Climate change impact on photovoltaic production, electricity demand and storage requirements in the south-west Indian Ocean

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Abstract

This paper studies the influence of temperature change until 2100 under different scenarios, on different aspects of the power system of an island in the south-west Indian Ocean. In particular, the influence of temperature on photovoltaic (PV) production and electricity consumption is first assessed. While the impact on PV production remains negligible (up to 1.5 % decrease in annual production), the impact on electricity consumption could be significant in the long term (up to +8.4 % on annual consumption). The complete electrical system is then simulated, in order to size the necessary PV installations and quantify the consequent storage requirements. While installed capacity could reach the island's full potential (1 200 MW, compared to 230 MW in 2022), storage requirements could rise to 1.8 GWh. It is therefore essential to anticipate the effects of climate change on the electricity grid.

1 Introduction

Floods, droughts, heatwaves... the effects of climate change are becoming increasingly visible. However, there is less public awareness of the fact that climate change is having a major impact on electricity production, particularly from renewable sources: dwindling water resources for hydroelectricity, lower yields from biomass production, damage to facilities caused by extreme weather events, and so on. Climate change is also having an impact on the way we consume: in a world driven by economic growth and the consequent increase in global consumption, climate change is causing a global rise in ambient temperature, which in turn means a greater need for cooling. However, these two aspects combined are problematic: a drop in renewable energy production is difficult to combine with an increase in energy consumption, in a world where we want to reduce our impact so as not to exacerbate the effects of climate change. It is therefore important to quantify the impact of climate change on the entire energy system, so that effective and coherent measures can be taken afterwards.

This article focuses on the impact of climate change on PV panels. The effects of increasing ambient temperature on the efficiency of these panels are well known in the scientific literature. In most studies, the authors assess the impact of changes in temperature and irradiance on PV production for a specific case study: Greece for [1], China for [2], Brazil for [3], with a section on economic potential assessment, or Italy for [4]. A large number of countries are being studied, on every continent. The majority of these articles conclude that there is little variation in PV production over the long term. Some articles go further in the analysis by assessing the impact of aerosols and clouds [5] or wind speed [6]. However, the changes obtained, although minor, are often studied on their own, and are not compared with the other impacts induced by climate change. This is the case, for example, with electricity consumption, which has been shown to be linked to temperature variations [7].

To the authors' knowledge, no study has been carried out addressing the impact of climate change on PV production and electricity consumption, and measuring the sizing of PV power plants and storage facilities needed to meet the demand. This is the focus of this study, with a case study on Reunion Island in the south-west Indian Ocean. The results obtained will enable decision-makers to better anticipate the effects of climate change in order to make the best possible decisions to prepare the future electricity grid for it. The methodology will first be presented, with climate change impacts on temperature and irradiance data, followed by the models used for photovoltaic production and electricity consumption. To conclude this methodological section, the framework used for sizing the installations is presented. The article ends with the results, a discussion and a conclusion.

2 Methodology

As explained in the introduction section, the present study aims to assess the impact of climate change on photovoltaic production, electricity consumption and storage requirements. The methodology presented is applied to the case study of Reunion Island, a small french territory located near Madagascar, in the south-west of the Indian Ocean. This territory is chosen because of its location in an area where the impact of global warming on the electricity network has not yet been studied, but also because of its specific energy context. The territory, dependent at 88.2 % on fossil imports for its energy mix in 2021 [8], is aiming for energy self-sufficiency in the coming years [9]. The island being located in a region with high solar radiation and moderate temperatures throughout the year, PV installations have been developing locally for several years and will certainly have a role to play in the future.

The first stage of the work involves processing future meteorological data, especially temperature data for the south-west Indian Ocean basin. The second stage involves finding a model for estimating photovoltaic production from meteorological data. In particular, historical temperature and irradiance data are used to approximate historical production data. Once the model has been found, electricity production from photovoltaic panels can be calculated from any temperature or irradiance data. Historical wind, rainfall or cloud cover data are not available in sufficient quantity for the case study and the impact of these parameters on PV production, often lower than that of irradiance and temperature [5,6], will not be assessed. Next, the model of electricity consumption evolution in Reunion Island in relation to temperature is evaluated. Once again, historical data are used. Finally, all the above work is combined in an electricity network optimisation tool, in order to quantify the photovoltaic and battery capacity required to meet local electricity demand. Methodology of the overall study can be seen in Figure 1.

