European countries. For example, Valor et al. (2001) showed a nonlinear relationship between temperature and electricity demand in Spain. Jovanovic et al. (2015) studied the effect of changing temperature on power demand in Kragujevac, Serbia, which demonstrated similar relationships. Canales et al. (2020) also established these relationships for Poland using data from 19 major cities and studied the impact of temperature on renewable energy capacities. These studies are based on activities and meteorological data and have not yet been used for long-term energy demand forecasting.

The second type of studies includes modeling studies that forecast energy demand and electrical loads. As summarized by Mir et al. (2020), there are several methods to forecast loads. For example, bottom-up models can project long-term energy demand by incorporating detailed processes that control load while considering technological progress. In contrast, top-down models such as econometric forecast models can simulate the relationships between socioeconomic drivers of power demand; however, they rarely describe the benefit from technological advances as an endogenous process. Such models are used to understand the impact of policies on electricity demand. Another method relies on time series data to project future values of the loads from previously observed power demand. Finally, some methods incorporate artificial intelligence, ranging from a simple ordinary least square regression (the method used in this study) to artificial neural networks or additive models.

Although these methods use socioeconomic indicators to project long-term power demand, the number of studies considering the impacts of climate is currently limited. At a country level, Auffhammer et al. (2016) established a relationship between power demand and temperature for 166 distinct load zones in the United States. They then projected the impact of climate change on power demand using output from 20 downscaled climate models (GCM). The models projected an increase in peak events in the US in frequency and intensity, which may cause outages if the grid's capacity is not increased. On a global scale, Van Ruijven et al. (2019) used a top-down approach to project future energy demand under two emission scenarios simulated with 21 ESMs. Their approach predicted a 25% increase in energy demand in the tropics, USA, Europe, and China under high warming.

The existence of regional gaps remains one of the major issues unaddressed by the literature. Yalew et al. (2020) highlighted that regions such as South Asia, the Middle East, North Africa, and the Pacific region are under-represented in such studies. No peer-reviewed publications investigate load forecasting in Qatar, with the exception of a conference paper (Gastli et al., 2013) that explored the link between temperature and humidity and power demand in the country during 2012. The question of the climate impact on power demand and its associated CO_2 emissions in Qatar and the Middle East more generally remains unexplored.

1.3 Description of the case study

Qatar has one of the highest GDPs per capita in the world ($93,521.4 PPP in 2021(World Bank, 2021)). Its power generation capacity was 10.5 GW in 2019 (Qatar's planning and statistics Authority, 2019). However, power outages have occurred during periods of extreme heat (Bayram et al., 2018) due to the inability of the grid to meet peak demand: the 200% increase in demand between 2000 and 2010 corresponds with the pressure put upon Qatar's electricity grid. Rapid population growth also occurred during the same years, increasing from 600,000 in 2000 to nearly 2 million in 2010, primarily due to immigration (UN, 2021). Relatedly, consumption per capita increased from 9.6 MWh/capita in 1990 to 16.6 MWh/capita in 2018 (IEA, 2019). Three factors can further explain the increase in electricity demand:

1) Qatar's GDP per capita increased dramatically during the 2000s to become one of the highest in the world (9th or 10th according to the International Monetary Fund and the World Bank, respectively (World Bank, 2021, IMF, 2021).

2) Electricity prices are highly subsidized by the government and are thus low for the residential sector. The price was 0.032 US$/kWh in Qatar in December 2020 compared to 0.148 US$/kWh in the US in the same period (GPP, 2021).

3) There are no clear incentives from the government to limit the demand for electricity due to its vast amount of fossil fuel resources. Thus, people can financially afford to use large amounts of electricity. The financial accessibility of electricity combined with the very hot climate results in a high demand for cooling and induces an increase in total electricity consumption.

As temperatures in Qatar are rising faster than the global average (IPCC, 2021), it is important to elucidate the effect of increasing hot days on per capita electricity consumption and to assess the further effect on CO_2 emissions under socioeconomic scenarios.

As of 2022, all of Qatar's electricity is produced by gas-fired power plants. Such power plants resulted in emissions of 23 $MtCO_2$ in 2018 (IEA, 2019). In 2008, Qatar published its "National Vision 2030" (GSDP, 2008), where its strategy for developing renewable energy first appeared. In 2017, Qatar announced its first concrete goal: by 2030, 20% of its electricity will be produced from solar energy (OBG, 2017). However, recent studies on the development of renewable energy in Qatar and other Gulf countries argue that actions and commitments on the part of the government as well as increased public awareness of environmental issues are necessary to develop renewables, reduce per capita electricity consumption, and induce behavioral changes in the energy consumption (Umar et al., 2020, Al-Marri et al., 2018). As stated above, there are currently few incentives to reduce individual energy consumption (Al-Marri et al., 2019), which leads Umar et al. (2020) to conclude that these announced ambitions are unlikely to be realized in a timely manner. With the projected increase in the population of Qatar (Kc and Lutz, 2017) and the future increase in temperatures (IPCC, 2021), the evolution of electricity demand under climate change and the consequences it could have on CO_2 emissions have become increasingly important to understand.

This study investigates how the changes in average daily temperature can influence daily electricity demands, as well as how much the CO_2 emissions related to electricity production in Qatar may increase with warming under changing socioeconomic drivers. These questions are addressed via a novel statistical model that estimates the daily electricity demand and associated CO_2 emissions from temperature data. Section 2 describes the data used to establish the relationship between temperature and electricity demand. This section also discusses how the model considers other factors, i.e., population, GDP, and the carbon intensity of electricity production. Section 3 applies the model to future climatic conditions based on downscaled CMIP6 (Coupled Model Intercomparison Project) temperature projections bias-adjusted for the region of Qatar until the end of the century. Section 3 also presents the results for electricity demand projections and associated CO_2 emissions and estimates the contribution of climatic and socioeconomic factors to the total emissions. Section 4 then draws conclusions on the importance of considering the temperature-emissions feedback in projections of future energy and emissions changes broadly for the Middle East.

2. Material and methods: Model development

We developed a statistical model describing the temperature dependence of electricity demand using hourly electricity data from Qatar for 2016. Qatar is chosen as a representative country of the Middle East, as good quality data on the country's daily electricity consumption is available for this year (Bayram et al., (2018)). Qatar's power company has no legal obligation to publish electricity demand, consumption, or production data regularly. However, as a member of the Gulf

Cooperation Council Interconnection Authority (GCCIA), Qatar provides electricity production online in real-time on the GCC website (GCC, 2016). There is no public archive; the data had to be retrieved by the minute from the website. We aggregated the data by hours and days to calibrate our statistical model. Figures 1a and 1b present these data at a daily timescale as a function of the daily average temperature in Qatar. Qatar's daily average temperatures are based on hourly temperature values from ERA5 reanalysis (CDS, 2017) at a resolution of 0.25°x0.25° averaged within Qatar's borders. Figure 1 shows a very strong relationship between electricity demand and temperature. We performed a regression analysis to study the relationship between the electricity demand (daily and peak load) and the temperatures (daily minimum, maximum, and average temperature). We found that the highest correlation can be obtained with the daily average temperature. We fitted polynomial functions with different orders (1, 2, and 3). For the rest of the study, we retained the order of 2, which offers a compromise between a high coefficient of determination and a low normalized RMSE for the total daily load (r^2 = 0.95, RMSE = 0.057) and for hourly loads (r^2 = 0.96 and RMSE = 0.055). To account for the effect of weekends and holidays on electricity demand in Qatar, we added two categorical variables to the model for each day: the DOW variable (day of week, i.e., Monday, Tuesday, etc.) and the binary variable holiday (yes or no). Note that what is equivalent to weekends in the West are Fridays and Saturdays in Qatar. A small but statistically significant effect for peak demand was identified for Fridays, but for total daily demand, the same effect was found to be insignificant (p-value is 0.120). No effects were found to be statistically significant on holidays and Saturdays for peak and total demand with p-values higher than 0.1.

