Climate Change Induced Increase on Power Demand and CO 2 Emissions in the Middle East (Qatar)

Léna Gurriaran[1], Katsumasa Tanaka[2], ISLAM SAFAK BAYRAM[3], Yiannis Proestos[4], Jos Lelieveld[4], and Philippe Ciais[5]

[1]LSCE
[2]CEA Saclay,National Institute for Environmental Studies (NIES)
[3]University Of Strathclyde,University of Strathclyde
[4]The Cyprus Institute
[5]IPSL

November 26, 2022

Abstract

The hotter the climate is, the higher the demand for cooling is, leading to more electricity consumption and CO2 emissions. To understand the effect of future regional warming on the electricity demand and CO2 emissions in the Arabian Peninsula region, we selected a representative country, Qatar, and developed a model that relates daily electricity demand with temperature. By combining this model with temperature projections from of 1 23 the CMIP6 database (bias adjusted and statistically downscaled), as well as GDP and population projections from four SSP scenarios, we calculated Qatar's demand for electricity until the end of the century. We found an average sensitivity of 1.7 GWh/°C for the electricity demand, equivalent to 0.4 MtCO2/°C for CO2 emissions. The electricity demand is projected to increase by 5 to 35% due to warming alone at the end of this century. Under SSP1, the warming-induced CO2 emissions could be offset by improvements of carbon intensity. Under SSP5, assuming no improvement of carbon intensity, future warming could add 20 to 35% of CO2 emissions per year by the end of the century, with half of the electricity demand related to extremely hot days becoming more frequent in the future. Our findings suggest that it is important to consider additional CO2 emissions arising from future warming in future temperature projections.

Climate Change Induced Increase on Power Demand and CO_2 Emissions in the Middle East (Qatar)

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

The hotter the climate is, the higher the demand for cooling is, leading to more electricity consumption and CO_2 emissions. To understand the effect of future regional warming on the electricity demand and CO_2 emissions in the Arabian Peninsula region, we selected a representative country, Qatar, and developed 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), as well as GDP and population projections from four SSP scenarios, we calculated Qatar's demand for electricity until the end of the century. We found an average sensitivity of 1.7 GWh/°C for the electricity demand, equivalent to 0.4 $MtCO_2$/°C for CO_2 emissions. The electricity demand is projected to increase by 5 to 35% due to warming alone at the end of this century. Under SSP1, the warming-induced CO_2 emissions could be offset by improvements of carbon intensity. Under SSP5, assuming no improvement of carbon intensity, 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 extremely hot days becoming more frequent in the future. Our findings suggest that it is important to consider additional CO_2 emissions arising from future warming in future temperature projections.

Keywords

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

1. Introduction

There is virtually a consensus that fossil fuel CO_2 emissions induce global warming[1], but how rising temperatures will in turn influence anthropogenic CO_2 emissions is a question that remains less addressed. According to the International Energy Agency[2], more than 40% of the global anthropogenic CO_2 emissions in 2018 originate from electricity and heat producers. But for the generation of the same amount of electricity, countries do not emit the same amount of CO_2. In Middle East countries, the vast majority of electricity is produced with fossil fuels. In Qatar, which is the focus of this study, 100% of the electricity is currently produced with natural gas[2,3]. The main electricity use in Qatar is air conditioning for the residential sector[4], so warmer conditions in the future will raise the electricity demand, unless decarbonization policies such as the installation of photovoltaics and improvements in building energy efficiency, or changes in habits counteract this response. We aim to study how the current occurrence of hot days and the regional warming in the future may influence the demand for electricity in Qatar, and the feedback of warming on electricity-related CO_2 emissions.

Qatar has one of the highest GDPs in the world (146 billion US$ in 2020 according to The World Bank[5]) and is equipped with an installed power generation capacity of 10.5 GW in 2019[6]. Yet, meeting the peak demand is still not guaranteed and power outages can occur during periods of extreme heat[7]. Qatar's electricity grid is under pressure due to an increase in demand by 200% between 2000 and 2010. At the same time a rapid growth in population took place, going from 600,000 inhabitants in 2000 to almost 2 millions in 2010 due to immigration[8]. The increase of the population has a direct impact on the total consumption and production of electricity, but we also observed an increase of the consumption per capita - from 9.6 MWh/capita in 1990 to 16.6 MWh/capita in 2018[2] - which can be partly explained by the following three factors: 1) Qatar's GDP per capita has increased dramatically during the 2000s, to be one of the highest in the world (9th or 10th according to the International Monetary Fund and The World Bank[5,9]), 2) electricity prices are highly subsidized by the government, 0.032 US$/kWh in Qatar in December 2020 against 0.148 US$/kWh in the US at the same time[10], and 3) There are no clear incentives from the government to limit the demand for electricity. Thus people can financially afford to use a lot of electricity do so. This combined with a very hot climate causing high demand for cooling, induced the increase in total electricity consumption. As temperatures in Qatar are rising faster than the global average[1] it is important to elucidate the contribution of the incidence of hot days in the per capita electricity consumption and to assess the contribution of warming vs. other factors on CO_2 emissions projections.

Today, all of Qatar's electricity is produced by gas-fired power plants, which results in the emissions of 23 $MtCO_2$ in 2018[2]. In 2008, Qatar published its "National Vision 2030"[11] where the subject of renewable energy deployment started to be addressed. In 2017 Qatar announced a first concrete goal : in 2030, 20% of its electricity will be produced from solar energy[12]. But according to recent studies about the development of renewable energy in Qatar and other Gulf countries, in order to develop renewables and reduce the per capita electricity consumption, it is necessary not only to have actions and commitments on the part of the government, but also to increase the awareness of the people about environmental issues so that their behavior in terms of energy consumption can change[13,14]. As mentioned above, there are so far little incentives to reduce individual energy consumption per capita[14], which leads Umar et al.[13] to conclude that these announced ambitions are unlikely to be realized in time. With the projected increase in population of Qatar[15], more or less a doubling by the end of the century, depending on which Shared Socioeconomic Pathway (SSP) we consider[16], and the increase in temperatures[1], it is legitimate to ask how the demand for electricity will evolve in this country in response to the change of average daily temperature and what consequences this could have on CO_2 emissions.

Specifically, in this study two research questions are addressed: 1) what is the current dependency of daily electricity demand on temperature and 2) how much will the CO_2 emissions related to the electricity production in Qatar increase from temperature change compared to other socio-economic drivers. Here we strive to answer those questions by developing an empirical statistical model to estimate the daily electricity demand and associated CO_2 emissions from temperature data. In section 2, we describe the data we used to establish the relationship between temperature and electricity demand and how we developed a model taking into account the effect of other factors, i.e. GDP, population and the carbon intensity of electricity production. In section 3, we apply it to possible future conditions, using downscaled CMIP6 (Coupled Model Intercomparison Project) temperature projections bias-adjusted for the region of Qatar until the end of the century. We present the results for electricity demand projections and associated CO_2 emissions and estimate the contribution of the different factors to the total emissions. Conclusions are drawn on the importance of considering the temperature-emissions feedback in projections of future energy and emissions changes in the Middle East.