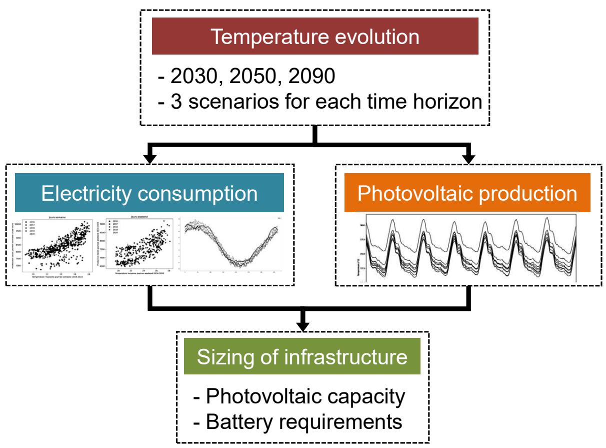


Figure 1: Methodology of the present study.

2.1 Climate change impact on temperature

To assess the impact of climate change on the south-west Indian Ocean, data from the BRIO project (Building Resilience in the Indian Ocean) [10] were obtained: average, minimum and maximum daily temperatures for different areas on the island from 2020 to 2100, according to three evolution scenarios. These three scenarios are based on the IPCC (Intergovernmental Panel on Climate Change) ones, and propose an optimistic (SSP1-2.6, called 1 in the following), a pessimistic (SSP5-8.5, called 3) and an intermediate (SSP2-4.5, called 2) trajectory for the evolution of greenhouse gas emissions.

In order to model the impact of average temperature evolution, each scenario is averaged over 20 years, to maintain trends but erase climate variability, to measure the impact in the short term (2030), medium term (2050) and long term (2090). From that, the daily average, maximum and minimum temperature for three time horizons for different places on the island studied is obtained, according to three different scenarios. The average temperature over the year for all the scenarios is represented on Figure 2. It can be seen that, in the short term, the average increase in temperature is barely noticeable. However, after 2050, and even more so over the long term, the average increase in temperature is apparent.

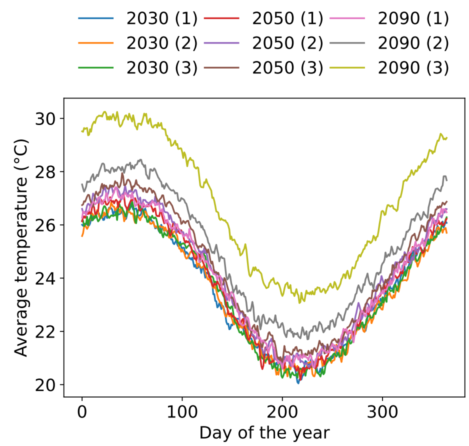


Figure 2: Daily mean temperature of the different scenarios averaged over the island for a year in Reunion Island.

The next step is to obtain hourly temperature profiles from these daily data. To do so, the methodology from [11] is followed. A data file of hourly typical meteorological year (TMY) temperatures for different places on Reunion Island is used with the Empirical_daily_temperature_curve() function from the R package chillR [12]. With the hourly coefficients obtained for each month of the year, previous minimum and maximum daily temperature data can be linked with the Empirical_hourly_temperatures() function of the same R package. Finally, hourly temperature profiles over different time horizons and according to different scenarios are obtained for different places.

To check the obtained profiles, it is possible to compare their daily average with the daily averages recovered from the BRIO project. On each day of the year, the observed difference in average temperatures is less than 1°C. However, this difference is not zero. It was therefore decided to add this observed difference to each hour of each day, in order to obtain an identical average daily temperature between the profiles constructed and the data from the BRIO project. This is achieved at the expense of the maximum and minimum daily temperatures observed by the BRIO project, which will no longer be respected in the constructed profiles.

2.2 Climate change impact on irradiance

One study has been carried out on the evolution of solar irradiation in Southern Africa [13]. The results show negligible overall change between now and the end of the 21st century. As there is no focus on Reunion Island, which could lead to results that differ from the overall trend, the conclusion of the study will be repeated here: it is assumed that irradiance will not change in the future in Reunion Island. Moreover, the evolution of the contribution of aerosols and cloud cover is neglected for the case study. Therefore, in the present work, an hourly TMY is used to model irradiance up to the year 2090. The TMY is based on historical data from 2000 to 2019.