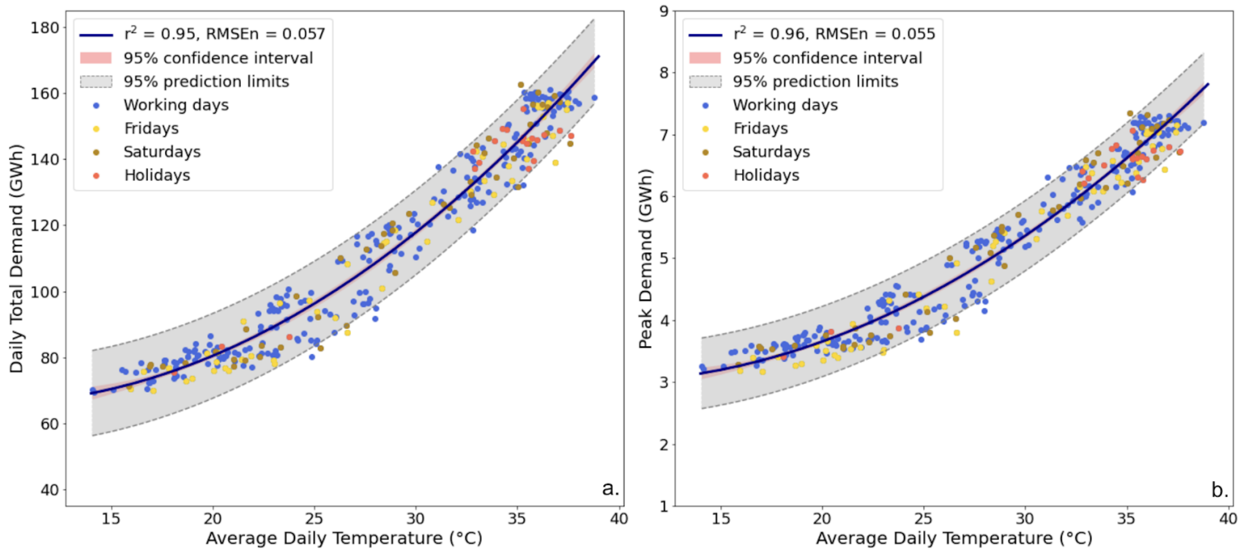

Figure 1. Relationships between temperature and power demand in Qatar

Daily total electricity demand (a) and peak demand (b) in Qatar as a function of Qatar's daily average temperature for 2016. Blue points represent working days, yellow points represent Fridays, brown points represent Saturdays, and red points represent holidays. The thick blue line is the second-order polynomial regression fit, with its 95% confidence interval in the pink area. The gray area indicates the 95% prediction limits (a 95% chance of finding the value of the electricity demand for a given temperature).

To understand the importance of the temperature effect on future CO_2 emissions from electricity production compared to the effects from socioeconomic drivers of population and GDP (Khalifa et al., 2019), we applied the Kaya Identity (Kaya, 1990), as shown in Eq. (1).

$$E = \frac{E}{TEP} \times \frac{TEP}{GDP} \times \frac{GDP}{pop} \times pop \qquad (1)$$

where E is the CO_2 emissions from electricity demand, TEP is the total electricity production, GDP is the gross domestic product, and pop is the population. $\frac{E}{TEP} = I$, where I is the carbon intensity of electricity production. We considered the effect of temperature in the term TEP: for each day, TEP is calculated with the quadratic function: $f(T_i) = aT_i^2 + bT_i + c$, where $f(T_i)$ denotes the daily demand and T_i the average temperature of the day i. The quadratic function was fitted to the daily electricity demand and temperature data of 2016. To calculate the annual demand, TEP_y, we summed the daily demand over the year y: $TEP_y = \sum_i f(T_{i,y})$. Then, we adjusted TEP_y with a scaling factor to account for the effect of population growth and GDP on power demand: $\frac{GDP_y \times pop_y}{GDP_{2016} \times pop_{2016}}$. According to Eq. (1), we multiply TEP_y by the carbon intensity of electricity production to calculate the CO_2 emissions associated with the electricity demand. Hence, we can write:

$$E_y = I_y \times TEP_y \times \frac{GDP_y \times pop_y}{GDP_{2016} \times pop_{2016}} \quad (2)$$

We chose to employ this simple approach due to the limitation of data that would be required to capture complex underlying relationships (Mir et al., 2020). More detailed modeling approaches are typically applied only over a short term. For long-term analyses such as this study, we argue that a simple approach is more appropriate, given the difficulty in explicitly describing how the socioeconomic system and the power sector may evolve throughout this century and affect CO_2 emissions. We further assume that temperature, population, GDP, and carbon intensity independently influence the CO_2 emissions from electricity production without cross-interactions.

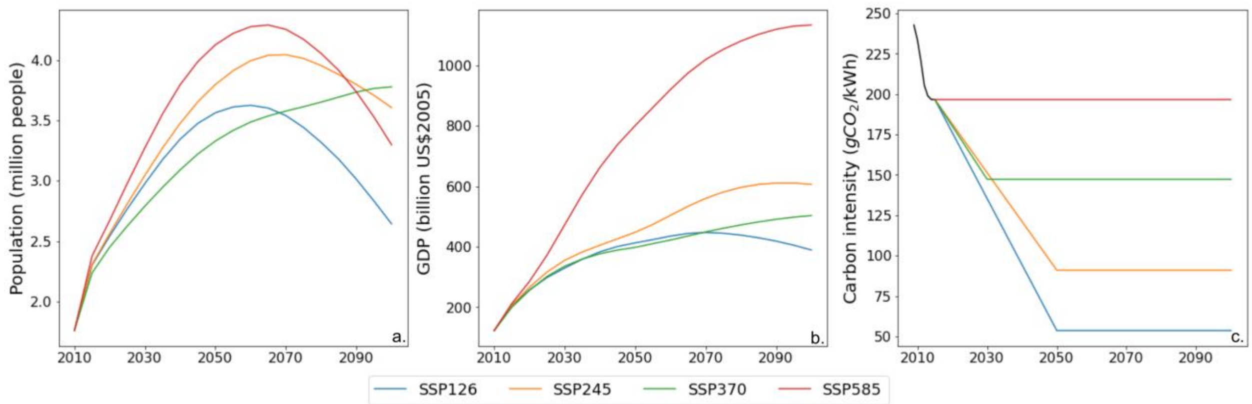

Figure 2. Projections of socioeconomic data for Qatar under different SSPs

Projections of (a) population, (b) GDP and (c) carbon intensity for Qatar until the end of this century for SSP1-2.6 (blue), SSP2-4.5 (yellow), SSP3-7.0 (green) and SSP5-8.5 (red). Population and GDP data were obtained from the SSP database (Kc and Lutz, 2017, Riahi et al., 2017, Dellink et al., 2017), *and carbon intensity values were calculated based on assumptions detailed in the Methods (section 2).*