2. Material and methods : model development

We developed a model of the temperature dependence of electricity demand, using hourly electricity data from Qatar for the year 2016. Qatar is chosen here as a representative country of the Middle East as we have access to daily electricity consumption data of good quality. The data are presented in Bayram et al.[7] and are available only for one year as it is difficult to access long-term high-frequency data. There is no legal obligation to regularly publish electricity demand, consumption or production data in Qatar, but as a member of the Gulf Cooperation Council Interconnection Authority (GCCIA) electricity production is provided online in real time on the GCC website[17]. There is no public archive so the data had to be retrieved every minute from the website. This has been done for the year 2016. We aggregated the data by hour and day, to calibrate our model. Hourly demand is used to model the daily peak demand and daily demand to model the daily total demand. Figure 1a and 1b present those data at a daily timescale as a function of the daily average temperature in Qatar. To get Qatar's daily average temperature we used hourly temperature values from ERA5 reanalysis[18] at a resolution of 0.25°x0.25°, averaged within Qatar's borders. Figure 1 shows the very strong relationship between the electricity demand and the temperature. We have applied regression analysis to study the effects of electricity demand (daily load and peak load) as a function of daily minimum, maximum and average temperature and found the best correlation is with the daily average temperature. We fitted polynomial functions with different orders (1, 2 and 3) and for the rest of the study we retained the order of 2, which offers the best compromise between a high correlation coefficient and a low normalized RMSE for daily total load (r^2 = 0.95, RMSEn = 0.057) and for hourly loads (r^2 = 0.96 and RMSEn = 0.055). To account for the effect of weekends and holidays on the electricity demand in Qatar, we added two categorical variables to the model: for each day we precise the variable DOW (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. For peak demand a small but statistically significant effect has been identified for Fridays but for daily total demand the same effect is not significant (p-value is 0.120). For holidays and Saturdays no effects were found statistically significant both for peak and total demand with p-values always higher than 0.1.

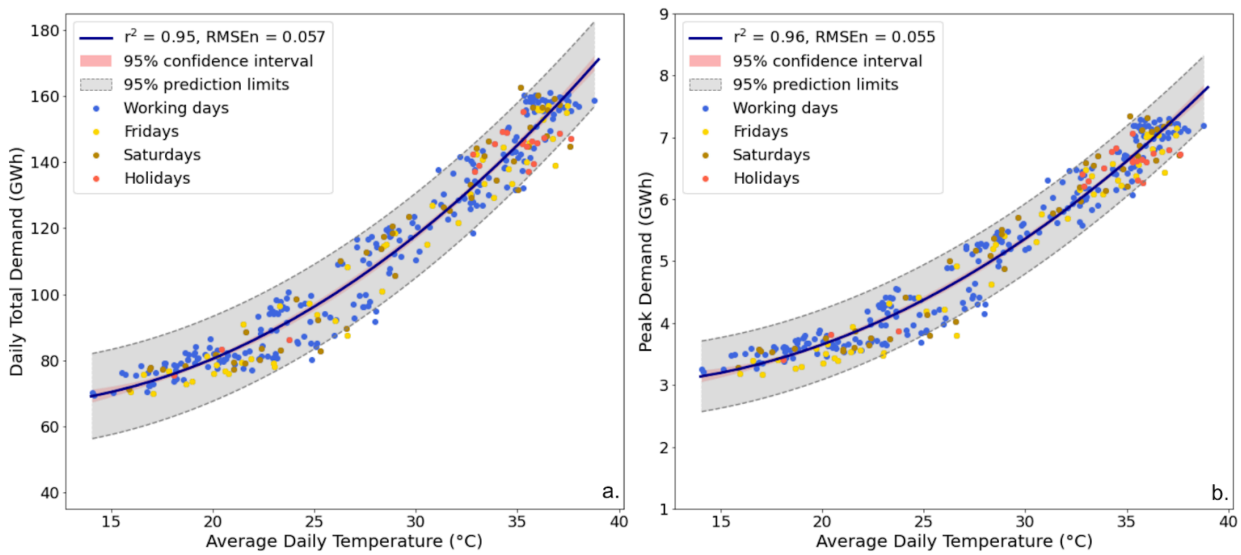

Figure 1. Model development based on data

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

To understand the importance of warmer temperatures on future CO_2 emissions from electricity production compared to socio-economic drivers of Population and GDP[19], we applied the Kaya Identity[20] 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 the total electricity demand, GDP the gross domestic product, and pop the population. $\frac{E}{TEP} = I$, where I is the carbon intensity of electricity production. We take into account the effect of temperature in the term TEP : for each day, TEP is calculated with the quadratic function fitted to the data of year 2016 applied to the average temperature of day i (T_i) : $f(T_i) = aT_i^2 + bT_i + c$. To get the annual demand, TEP_y, we sum the daily demand over year y : $TEP_y = \sum_i f(T_i)_y$. Then we scale TEP_y with the population and GDP of year y. According to Eq. (1), to get the CO_2 emissions associated to the electricity demand we multiplied TEP_y by the carbon intensity of electricity production. Hence, we can write:

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

We assume that temperature, population, GDP and carbon intensity are independent factors controlling the CO_2 emissions from electricity production.

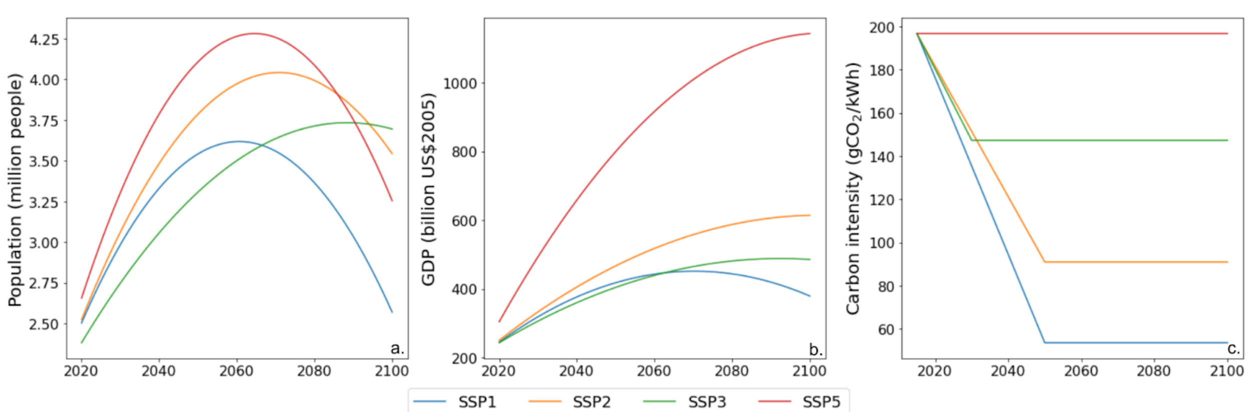

Figure 2. Socio-economic data used and their projection by SSP

Projection of (a) population, (b) GDP and (c) carbon intensity for Qatar until the end of the century for SSP1 (blue), SSP2 (yellow), SSP3 (green) and SSP5 (red). Population and GDP data come from the SSP database[15,16,25] 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[21–23], for 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) and four SSPs[24]. We considered SSP126; the sustainability scenario, SSP245; the middle of the road scenario, SSP370; the regional rivalry scenario, and SSP585; the fossil-fueled development scenario. For each SSP we used specific projections for temperature (CMIP6), population and GDP (SSP database [15,16,25] cf. Figures 2a and 2b). 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, and used in this study for the emission factor of gas. Concerning the evolution of the carbon intensity, we made assumptions based on literature and SSP storylines as follows:

- <u>SSP1 - the “road for sustainability"</u>: Qatar will exploit 100% of its renewable energy resources at maximum. Okonkwo et al.[3] identified the various renewable energies 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) and only the remaining 8% would be produced from natural gas. Then the carbon intensity remains constant for the rest of the century.
- <u>SSP2 - “Middle of the road”</u>: Qatar will not exploit 100% of its renewable energy potential but will still make a significant effort in this direction and would reach 30% of

electricity produced from solar PV and 30% from wind energy by 2050. Then the carbon intensity remains constant 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 announced by the government[12]. Then the carbon intensity remains constant for the rest of the century.
- SSP5 - "Fossil-fueled development": The emission factors reported by Qatar in their 2011 national contribution to the UNFCCC will remain the same and be used as the carbon intensity 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. To estimate the CO_2 emissions from solar PV, concentrated solar power and pumped-storage hydroelectricity we used the emission factors from the Base Carbon[26] and for biofuels, the emission factors from the IPCC Guidelines for National Greenhouse Gas Inventories[27]. Validation of the model and quantification of biases are presented in supplementary material.

3 Results

3.1 Impact of temperature on electricity demand in Qatar

3.1.1 Annual average temperature and electricity demand

First, we are interested only in the effect of temperature on electricity demand. We applied Eq. (2) using mean daily temperature projections but keeping GDP and population constant at their 2016 values from the IIASA database. Figure 3 presents the results for the total daily demand, smoothened with a 10-year rolling average. Results for the daily maximum hourly demand are shown in supplementary material (Figure S3). They are very similar in terms of trend and magnitude. When looking at the result in Figure 3 we see that there is a clear distinction between the SSPs from 2040-2050. In Figure 3c, there is a +15-20% increase in the demand for electricity attributable only to the effect of temperature warming. There is a spread among the climate models, but it is smaller than the differences between scenarios, except for SSP585 where climate models show increasingly divergent results by the end of the century. If we look at SSP585, the high-end ("fossil-fueled development") scenario, the total annual demand could increase by +35% compared to 1980, due to the effect of warming alone, with a mean warming of +4°C in 2080-2100 relative to the current decade. And even under the lowest SSP126 scenario, the additional electricity demand reaches +10% above current values due to the 1°C warming by the end of this century.

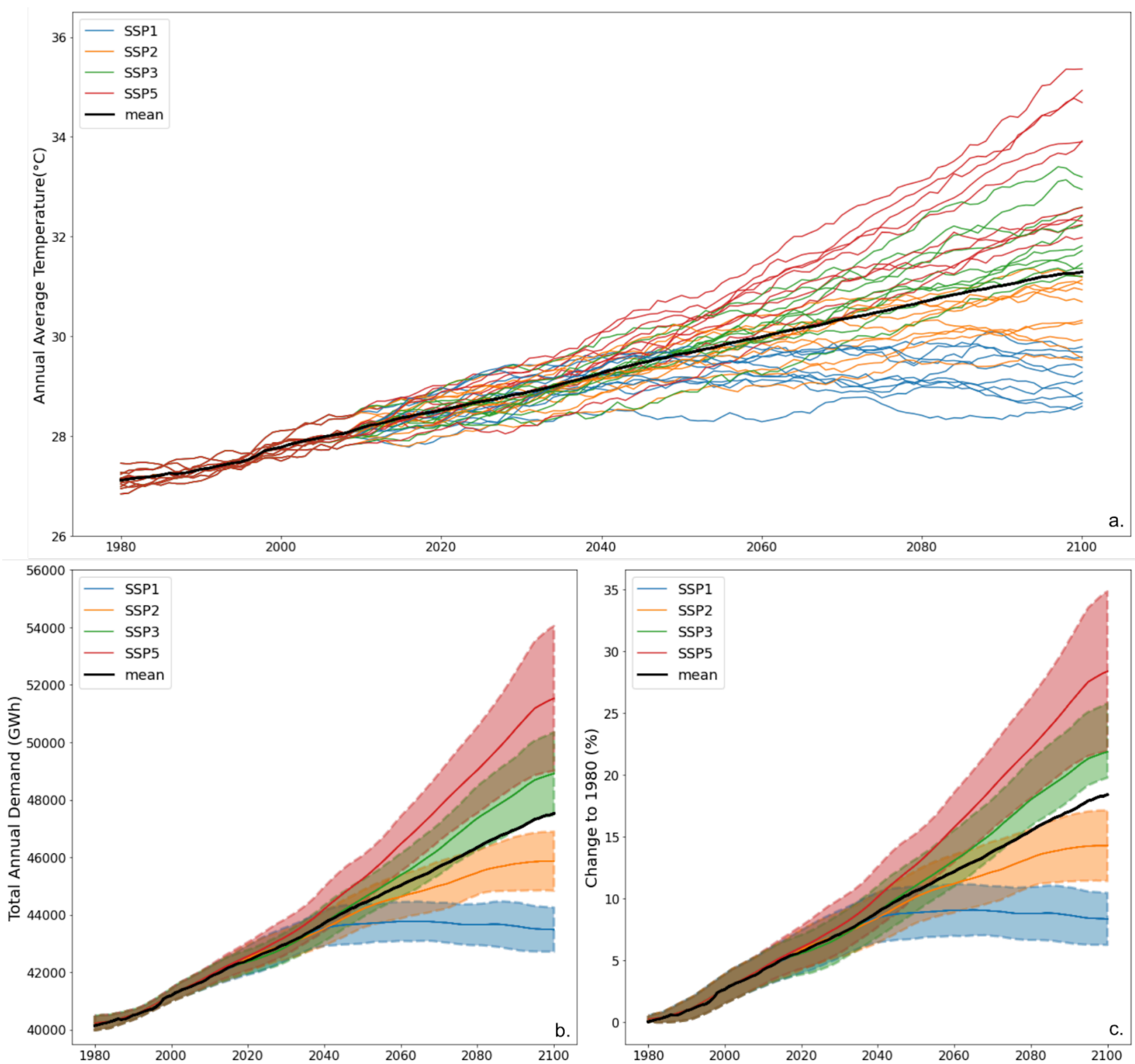

Figure 3. Projection of electricity demand with average temperature

(a) Bias-adjusted annual average temperature over Qatar from the CMIP6 database for SSP126 (blue), SSP245 (orange), SSP370 (green) and SSP585 (red) with 10-year rolling average. For each SSP one curve represents the output of one of the ten CMIP6 GCM models we used. (b) Total annual demand calculated with the quadratic temperature dependency 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 the interval in which the 1- error is included.

3.1.2 Extreme annual temperature and electricity demand

To diagnose the effect of extremely low and high temperature, we defined a low temperature threshold equal to the 5th percentile of the 2016 temperature distribution (16.8°C) under which days are categorized as “cold” days. We did the same for hot days with an upper threshold equal to the 95th percentile of the 2016 temperature distribution (36.8°C). Figure 4a shows that the annual number of cold days is going to decrease for all SSPs and could even reach zero for SSP585. Conversely, Figure 4b shows that the annual number of hot days will dramatically increase for all SSPs (except SSP126) compared to the current decade. For SSP126, this number stabilizes after 2040 at around 50 hot days per year. Thus, the demand in electricity during cold periods is going to decrease through the century and should reach very low levels for SSP245, SSP370 and SSP585 and be responsible for less than 1% of the annual demand (Figure 4c and 4e). Conversely, demand on hot days will increase and could represent more than half of the annual consumption (SSP585). One last thing to notice is that there is a larger distinction between pathways for hot temperature than those for cold temperatures. Based on those results we can suppose that most of the increase in electricity demand is attributable to increased demand for air conditioning, as the average temperature over Qatar is increasing and heat waves are predicted to become more and more frequent and severe[28].