2.3 Photovoltaic production model

To estimate electricity production from photovoltaic power plants, the following model is used [14]:

$$P_{prod} = \frac{R}{1000} \times P_{install} \times \eta \times (1 + \alpha(T_m - 25°C)) \tag{1}$$

with P_{prod} the available power output in W, R the irradiance in W/m^2, $P_{install}$ the installed power in W, η the efficiency of the system, corresponding to the product of the overall conversion losses and the efficiency of the inverter, α the temperature coefficient in %/°C and T_m the module temperature in °C, defined as follows:

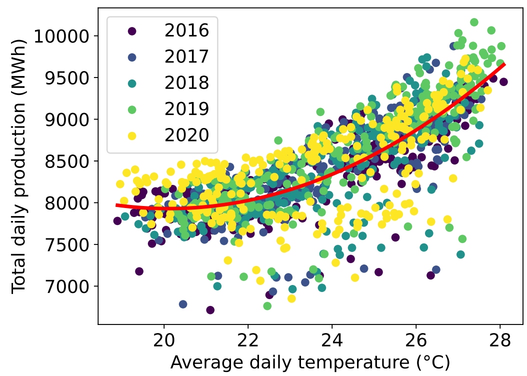
$$T_m = T_{amb} + \gamma \times R \tag{2}$$

In Eq. 2, T_{amb} is the ambient temperature in °C and γ is the panel mounting parameter in °C.m^2/W.

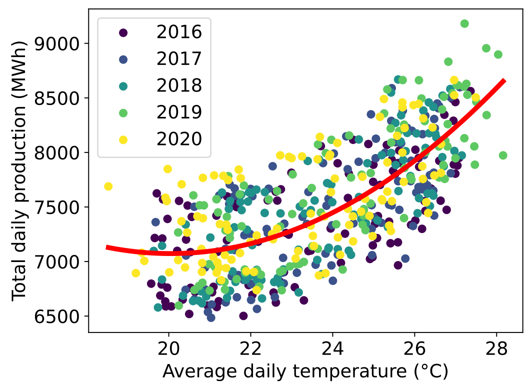
In order to find the parameters that characterise the case study's photovoltaic installations, i.e. η, α and γ, the least squares method is used. It is used with data from 2017 on photovoltaic production, installed capacity, ambient temperature and irradiance. Only daytime values are used, as there is no production at night. The following results are obtained: η = 0.81506071, α = -0.35 %/°C and γ = 0.0599782 °C.m^2/W. The hourly photovoltaic production can then be obtained for any desired instant. The only data required to run the model is installed power, temperature data and irradiance data. The impact of temperature on panel ageing is not taken into account, first because of a lack of historical data to characterise local conditions, and second because panels will have to be replaced several times by 2090.

2.4 Electricity consumption model

As mentioned in the introduction, it has been shown in the literature that temperature has an impact on electricity consumption, particularly during cold and hot periods. For the case study, which is a tropical area, the correlation is significant during the hot season, with a higher use of air conditioning. In particular, two articles present a non-linear correlation between electricity consumption and



(a)



(b)

Figure 3: Correlation between electricity production and temperature; (a) during week days, (b) during weekend days.

temperature, based on historical data from two different case studies [15, 16]. In the second article, an interesting method of filtering is used to measure the impact of population, technological advances and seasonal activities on the correlation studied. In the present study, not enough data is available to establish the influence of such parameters. Daily electricity production data from 2016 to 2020 were obtained, as well as average temperature data over the same period. The graph showing the correlation obtained between these two data can be seen in Figure 3, where weekdays have been separated from weekend days, in order to obtain two different models, taking into account the drop in activity during weekends. The two correlations found are the following, with P the daily production in MWh and T the average daily temperature in °C:

$$P_{wk} = 27.067 \times T^2 - 1088.3 \times T + 18869 \tag{3}$$

for week days and

$$P_{wkd} = 23.989 \times T^2 - 961.68 \times T + 16711 \tag{4}$$

for weekend days. Once the correlation has been obtained, it is possible to estimate the difference in production impacted by a difference in temperature, using the following equation:

$$\begin{aligned} P_{wk,X} = P_{wk,Y} &+ 27.067 \times (T_X^2 - T_Y^2) \\ &-1088.3 \times (T_X - T_Y) \end{aligned} \tag{5}$$

$$\begin{aligned} P_{wkd,X} = P_{wkd,Y} &+ 23.989 \times (T_X^2 - T_Y^2) \\ &-961.68 \times (T_X - T_Y) \end{aligned} \tag{6}$$

Here, the T_X data is the temperature data obtained from the BRIO project and the T_Y data is the temperature data for the year 2019, chosen as reference because of data availability. Finally, the P_Y data is the production data for 2019 with an additional factor taking into account the increase in consumption on a trend basis until 2030, then on a constant basis in 2050 and 2090, assuming an improvement in energy efficiency and a better energy demand management.