Finally, Eqs. (1) and (2) were applied for projecting the electricity demand and CO_2 emissions using daily average temperature projections from the downscaled CMIP6 database, bias-adjusted for the region of Qatar (Cucchi et al., 2020, Werner and Cannon, 2016, Cannon et al., 2015), from ten General Circulation Models (CESM2-WACCM, CMCC-CM2, EC-Earth3, EC-Earth3-Veg, GFDL-ESM4, INM-CM4-8, INM-CM5-0, MPI-ESM1-2, MRI-ESM2-0, NorESM2). We considered four SSPs (O'Neill et al., 2017): SSP1-2.6, the sustainability scenario; SSP2-4.5, the middle of the road scenario; SSP3-7.0, the regional rivalry scenario; and SSP5-8.5, the fossil-fueled development scenario. We used specific temperature, population, and GDP projections for each SSP. The population and GDP projections (cf. Figures 2a and 2b) were obtained from the SSP database (Kc and Lutz, 2017, Riahi et al., 2017, Dellink et al., 2017). these quantitative projections for different storylines are developed by the Integrated Assessment Modeling community. The population projections were converted from the SSP storylines for 195 countries, considering age, gender, and level of education (KC and Lutz, 2017). Considering the level of education allows a better understanding of socio-economic issues that can influence demographics. These projections are available at the country level, hence, we used specific projections for Qatar. GDP projections were also developed from the SSP storylines for 184 countries, including Qatar (Dellink et al., 2017). Here we use them as an indicator of possible futures rather than a prediction since it is inherently impossible to make a long-term prediction of the socioeconomic system.

In 2011, Qatar released its Initial National Communication to the UNFCCC, in which national GHG emission factors for the power sector and water desalination (14.9 tC/TJ) were reported. These emission factors were used in this study. Concerning the evolution of carbon intensity, we made assumptions based on the literature and SSP storylines as follows:

- SSP1 — the “road for sustainability”: Qatar will fully exploit its renewable energy potential by 2050. Okonkwo et al. (2021) identified various renewable energy opportunities in Qatar and their potential. Based on that study, we established a scenario in which by 2050, Qatar would produce 92% of its electricity from renewable energies (40% with wind energy, 35% with concentrated solar power, 15% with biomass, and 2% with pumped-storage hydroelectricity); only the remaining 8% would be produced from natural gas. With this assumed energy mix, we obtained a carbon intensity of ~50 CO_2eq/kWh in 2050, which represents a decrease of approximately 75% compared to the current value. Then, the carbon intensity is assumed to remain constant for the rest of the century.
- SSP2 — “Middle of the road”: Qatar will not fully exploit its renewable energy potential but will still make significant progress in this direction. It will reach 30% of electricity produced from solar PV and 30% from wind energy by 2050. Then, the carbon intensity is assumed to be at the 2050 level for the rest of the century.

- SSP3 — "Regional rivalry": Qatar will keep to its ambitions of 20% of electricity produced by solar energy by 2030, as announced by the government (OBG, 2017). Then the carbon intensity is assumed to be at the 2030 level for the rest of the century.
- SSP5 — "Fossil-fueled development": The emission factors reported by Qatar in their 2011 National Communication to the UNFCCC are assumed for the rest of the century.

Changes in carbon intensity until the end of the century obtained with these assumptions are presented in Figure 2c. The projected decreases in carbon intensity for SSP1-2.6, SSP2-4.5, and SSP3-7.0 result from assumed environmental policies aiming to decarbonize Qatar's power sector. We made assumptions about the evolution of environmental policies in Qatar, exploiting the data available to be consistent with the SSP narratives. To estimate the CO_2 emissions from solar PV, concentrated solar power, and pumped-storage hydroelectricity, we used standard emission factors from the Base Carbon (ADEME, 2021). The emission factors for biofuels were taken from the IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006). The emission factor for natural gas (14.9 tC/TJ, i.e., ~196 gCO_2eq/kWh) was from Qatar's Initial National Communication to the UNFCCC. Validation of the statistical model can be found in the supplementary materials.

3 Results

3.1 Temperature impact on electricity demand in Qatar

3.1.1 Annual average temperature and electricity demand

First, we looked at the effect of temperature on electricity demand. We applied Eq. (2) using mean daily temperature projections while keeping population and GDP constant at their 2016 values. Figure 3 shows the results for the total daily demand, smoothened with a 10-year rolling average. Projections for the daily maximum hourly demand are shown in the supplementary materials (Figure S3), as they are very similar in trend and magnitude to the projections obtained for the total daily demand. Figure 3 shows clear differences between the SSPs during 2040-2050. In Figure 3c, there is a 15-20% increase in the electricity demand attributable only to the effect of warming. The spreads arising from different climate models are smaller than those from SSPs. Under SSP5-8.5, climate models show increasingly divergent results by the end of the century. Under this scenario, the total annual demand is projected to increase by 35% at the end of the century compared to the 1980 level due to the effect of warming alone, with a mean warming of 4°C in 2080-2100 relative to the current decade. Even under the most optimistic SSP1-2.6 scenario, the additional electricity demand reaches 10% above the current level due to the 1°C warming by the end of this century.