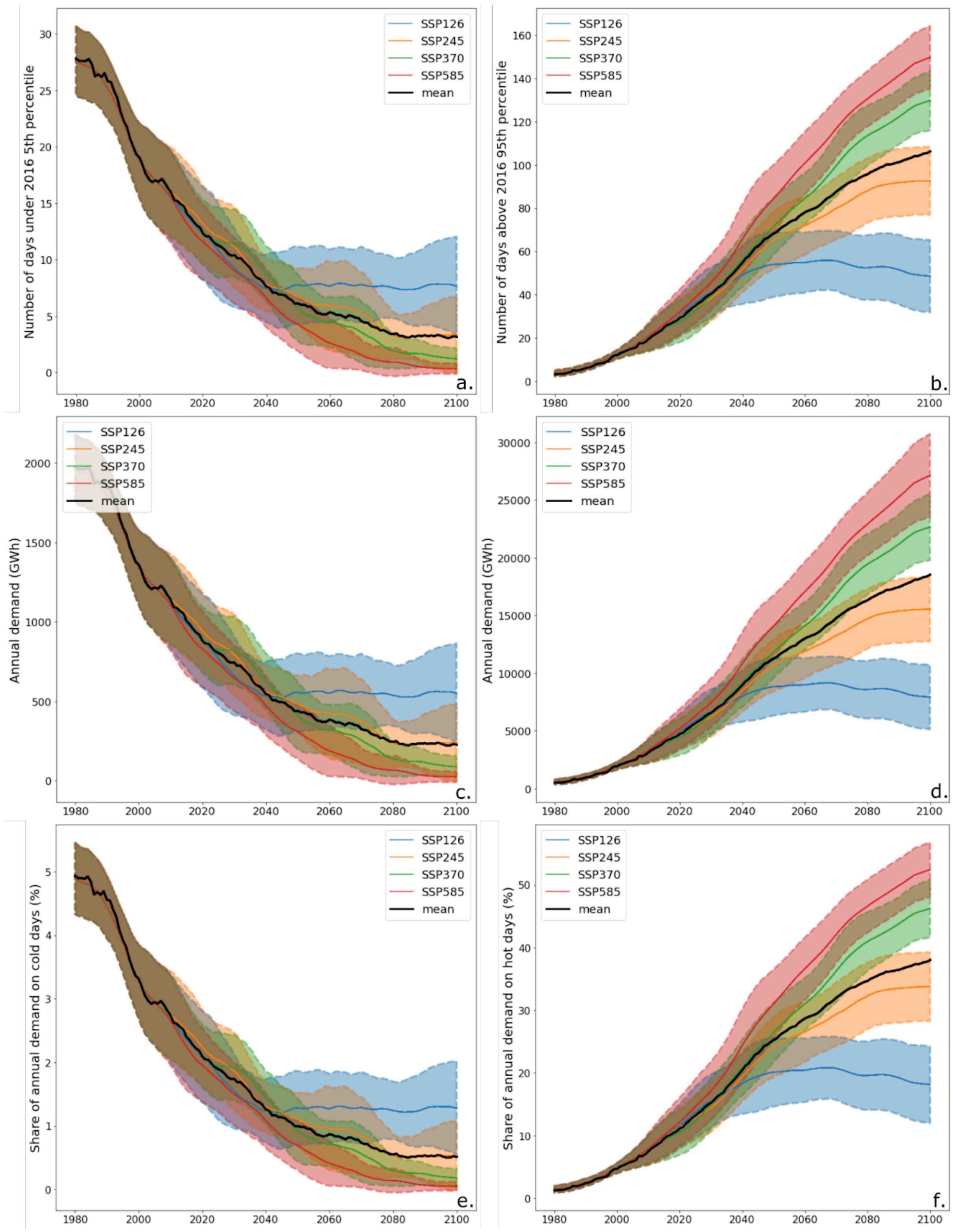

Figure 4. Electricity demand and extreme temperatures

Year by year evolution of the number of days under the cold days threshold (a) and above the hot days threshold (b), of the associated simulations of total annual demand (c and d) and of the share of the annual demand represented by the cold and hot days (e and f).

3.2 Implication for CO_2 emissions in Qatar

Finally, 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 (1980 - 2020) and for the rest of the century. Results are presented in Figure 5. We investigated the contribution of the four independent factors: temperature, population, GDP and carbon intensity.

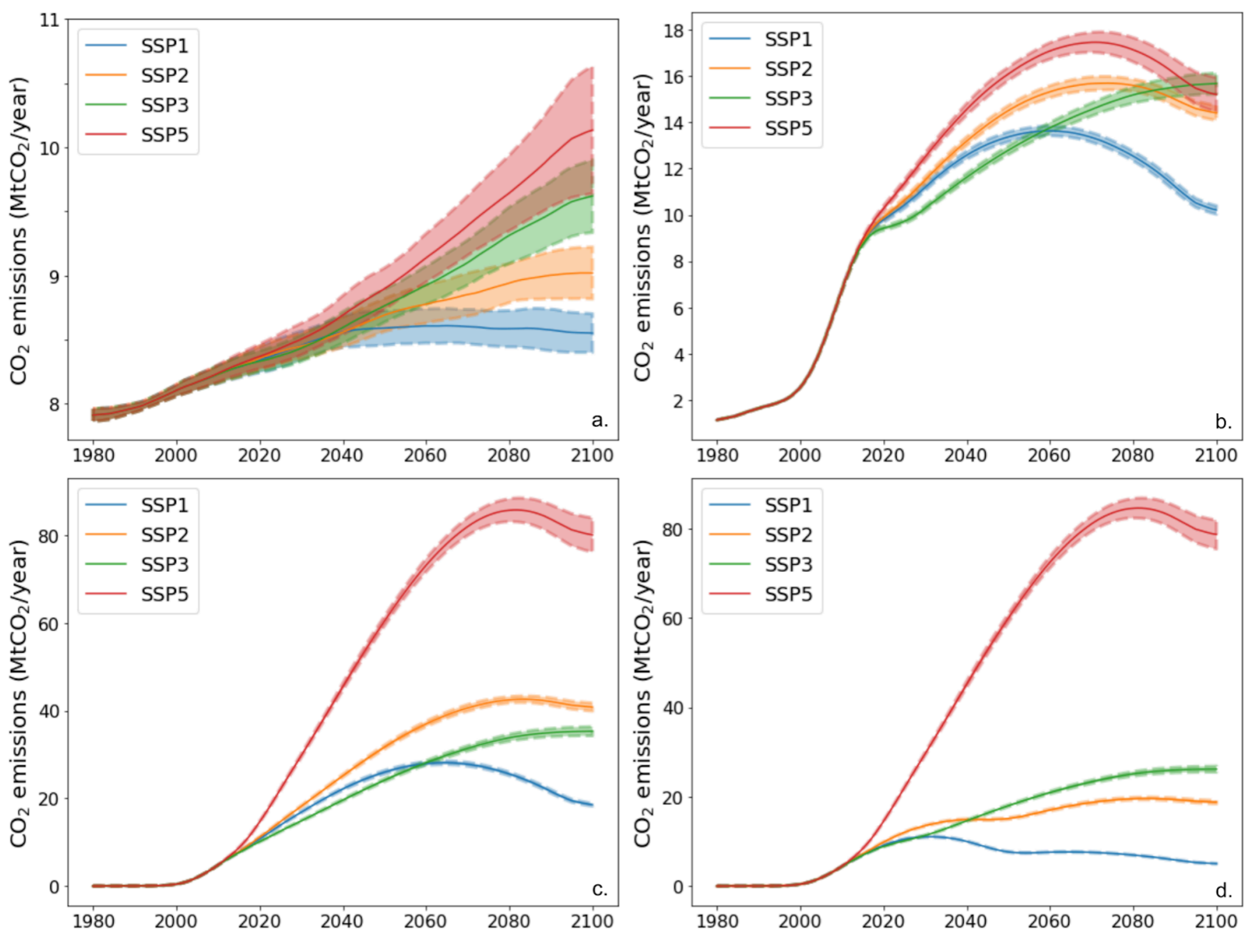

Figure 5. CO_2 emissions projected

Projections of CO_2 emissions calculated with the model for four SSPs taking into account (a) the effect of temperature, (b) the effect of temperature and population, (c) the effect of temperature, population and GDP and (d) the effect of temperature, population, GDP and carbon intensity on the electricity demand.

The first factor we looked at is temperature (Figure 5a). Except for SSP126, the effect of temperature on CO_2 emissions is a constant increase over time. The more the temperature is projected to rise, the more the CO_2 emissions will rise, in response to the increased demand for air conditioning. Depending on the pathways we could reach by the end of the century + 0.2 (SSP126) to + 2 Mt (SSP585) of CO_2 emitted per year due only to temperature increase. Figure 6a shows that for the historical period, temperature is the main factor contributing to total CO_2 emissions, along with carbon intensity and its importance is constant through time (Figure 6a-c). If we look at the total period of study (Figure 6d) we see that the temperature factor accounts for 1/4 to 1/6 of the total CO_2 emissions increase. When we add the effect of population to the effect of temperature, it changes the shape of the CO_2 emissions curves through time (Figure 5b). As the population is projected to increase at least in the first half of the century for all SSPs, we also expect more CO_2 emissions from a higher electricity consumption. However in the second half of the century, for a majority of SSPs the annual emissions decrease associated with a decrease in population, except for SSP370 where the population is expected to continue to grow during all the century. In Figure 6, we can see that the importance of the population factor for the total emissions increases through time but it is comparable between all SSPs and thus does not explain a lot the difference of emissions on the whole period. When we add the effect of GDP (Figure 5c), CO_2 emissions increase in a considerable way. For SSP585, they are predicted to reach 80 Mt/year at its peak. In Figure 6 we see that the GDP effect becomes very important with time and explain almost on its own the variability in terms of emissions between the SSPs and especially why emissions in SSP585 are predicted to be at this point more important. Finally, with assumed carbon intensity changes described in section 2 (Figure 2c) we have the full picture (cf. Figure 5d). Proportionally speaking, changes of carbon intensity has a more important effect on the historical period for SSP126 and SSP245 but not for the other scenarios. This is expected as the carbon intensity was assumed to decrease by more than 70% between 2015 and 2050 for SSP126 and by more than 50% over the same period for SSP245. It makes the CO_2 emissions from all SSPs except SSP585 lower compared to the previous case, where it was constant (14.9 tC/tJ). Finally, when we look year by year, in the second half of the century, the CO_2 emissions in SSP585 will be at least twice larger than those of all other SSPs.

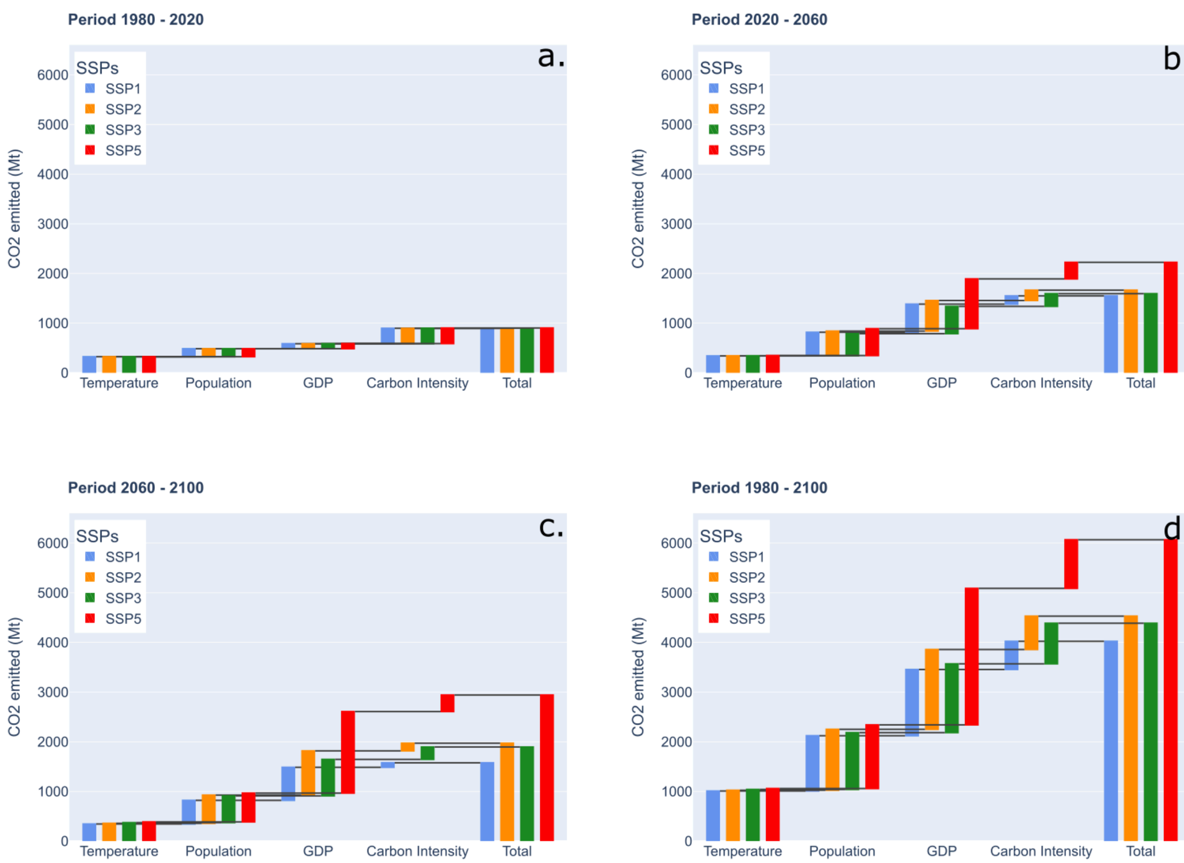

Figure 6. Cumulative CO_2 emissions

Cumulative CO_2 emissions represented by contributing factors for the period 1980 - 2020 (a), 2020 - 2060 (b), 2060 - 2100 (c) and 1980 - 2100 (d).