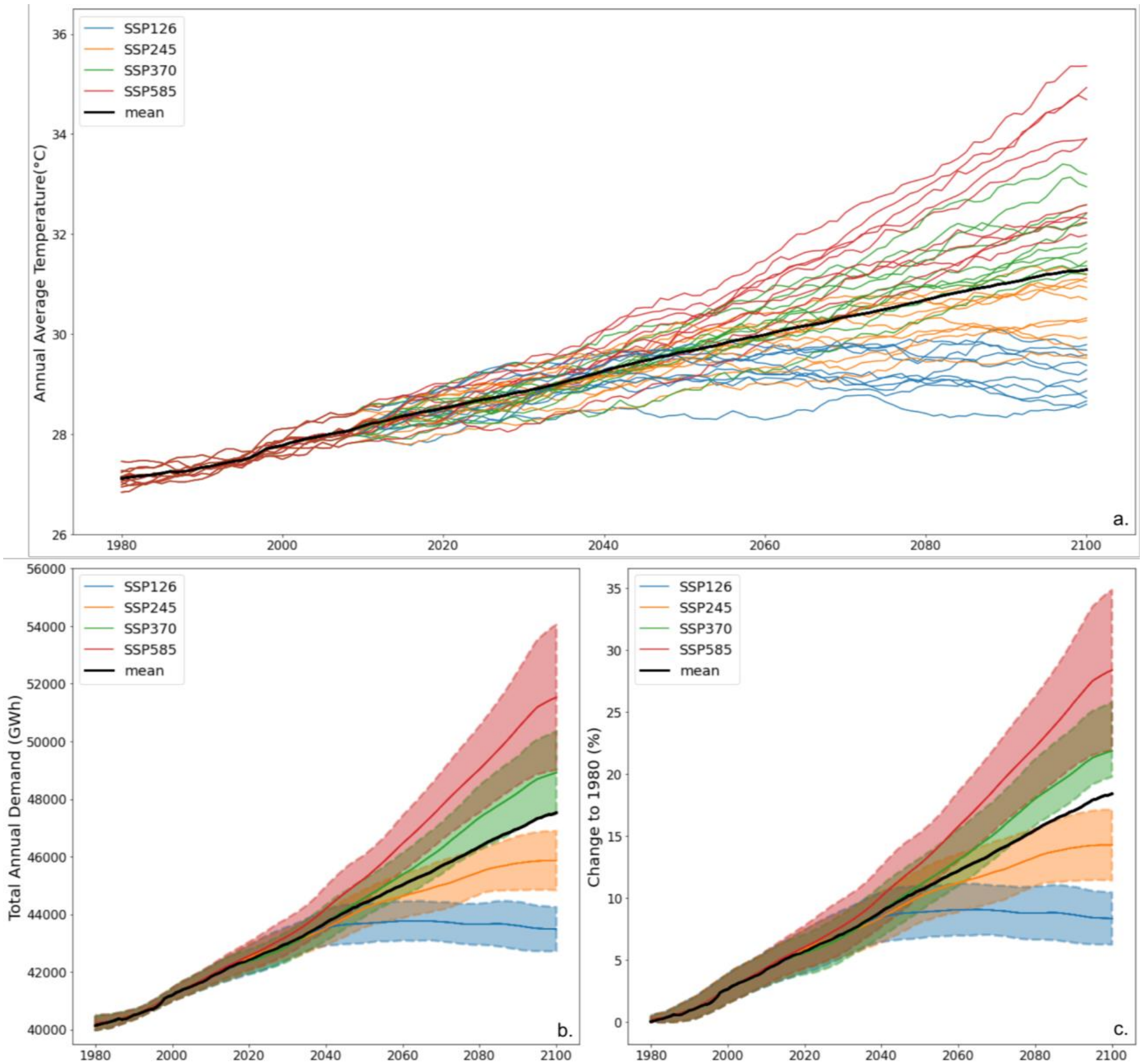

Figure 3. Projection of electricity demand and average temperature

(a) Bias-adjusted annual average temperature over Qatar from the CMIP6 database for SSP1-2.6 (blue), SSP2-4.5 (orange), SSP3-7.0 (green), and SSP5-8.5 (red) (in 10-year rolling average for the sake of presentation). Each line represents the output of one of the ten CMIP6 GCMs. (b) Total annual demand calculated with the statistical model. (c) Change in demand compared to the year 1980 (in percentage). For (b) and (c), the thick colored lines show the average of the different SSPs and the colored areas with the 1-sigma error ranges.

3.1.2 Extreme annual temperatures and electricity demand

To diagnose the effect of extremely low and high temperatures, we set a low-temperature threshold at the 5th percentile of the 2016 temperature distribution (16.8°C), under which days are categorized as “cold” days. Likewise, we defined hot days with an upper threshold at the 95th percentile of the 2016 temperature distribution (36.8°C). Figure 4a shows that the number of cold days per year is projected to decrease under all SSPs and even reach zero under SSP5-8.5. In contrast, Figure 4b shows that the number of hot days per year is projected to increase dramatically under all SSPs (except SSP1-2.6). For SSP1-2.6, the number of hot days remains approximately 50 after 2040. This indicates that the electricity demand during cold periods can decrease over the century and reach very low levels under SSP2-4.5, SSP3-7.0, and SSP5-8.5 (i.e., less than 1% of the annual demand (Figure 4c)). In contrast, we found that the electricity demand during hot periods would increase and could represent more than half of the annual consumption under SSP5-8.5 (Figure 4d). Our results suggest that most of the projected increase in electricity demand is attributable to an increased demand for air conditioning because the average temperature in Qatar is increasing, and heat waves are projected to become more frequent and severe (Zittis et al., 2021).