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 model specifically for Qatar by making use of electricity consumption data available for this country. Now we extend the analysis to the entire GCC countries to get an insight into what the temperature-emission relationship we obtained for Qatar might mean to the entire GCC countries.

Since GCC countries have common climatic conditions and share similar socioeconomic and industrial frameworks, 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 with Qatar as they have comparable fossil fuel resources (in all these countries electricity is produced mainly from natural gas, except from Saudi Arabia which use also crude oil in significant amounts[29]) and renewable resources (mainly wind and solar) although they do not necessarily have the same potential[30]. Their governments have set targets for 2030[31] but they are also facing the same challenges towards the development of these renewable energies the major one being reluctance of citizens to switch to renewable energy for financial reasons[32]. Therefore, it is reasonable to think that we can transpose what we have modeled for Qatar to these countries by just adjusting the population, GDP and temperature figures, to obtain their projected CO_2 emissions related to their electricity production. Thus, we calculated the additional CO_2 emissions related to the change in electricity demand due to temperature increase for these six 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)[33,34,35], which allows to estimate the global temperature change caused by the emissions from the electricity production of the GCC countries. The results, as well as further details of the methodology, are provided in supplementary material (Figure S4). Depending on the SSP, the additional CO_2 emissions from the temperature-energy demand feedback from the GCC countries range from 0.303% (SSP126) to +2.045% (SSP245) by the end of this century. The impact of this feedback in GCC countries on global temperature is gradually increasing from SSP126 to SSP585 and represents a contribution to the global mean temperature ranging from 0.082% (SSP126) to 0.278% (SSP585).

4 Discussion and conclusion

For the development of future projections of electricity demand and CO_2 emissions, we used the Kaya identity which contains strong hypotheses about the relationships between electricity demand and GDP, electricity demand and population and the evolution of carbon intensity. We adopted a linear relationship and unidirectional causality from GDP to electricity consumption. Those hypothesis can be discussed, and are the subject of numerous studies, the relationship between GDP and electricity demand being country specific and difficult to generalize[36]. From a literature search we did not find any specific study on Qatar. There is evidence that this hypothesis is true for renewable energy consumption[37]. But depending on the type of electricity production, the unidirectional nature of the relationship can be questioned[38,39]. In a study by Alsaedi and Tularam[38], a bidirectional causal relationship between electricity consumption and GDP was found in Saudi Arabia. Another study by Ali and Alsabbagh[40] showed that Kuwait's economic growth is one of the two major factors explaining domestic electricity consumption but the study did not address industrial consumption. As the economies of Saudi Arabia and Kuwait and their electricity production are similar to that of Qatar, in terms of its reliance on fossil fuels, we assume that the same relationship applies to Qatar. We adopted a similar hypothesis for the effect of population growth, i.e. a linear growth of the demand in electricity with an increase in population. But here also, if this can be easily applied for domestic consumption[40] it is not necessarily true for industrial consumption. However, Al-Bajjali and Shamayleh[41] showed that electricity consumption growth is clearly associated with population growth at the scale of Jordan but there is also a positive effect of urbanization on consumption which can be important. In a study conducted in the province of Shandong in China, which has a large industrial sector, Wu et al.[42] showed that among other factors such as GDP or income, total population is the one with the greatest influence on electricity consumption. In a study by Andrijevic et al.[43] it is shown that important regional inequalities in access to air conditioning arise from urbanization dynamics and income inequalities. We have relied on these studies to justify our hypotheses concerning the evolution of demand with electricity and population but for the moment the socio-economic relationships we have used are simple and idealized. To know if the unidirectionality and linearity of the GDP-electricity demand and population-electricity demand relationships are the best approximation to use in the case of Qatar, it would be necessary to conduct a specific study on Qatar based on GDP and population data in relation to the demand for electricity (residential and industrial) and to take into account the effect of urbanization and income inequality, a particular problem in Middle East.

Finally, for our simple assumptions on future carbon intensity changes, we used the current energy policy of Qatar and its potential in renewable energy as well as the storylines of the different SSPs[24]. There are several studies that make an inventory of the renewable energy sources present in the Arabian Gulf states and evaluate their potential and also review the existing policies of these states for renewable energy development[30,32,44]. But still, our assumptions on the evolution of carbon intensity are idealized. If the potential in renewable energy is something scientifically quantifiable and does not evolve in time (without taking into account the effects of global warming), the means implemented to exploit this potential are dependent on the will of the government and the population's habits. But we cannot predict what can happen on the political level and what influence government policies about the exploitation of renewable energy. For example, there is an ongoing debate on how realistic scenarios like SSP585 are at a general level[45]. Here for SSP585 we assume, based on SSP5 storyline, that the carbon intensity does not change at all from now. This is highly unlikely given that the current Qatari government has at least committed to achieving a 20% solar energy mix by 2030.

Other factors not investigated here can also have an influence on final CO_2 emissions. For example, Alrawi et al.[4], showed that the per-capita consumption is significantly different from per-household consumption, thus the implementation of policies or strategies to better insulate the houses and reduce inside home comfort temperature could have an effect on the demand.

BIBLIOGRAPHY

1. 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 (IPCC).

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

3. 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.

4. 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.

5. World Bank, and OECD GDP (current US$). The World Bank Data. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD.

6. Planning and Statistics Authority (2019). Chapter III Electricity and Water Statistics (State of Qatar).

7. 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.

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

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

10. Electricity Prices GlobalPetrolPrices. https://www.globalpetrolprices.com/electricity_prices/.

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

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

13. 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.

14. 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.

15. 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

16. 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.

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

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

19. 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.

20. 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).

21. 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.

22. 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.

23. 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.

24. 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.

25. 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.

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

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

28. 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.

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

30. 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.

31. 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.

32. 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.

33. 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

34. 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

35. 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

36. 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.

37. 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.

38. 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.

39. 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.

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

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

42. Wu, L., Gao, X., Xiao, Y., Yang, Y., and Chen, X. (2018). Using a novel multi-variable grey model to forecast the electricity consumption of Shandong Province in China. Energy 157, 327–335.

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

44. 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.

45. 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

Supplementary Material

Validation of the model

To evaluate the model, we applied it to the 2016 daily mean temperature data and recalculated the demand. We then compared the modeled electricity demand with the observed one. There is a very strong correlation coefficient for the linear regressions between the electricity demand modeled and observed (r^2 = 0.95 and RMSEn = 0.055 for daily total load and r^2 = 0.96 and RMSEn = 0.053 for daily maximum hourly load, cf. Figure S1).