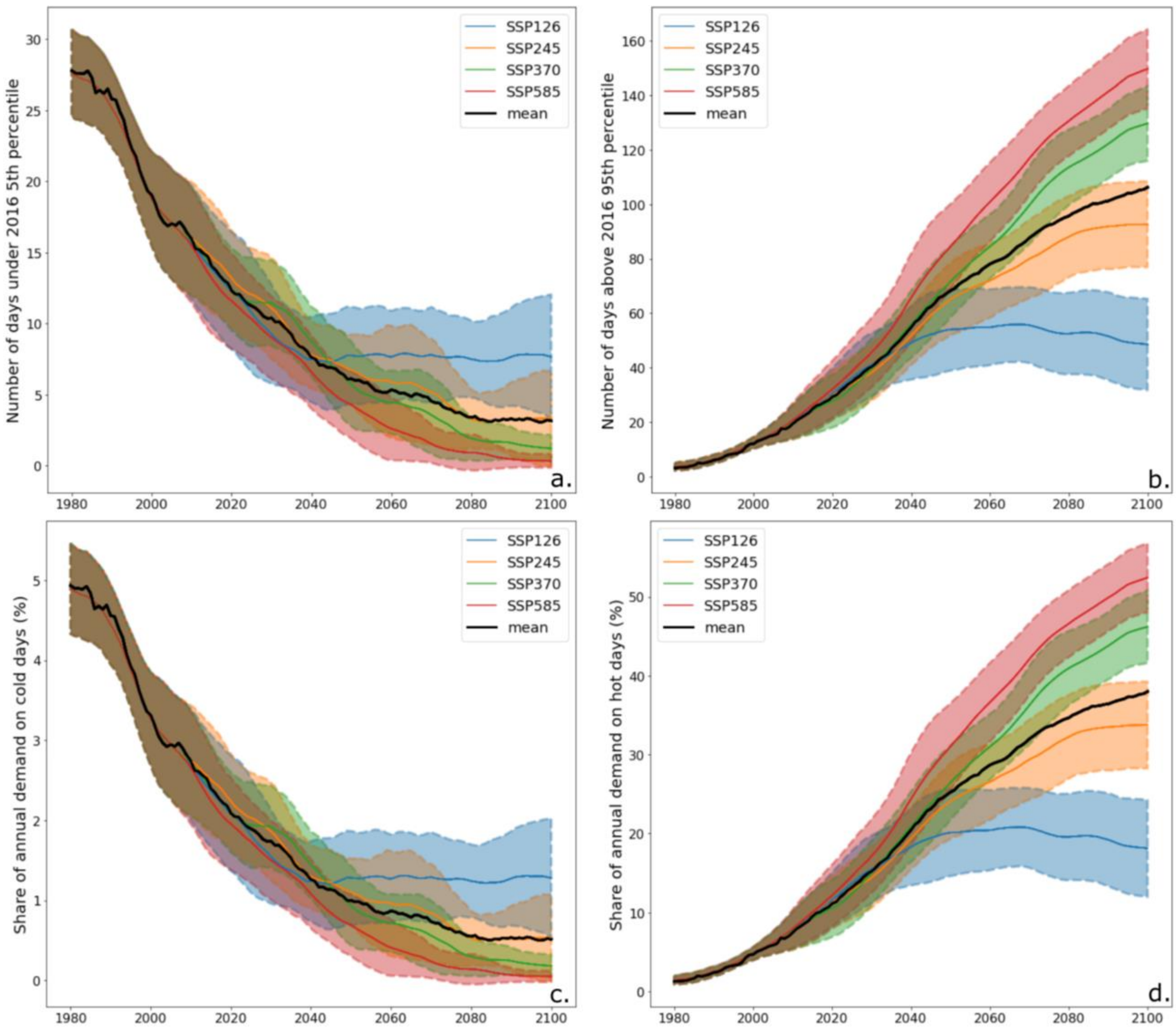

Figure 4. Electricity demand and extreme temperatures

Year-by-year evolution of the number of cold days (a) and hot days (b) per year and the share of the annual demand during those cold and hot days (c and d). The colored areas represent the 1-sigma error ranges.

3.2 Implication for CO_2 emissions in Qatar

To calculate the CO_2 emissions associated with the electricity demand, we used Eq. (2). We calculated the CO_2 emissions for the historical period (2010 - 2020) and the rest of the century. We investigated the contribution of the four independent factors: temperature, population, GDP, and carbon intensity. The results are presented in Figures 5 and 6.

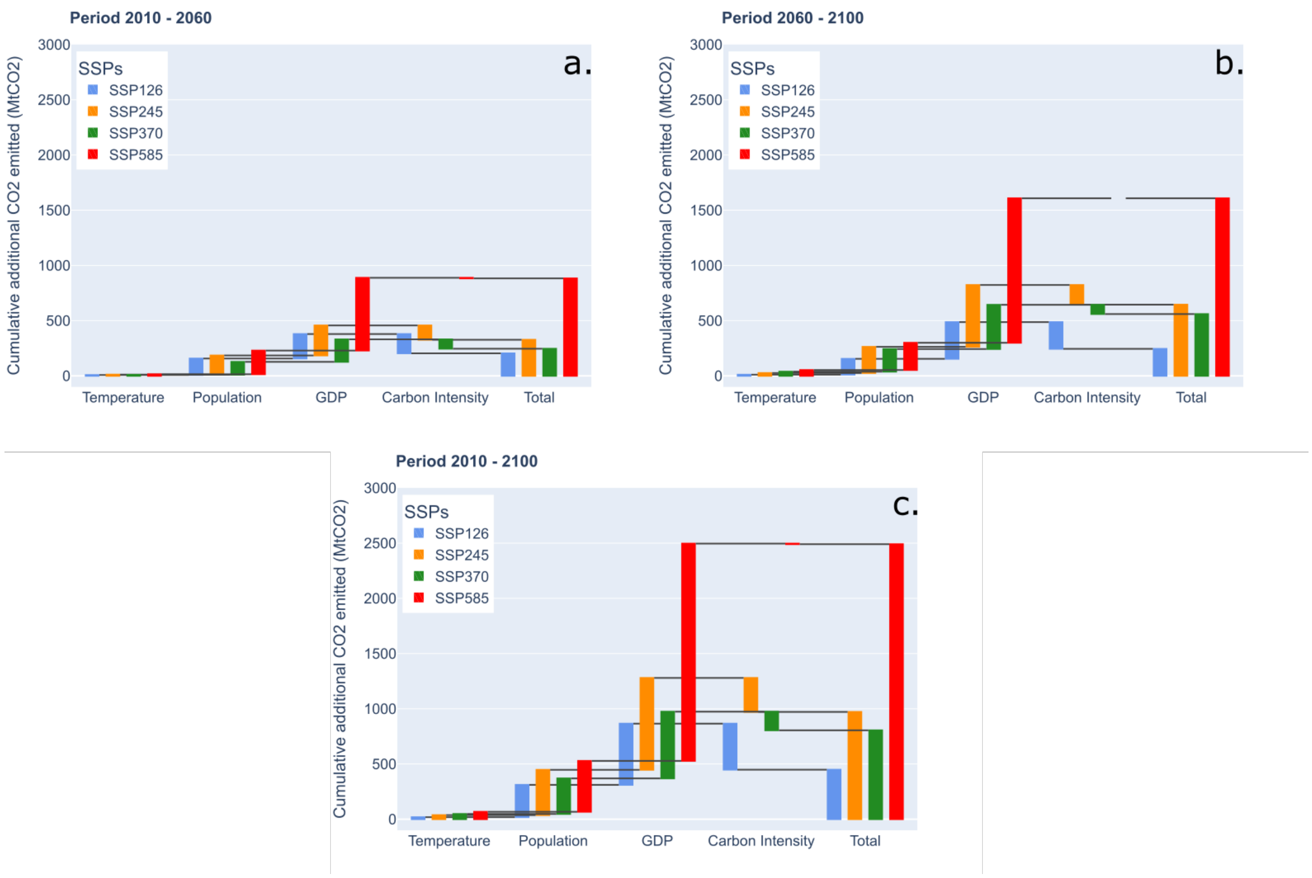

Figure 5. Attribution of additional CO_2 emissions to different factors

Contributions of changes in climate, population, GDP, and carbon intensity to the changes in cumulative CO_2 emissions from power generation over periods 2010-2060 (a), 2060-2100 (b), and 2010-2100 (c). The figure shows the change in cumulative additional CO_2 emissions due to each factor relative to the level with all other factors kept at current values.

Figure 5 shows the attribution of the additional cumulative CO_2 emissions to the different factors when only one factor varies, for two periods: the earlier period from 2010 to 2060 (Figure 5a) and the later period from 2060 to 2100 (Figure 5b). The additional cumulative CO_2 emissions attributed to each factor are obtained by varying only the factor considered and keeping the other factors constant at the level of 2016. Figure 5 highlights that the importance of the population factor for the total emissions is constant through time and comparable between all SSPs. Thus, it does not explain the difference in emissions over the whole period. Figure 5 also shows that the GDP effect increase in importance with time and explains almost all of the cumulative emissions changes between the SSPs, especially why emissions in SSP5-8.5 are projected to be more important at this point than those of other scenarios. Indeed, in the second half of the century, the cumulative CO_2 emissions in SSP5-8.5 will be more than twice as large as those in all other SSPs; this occurrence is also visible in the evolution of annual emissions (figure 6). Furthermore, the results for the entire period (Figure 5c) show that when temperature alone is considered, it is not an important factor compared to other factors in determining the additional CO_2 emissions.

Figure 6 gives a more nuanced picture by representing the annual CO_2 emissions with and without the effect of temperature change for all SSPs. This result highlights that when combined with the effect of socioeconomic factors, climate change accentuates the changes in annual emissions. The difference in annual emissions between the two scenarios (with and without temperature change) increases over time and with the level of global warming. Under SSP5-8.5, the difference in emissions due to a warmer climate reaches more than 10 $MtCO_2$ per year, while under SSP1-2.6, it is hardly perceptible. This emphasizes the importance of considering the effect of climate change when following a given economic scenario with high warming. Otherwise, the impact on CO_2 emissions may be underestimated.

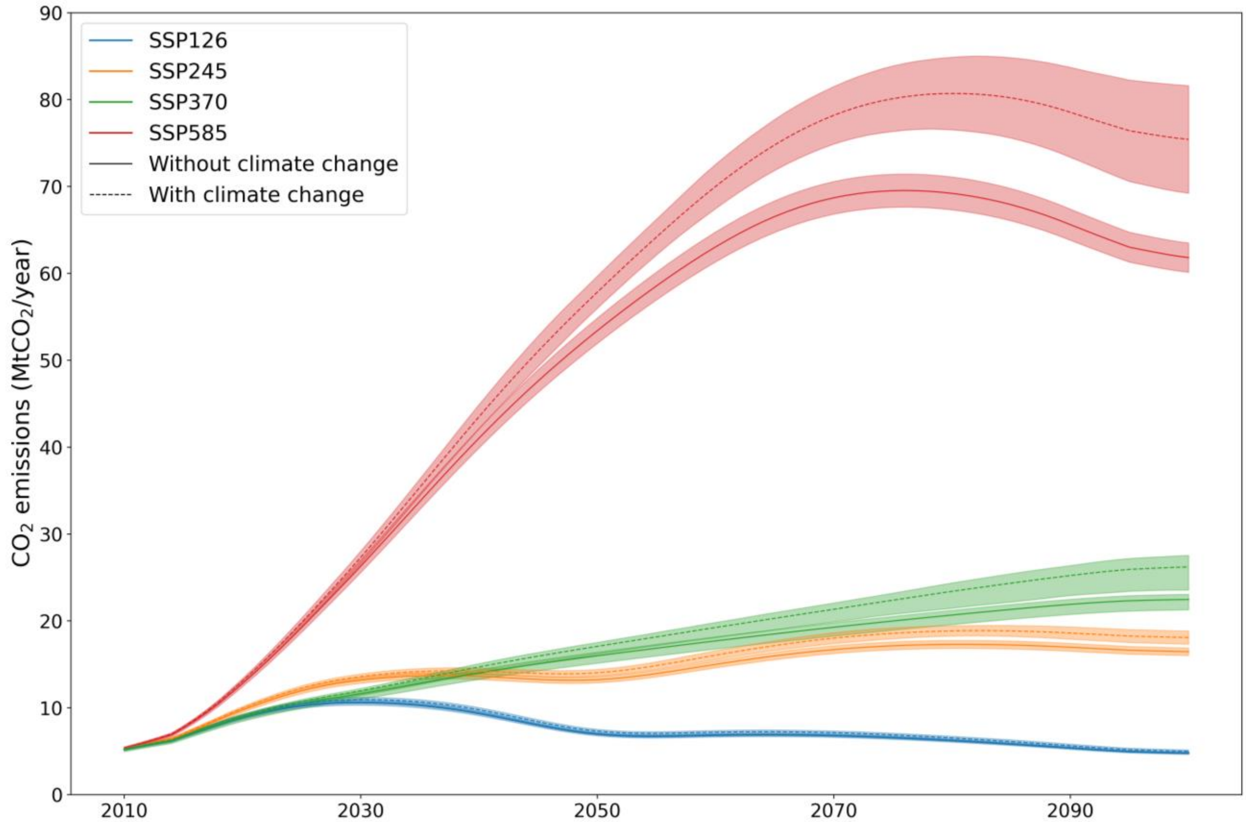

Figure 6. Projection of CO_2 emissions with socio-economic effects and with or without climate change effect

Projection of the evolution of CO_2 emissions through the century from socio-economic changes with no climate change (straight lines) and with the effect of socio-economic changes and climate change (dashed lines). The colored areas represent the standard 95% confidence intervals.

3.3 Generalization of the study to Gulf Cooperation Council (GCC) countries

The Arab states around the Gulf form a regional union, with the aim of intergovernmental and economic cooperation, known as the GCC. This organization brings together the following six countries: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. In this study, we developed a statistical model specifically for Qatar using electricity consumption data available for this country. Now, we extend the analysis to all GCC countries to gain insight into what the temperature-emission relationship we obtained for Qatar might mean to all GCC countries.

Since GCC countries have common climatic conditions and share similar socioeconomic and industrial structures, we assume that the relationship between temperature and electricity demand is the same in all these countries. We further assume that the carbon intensity of these countries is at the same level as Qatar due to their vast fossil fuel resources (in all these countries, electricity is produced mainly from natural gas, except for Saudi Arabia, which also uses crude oil in significant amounts (Akhonbay, 2020) and renewable resources (mainly wind and solar). However, these countries do not necessarily have the same potential (Bhutto et al., 2014) for development of renewable energies. The governments of GCC countries have set decarbonization targets for 2030 (Praveen et al., 2020). Still, they are also facing the same challenges regarding the development of renewable energies as Qatar; their major challenge is the reluctance of citizens to switch to renewable energy for financial reasons (Al-Maamary et al., 2017). Here, we upscale our model for Qatar to these countries by linearly adjusting to the population, GDP, and temperature of these countries and project CO_2 emissions based on the electricity production of GCC countries. To quantify the final impact of these additional CO_2 emissions on global temperature, we used the simple climate model Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate model (ACC2) (Tanaka and O'Neill, 2018, Tanaka et al., 2007, Tanaka et al., 2021), which allows for estimating the global temperature change caused by the emissions from the electricity production of the GCC countries. The results and further details of the methodology are provided in the supplementary materials (Figure S4). Depending on the SSP, the temperature-energy demand feedback from the GCC countries shows additional CO_2 emissions that range from 0.303% (SSP1-2.6) to 2.045% (SSP2-4.5) of the total CO_2 emissions generated via the electricity production by the end of this century. The further impact of this feedback in GCC countries on global temperature ranges from 0.082% (SSP1-2.6) to 0.278% (SSP5-8.5) by the end of this century.

4 Discussion

To develop future projections of electricity demand and CO_2 emissions, we made assumptions about the relationship between electricity demand and population and the relationship between electricity demand and GDP. Narayan and Prasad (2008) show that the relationship between GDP and electricity demand is country-specific and depends on development stage. As there is no relevant study on Qatar, to our knowledge, we adopted a unidirectional causality from GDP to electricity consumption, *i.e.,* we assume that GDP impacts demand but that the demand does not have any feedback on GDP. This is an initial, simple approach, and deserves discussion. For example, there is evidence of a long-run unidirectional relationship from GDP to electricity consumption for renewable energy consumption (Kula, 2014). However, with fossil fuels, the unidirectional nature of the relationship can be questioned (Alsaedi and Tularam, 2020, Ikegami and Wang, 2016). Indeed, in a study by Alsaedi and Tularam (2020), a bidirectional causal relationship between electricity consumption and GDP was found in Saudi Arabia. This country has an energy sector similar to that in Qatar. These studies show that the relationship between GDP and electricity demand is probably not as simple as the unidirectional relationship used in our study.