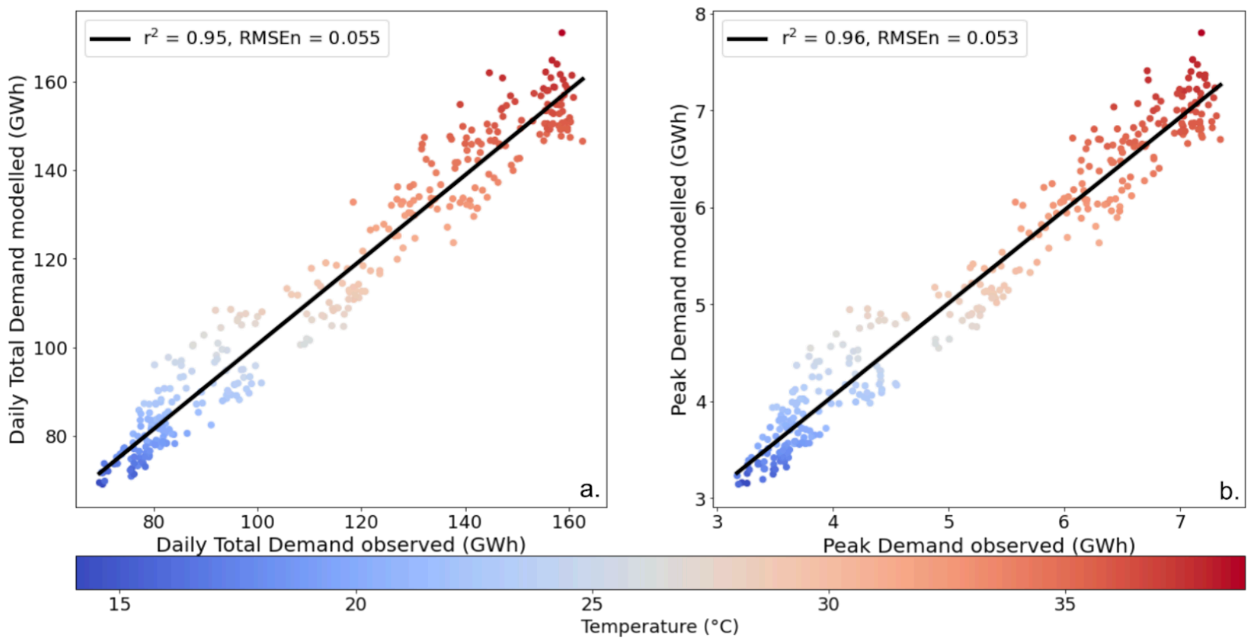

Figure S1. Actual electricity demand modeled versus electricity demand observed in Qatar for the year 2016 for daily total demand (a.) and peak demand (b.). Colors indicate the daily average temperature over Qatar.

Few official data are available to compare our results with observation but the state owned Qatari company Kahramaa, the sole producer of electricity in Qatar, published reports on its activity[28]. In particular, they released figures for the annual electricity generation in Qatar for the years 2015 to 2019, with the average for this 5 years at 45,430 GWh. The order of magnitude is consistent with our estimate. From 2014 Qatar's government also published its monthly statistics report in which they released their monthly electricity generation[29]. We did a cross validation of our results by aggregating them by month and comparing them to the government's data (cf. Figure S2). We model well the seasonal variability and our orders of magnitude are accurate. Visually it seems that our results are closer to the observations when we take into account only the effect of temperature and not the population and the GDP. The difference between our results and the observations seems to be slightly overestimated for the warmest (June, July, August) and coldest (November, December, January)months, respectively. Biases have been quantified for these two categories of months and for the simulation temperature only and the simulation temperature + population + GDP (Table S1).

	Temperature only	Temperature + population + GDP
Cold months	-0.4%	0.6%

Hot months	-1.9%	4.1%

Table S1. Biases for cold and hot months (respectively November, December, January and June, July, August) for the simulation with only the effect of temperature on the demand and the one with the effect of temperature, population and GDP expressed in percentage of difference with the government data.

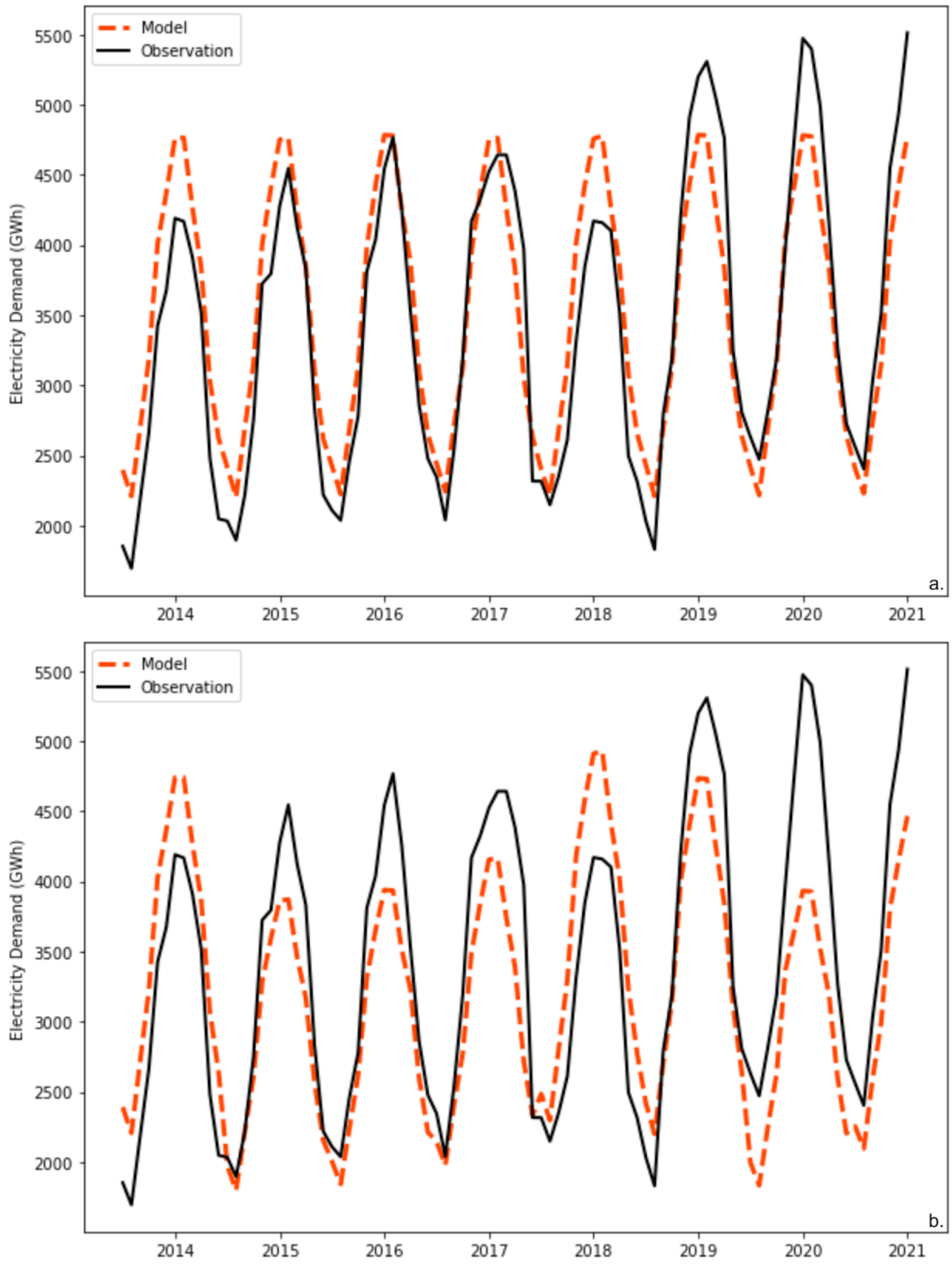

Figure S2. Comparison of monthly electricity demand reported by the Qatari government (black curves) and modeled monthly demand (dashed red curves) with the effect of (a.) temperature and (b.) temperature, GDP and population. The years indicate the month of June.

We have defined two categories of day: extremely cold days with an average temperature under 14.1°C, the 2016 minimal average daily temperature and extremely hot days above 38.8°C, the 2016 maximum daily average temperature. The values of the electricity demand calculated with our model for these days are to be taken with precaution, as they are extrapolated to a domain without data. Table S2 shows the percentage these days represents for the period 1980 - 2100. We can see that for all SSPs there are much more extremely hot days than extremely cold days and the number of extremely cold days stays constant (around 0.2%). In contrast the number of extremely hot days increases with the radiative forcing and goes from 1.2% for SSP126 to 11.5% for SSP585.

	SSP 126	SSP 245	SSP 370	SSP 585
Extremely cold days	0.27%	0.21%	0.22%	0.20%
Extremely hot days	1.2%	7.6%	9.3%	11.5%

Table S2. Percentage of extremely cold days (under 2016 minimal daily average temperature, i.e. 14.1°C) and extremely hot days (above 2016 maximum daily average temperature, i.e. 38.8°C) for the different SSPs for the whole period of study (1980 - 2100).

The model presented in this study is a statistical model based on electricity demand and temperature data. To develop this model we only had electricity consumption data for one year which was sufficient to produce a very robust relationship between electricity demand and temperature (r^2 = 0.95, RMSEn = 0.057). On the other hand, we do not have enough data of electricity demand during hot or cold waves if we want to look more closely at the response of the electricity demand to extreme temperature events, which is why in our study of extreme annual temperature and electricity demand (section 3.1.2) we took the 5% highest and lowest temperatures and not only the highest or lowest temperature of the year. Little data is available to validate the electricity demand model. By aggregating our results by year and by month, we were able to compare them to the limited data on electricity demand disclosed by the government and the company Kahramaa which allowed us to validate our model at least in terms of order of magnitude with a mean bias of ±4.1% by year (section 3.1.1). But for the study of extreme temperature and the calculation of CO_2 emissions associated with the production of electricity in Qatar it would seem that this study is the first of its kind.

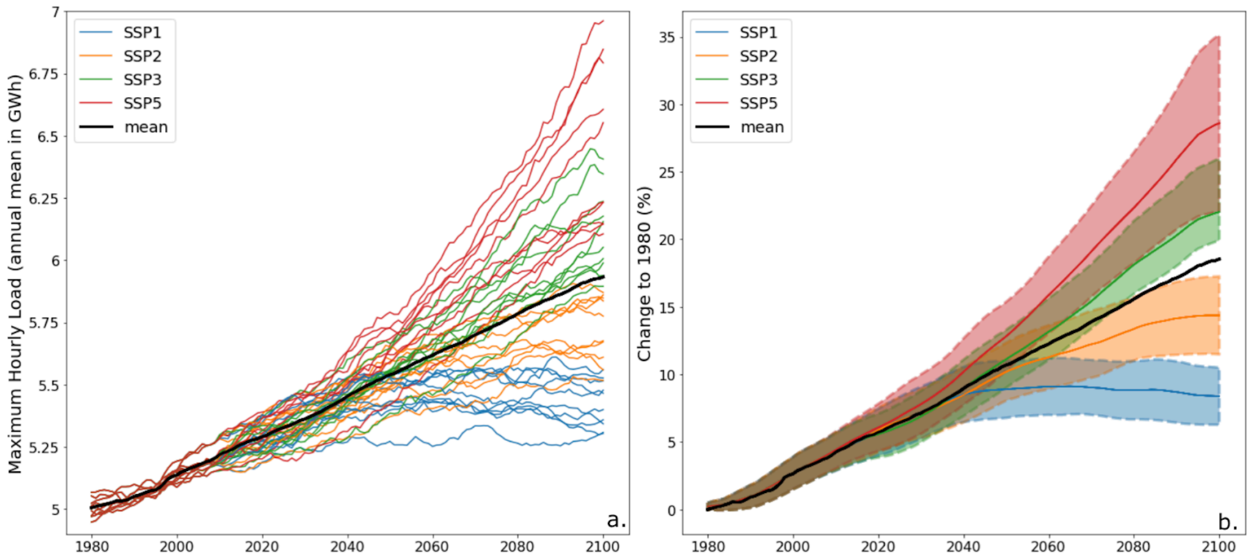

Figure S3. Daily maximum hourly demand (annual average) calculated with the quadratic model (cf. equation 3) that simulates the effect of temperature on the demand. On panel a., each curve represents the results obtained with one of the 10 models for each SSP with10-year rolling average. On panel b., it is the change in demand compared to the year 1980 (in percentage) that is represented. The thick colored lines show the average of the different SSPs and the colored areas the interval in which the 1- error is included.

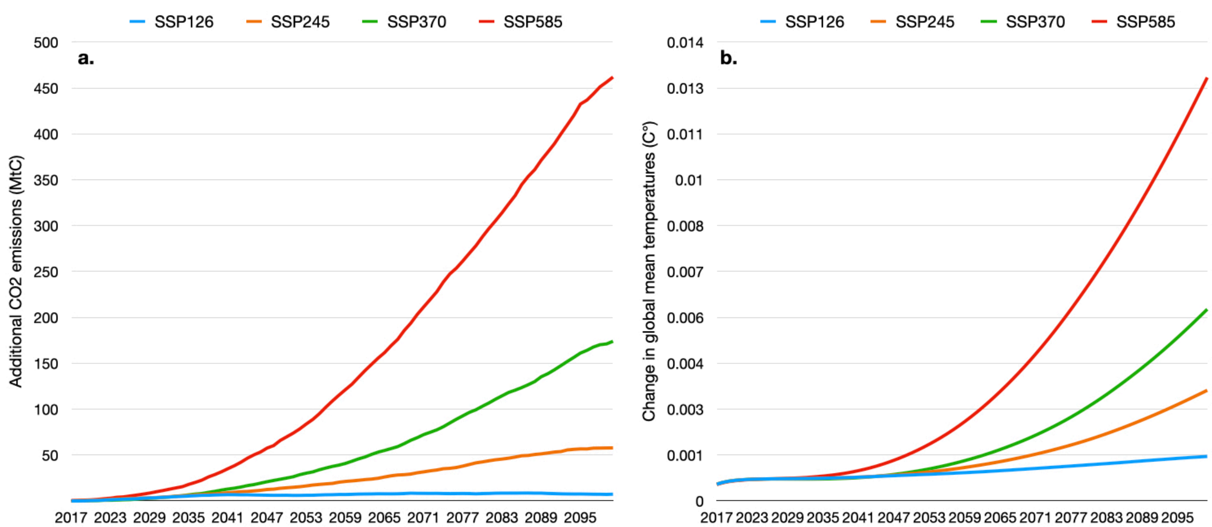

Figure S4. Additional CO_2 emissions (a.) and the resulting global temperature change (b.) obtained when we add the temperature feedback on electricity demand compared to a baseline scenario with no effect of temperature on the demand. The additional CO_2 emissions are obtained by taking the difference between the CO_2 emissions calculated with the method described in the article, i.e. by taking into account the effect of the variation over time of the 4 factors (temperature, population, GDP, and carbon intensity) and the CO_2 emissions calculated in the same way but by keeping the temperature at the 2016 level. The additional temperature change is obtained by using the simple climate model ACC2 with these additional CO_2 emissions (see main text).