For the effect of population growth on electricity demand, we adopted a hypothesis similar to that for GDP, *i.e.,* linear growth of the demand for electricity with an increase in population. Although this seems true for domestic demand (Ali and Alsabbagh, 2018), it is not necessarily the case for industrial consumption. However, in our projections of the electricity demand in Qatar, we consider the individual and industrial demand without distinction. This lack of distinction is a limitation of our study.

Several studies create an inventory of the renewable energy sources present in the Arabian Gulf states, evaluate their potential, and review the existing policies of these states for renewable energy development (Bhutto et al., 2014, Al-Maamary et al., 2017, Elrahmani et al., 2021). In the case of Qatar, the potential of renewable energy was quantified by Okonkwo et al. (2021). We used figures from this study to establish our carbon intensity projections. However, the future development of low-carbon energy instead of fossil fuels depends on the government's will. We assumed that this intent is accounted for in the SSPs' narratives. Nevertheless, as these figures are designed for global applications, we had to adapt them for Qatar, which entailed strong assumptions about the future share of renewables in each SSP narrative. For example, for SSP5-8.5, we assumed that the carbon intensity would not experience any changes from the present. This allows us to study what can happen in a very carbon-intensive scenario, which is not in line with the pledge of the Qatari government to achieve a 20% solar energy mix by 2030. Furthermore, there is an ongoing debate on the future likelihood of scenarios such as SSP5-8.5 based on recent emissions trends (Hausfather and Peters, 2020).

Finally, important aspects that impact electricity demand are not explicitly considered in our study, such as urbanization and income inequalities. Indeed, Al-Bajjali and Shamayleh (2018) showed that Jordan has experienced a positive effect of urbanization on consumption, which may be important, and Andrijevic et al. (2021) showed that significant regional inequalities in access to air conditioning arise from urbanization dynamics and income inequalities.

5 Conclusion

Our study quantified the impact of climate and socioeconomic factors on power demand in Qatar and how the change in power demand can further influence CO_2 emissions. Qatar's hot climate is one of the drivers of its high per capita power demand. Our results show that regardless of scenario, the power demand increases with future climate change: a 4.2% increase in the power demand of GCC countries occurs per degree of warming. When considered alone, the effect of climate change on the power demand and the further effect on CO_2 emissions are small relative to socioeconomic factors, i.e., population, GDP, and carbon intensity. However, when CO_2 emissions are calculated considering the impact of climate change combined with the evolution of socioeconomic factors, CO_2 emissions can be significantly higher. Carbon intensity can be decreased through decarbonization policies, which play an important role in reducing the CO_2 emissions from power generation in Qatar and the Middle East.

References

IPCC, 2021 Masson-Delmotte, V., Zhai, P., A., Pirani, L., Connors S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al. (2021). Summary for Policy Maker - Climate Change 2021: The Physical Science Basis. Contribution of WG1 to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

IEA, 2019 Energy Transition Indicators (IEA, Paris).

Okonkwo et al., 2021 Okonkwo, E.C., Wole-Osho, I., Bamisile, O., Abid, M., and Al-Ansari, T. (2021). Grid integration of renewable energy in Qatar: Potentials and limitations. Energy 235, 121310.

Alrawi et al., 2019 Alrawi, O., Bayram, I.S., Al-Ghamdi, S.G., and Koc, M. (2019). High-Resolution Household Load Profiling and Evaluation of Rooftop PV Systems in Selected Houses in Qatar. Energies 12, 3876.

Valor et al., 2001 Valor, E., Meneu, V., Caselles, V. (2001). Daily Air Temperature and Electricity Load in Spain. American Meteorological Society 40, 1413-1421.

Jovanovic et al., 2015 Jovanovic, S., Savic, S., Bojic, M., Djordjevic, Z., Nikolic, D. (2015). The impact of the mean daily air temperature change on electricity consumption. Energy 88, 604-609.

Canales et al., 2020 Canales, F.A., Jadwiszczak, P., Jurasz, J., Wdowikowski, M., Ciapala, B., Kaźmierczak B. (2020) The impact of long-term changes in air temperature on renewable energy in Poland. Science of the Total Environment 729, 138965.

Mir et al., 2020 Mir, A.A., Alghassab, M., Ullah, K., Khan, Z.A., Lu, Y., Imran, M. (2020) A Review of Electricity Demand Forecasting in Low and Middle-Income Countries: The Demand Determinants and Horizons. Sustainability, 12. 5931

Auffhammer et al., 2016 Auffhammer, M., Baylis, P., and Hausman, C.H. (2016) Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. PNAS, 114 (8) 1886-1891

Yalew et al., 2020 Yalew, S.G., van Vliet, M.T.H., Gernaat, D.E.H.J., et al. Impacts of climate change on energy systems in global and regional scenarios. Nat Energy 5, 794–802 (2020). https://doi.org/10.1038/s41560-020-0664-z

Van Ruijven et al., 2019 van Ruijven, B.J., De Cian, E. & Sue Wing, I. Amplification of future energy demand growth due to climate change. Nat Commun 10, 2762 (2019). https://doi.org/10.1038/s41467-019-10399-3

Gastli et al., 2013 Gastli, A., Charabi, Y., Alammari, R., and Al-Ali, A. (2013). Correlation Between Climate Data and Maximum Electricity Demand in Qatar. 7th IEEE GCC Conference and Exhibition (GCC), pp. 565-570.

World Bank, 2021 World Bank, and Eurostat-OECD PPP program (GDP per capita, PPP). The World Bank Data. https://donnees.banquemondiale.org/indicateur/NY.GDP.PCAP.PP.CD.

Qatar's Planning and Statistics Authority, 2019 Planning and Statistics Authority (2019). Chapter III Electricity and Water Statistics (State of Qatar).

Bayram et al., 2018 Bayram, I.S., Saffouri, F., and Koc, M. (2018). Generation, analysis, and applications of high resolution electricity load profiles in Qatar. J. Clean. Prod. 183, 527–543.

UN 2021 UN Department of Economics and Social Affairs Revision of World Population Prospects. https://population.un.org/wpp/.

IMF 2021 International Monetary Fund GDP, current prices. IMF Datamapper. https://www.imf.org/external/datamapper/NGDPD@WEO/OEMDC/ADVEC/WEOWORLD.

GPP 2021 Electricity Prices GlobalPetrolPrices. https://www.globalpetrolprices.com/electricity_prices/.

GSDP 2008 General Secretariat for Development Planning (2008). Qatar National Vision 2030 (General Secretariat for Development Planning).

OBG 2017 Oxford Business Group Qatar gets serious about solar. https://oxfordbusinessgroup.com/news/qatar-gets-serious-about-solar.

Umar et al., 2020 Umar, T., Egbu, C., Ofori, G., Honnurvali, M.S., Saidani, M., and Opoku, A. (2020). Challenges towards renewable energy: an exploratory study from the Arabian Gulf region. Proceedings of the Institution of Civil Engineers - Energy 173, 68–80.

Al-Marri et al., 2018 Al-Marri, W., Al-Habaibeh, A., and Watkins, M. (2018). An investigation into domestic energy consumption behaviour and public awareness of renewable energy in Qatar. Sustainable Cities and Society 41, 639–646.

Kc and Lutz, 2017 Kc, S., and Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Glob. Environ. Change 42, 181-192

Riahi et al., 2017 Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., et al. (2017). The Shared Socioeconomic

Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Change 42, 153–168.

GCC, 2016 GCC Demand Now. Gulf Cooperation Council Interconnection Authority. https://www.gccia.com.sa/.

CDS 2017 Copernicus Climate Change Service Climate Data Store (CDS) (2017). ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate.

Khalifa e al., 2019 Khalifa, A., Caporin, M., and Di Fonzo, T. (2019). Scenario-based forecast for the electricity demand in Qatar and the role of energy efficiency improvements. Energy Policy 127, 155–164.

Kaya, 1990 Kaya, Y. (1990). Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios (IPCC Energy and Industry Subgroup, Response Strategies Working Group).

Cucchi et al., 2020 Cucchi, M., Weedon, G.P., Amici, A., Bellouin, N., Lange, S., Müller Schmied, H., Hersbach, H., and Buontempo, C. (2020). WFDE5: bias-adjusted ERA5 reanalysis data for impact studies. Earth Syst. Sci. Data 12, 2097–2120.

Werner and Cannon, 2016 Werner, A.T., and Cannon, A.J. (2016). Hydrologic extremes – an intercomparison of multiple gridded statistical downscaling methods. Hydrol. Earth Syst. Sci. 20, 1483–1508.

Cannon et al., 2015 Cannon, A.J., Sobie, S.R., and Murdock, T.Q. (2015). Bias Correction of GCM Precipitation by Quantile Mapping: How Well Do Methods Preserve Changes in Quantiles and Extremes? J. Clim. 28, 6938–6959.

O'Neill et al., 2017 O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change 42, 169–180.

Dellink et al., 2017 Dellink, R., Chateau, J., Lanzi, E., and Magné, B. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. Glob. Environ. Change 42, 200–214.

ADEME 2021 ADEME Documentation Base Carbone. Bilan GES ADEME. https://www.bilans-ges.ademe.fr/fr/accueil/contenu/index/page/presentation/siGras/0.

Eggleston et al., 2006 Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (2006). IPCC Guidelines for National Greenhouse Gas Inventories (IPCC).

Zittis et al., 2021 Zittis, G., Hadjinicolaou, P., Almazroui, M., Bucchignani, E., Driouech, F., El Rhaz, K., Kurnaz, L., Nikulin, G., Ntoumos, A., Ozturk, T., et al. (2021). Business-as-usual will lead to super and ultra-extreme heatwaves in the Middle East and North Africa. npj Climate and Atmospheric Science 4, 1–9.

Akhonbay, 2020 Akhonbay, H.M. (2020). The Economics of Renewable Energy in the Gulf H. M. Akhonbay, ed. (Routledge).

Bhutto et al., 2014 Bhutto, A.W., Bazmi, A.A., Zahedi, G., and Klemeš, J.J. (2014). A review of progress in renewable energy implementation in the Gulf Cooperation Council countries. J. Clean. Prod. 71, 168–180.

Praveen et al., 2020 Praveen, R.P., Keloth, V., Abo-Khalil, A.G., Alghamdi, A.S., Eltamaly, A.M., and Tlili, I. (2020). An insight to the energy policy of GCC countries to meet renewable energy targets of 2030. Energy Policy 147, 111864.

Al-Maamary et al., 2017 Al-Maamary, H.M.S., Kazem, H.A., and Chaichan, M.T. (2017). Renewable energy and GCC States energy challenges in the 21st century: A review. International Journal of Computation and Applied Sciences 2, 11–18.

Tanaka and O'Neill, 2018 Tanaka, K., and O'Neill, B.C. (2018). The Paris Agreement zero-emissions goal is not always consistent with the 1.5°C and 2°C temperature targets. Nature Climate Change 8, 319-324

Tanaka et al., 2007 Tanaka, K., Kriegler, E., Bruckner ,T., Hooss. G., Knorr. W., Raddatz, T. (2007) Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate Model (ACC2) – description of the forward and inverse modes. Reports on Earth System Science, vol 40. Max Planck Institute for Meteorology, Hamburg

Tanaka et al., 2021 Tanaka, K., Boucher, O., Ciais, P., Johansson, D.J.A., Morfeldt, J. (2021) Cost-effective implementation of the Paris Agreement using flexible greenhouse gas metrics. Science Advances 7 (22):eabf9020. doi:10.1126/sciadv.abf9020

Narayan and Prasad, 2008 Narayan, P.K., and Prasad, A. (2008). Electricity consumption–real GDP causality nexus: Evidence from a bootstrapped causality test for 30 OECD countries. Energy Policy 36, 910–918.

Kula, 2014 Kula, F. (2014). The Long-run Relationship Between Renewable Electricity Consumption and GDP: Evidence From Panel Data. Energy Sources Part B: Econ. Plan. Policy 9, 156–160.

Alsaedi and Tularam, 2020 Alsaedi, Y.H., and Tularam, G.A. (2020). The relationship between electricity consumption, peak load and GDP in Saudi Arabia: A VAR analysis. Math. Comput. Simul. 175, 164–178.

Ikegami and Wang, 2016 Ikegami, M., and Wang, Z. (2016). The long-run causal relationship between electricity consumption and real GDP: Evidence from Japan and Germany. Journal of Policy Modeling 38, 767–784.

Ali and Alsabbagh, 2018 Ali, H., and Alsabbagh, M. (2018). Residential Electricity Consumption in the State of Kuwait. Environment Pollution and Climate Change 2, 1–7.

Al-Bajjali and Shamayleh, 2018 Al-Bajjali, S.K., and Shamayleh, A.Y. (2018). Estimating the determinants of electricity consumption in Jordan. Energy 147, 1311–1320.

Andrijevic et al., 2021 Andrijevic, M., Byers, E., Mastrucci, A., Smits, J., and Fuss, S. (2021) Future cooling gap in shared socioeconomic pathways. Environmental Research Letters 16 094053

Elrahmani et al., 2021 Elrahmani, A., Hannun, J., Eljack, F., and Kazi, M.-K. (2021). Status of renewable energy in the GCC region and future opportunities. Curr. Opin. Chem. Eng. 31, 100664.

Hausfather and Peters, 2020 Hausfather, Z., and Peters, G.P. (2020) RCP8.5 is a problematic scenario for near-term emissions. Proceedings of the National Academy of Sciences Nov 2020, 117 (45) 27791-27792; DOI: 10.1073/pnas.2017124117