2.5 Storage requirements and sizing of PV capacity

To size PV installations and battery requirements, the PyPSA [17] tool is used. This tool, once adapted to our case study, can be used to model the island's electricity network and optimise it. In particular, the modelling takes into account each substation, linked by the electricity transmission lines. Each substation is assigned electricity consumption data, as well as storage data and installed power generation data. The variables of the optimisation problem are: the installed PV power at each substation, the size of the batteries at each substation, the capacity of the power lines, and finally the hourly dispatch of the electricity. Optimisation is carried out with a minimisation of the operating costs of electricity generation technologies, as well as the investment costs of PV capacity, batteries and power lines. The main equations governing the problem are detailed in [18], and the modeling of the system can be seen in Figure 4.

The consumption data for each substation are those discussed above for baseline consumption, plus additional consumption for 2050 and 2090, corresponding to the electrification of the private vehicle fleet. As a reminder, the island is aiming for energy autonomy. The switch from the current fleet to electric vehicles implies an additional consumption of around 1 GWh per year for the whole island [19]. However, the transition of the air and maritime sectors is not considered in the present study. As the large-scale processes and political will are not yet fully known, it is difficult to estimate hourly energy consumption data (in the present case) for these sectors.

Regarding the installed capacity data for each substation, a value is assigned for each type of power generation for the 2030 horizon and one for both 2050 and 2090 horizons. The values for the whole island are given in Table 1, and are

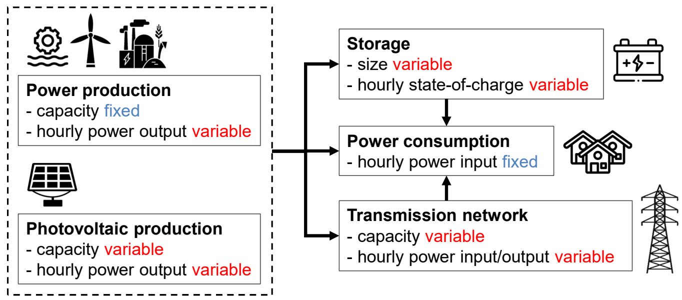


Figure 4: Modeling of the substations of the grid in the optimisation tool.

determined with potential data for the long-term, as well as current and future projects for the medium term [18]. The allocation by substation is also based on potential data [19]. Three new means of electricity generation are considered as from 2050, which explains why their installed capacity is set at 0 for 2030: offshore wind, ocean thermal energy conversion (OTEC) and geothermal energy. To optimise installed PV capacity, the minimum possible is set using the installed capacity for 2019 [20], and the maximum installed capacity is decided in the same way as for other sectors, using potential studies. Finally, no limit is fixed on the size of the batteries at each substation. The capacity of most of the power lines is set at 44.7 MVA, and the one of a few lines is set at 26.2 MVA [19].

Table 1: Installed power generation capacity for the different horizons.

	Capacity 2021 (MW)	**Capacity 2030 (MW)**	**Capacity 2050-2090 (MW)**
PV	224	600 max.	1 200 max.
Hydroelectricity	134	150	233
Onshore wind	16.5	50	146
Offshore wind	0	0	40
Biomass	45.4	477	303
OTEC	0	0	31
Geothermal energy	0	0	15
Fossil	501	0	0

3 Results

The first obtained results are the influence of temperature changes on photovoltaic production and electricity consumption respectively. These results can be seen in Table 2.

Table 2: Results of temperature evolution influence on PV production and electricity consumption.

Scenario	**Reduction in annual PV production (%)**	**Increase in annual electricity consumption (%)**
2030 (1)	0.26	0.01
2030 (2)	0.23	0.03
2030 (3)	0.25	0.03
2050 (1)	0.37	0.11
2050 (2)	0.47	0.44
2050 (3)	0.57	0.78
2090 (1)	0.43	0.28
2090 (2)	0.83	2.46
2090 (3)	1.53	8.36

Regarding PV production, the obtained results confirm those of the literature on the various case studies simulated: the drop in panel yield remains negligible over the long term, taking only the temperature factor into account. Regarding electricity consumption, the variation obtained here focuses on the difference in temperature compared with average temperatures in 2019, and does not take into account more comprehensive factors that could influence the correlation obtained and thus this variation, such as population growth or energy efficiency, for example. While the variation is negligible in the short term, it can be seen that it is more significant in the long term.

Once these preliminary results have been obtained, it is possible to simulate the island's entire electrical system, in order to obtain the dimensions of the PV installations and the battery sizes needed to meet demand. These results can be seen in Figure 5. Other results are obtained from these simulations, such as the composition of the hourly electricity mix or the reinforcements required on the electricity transmission network.

As expected, as the temperature rises over the long term, impacting on PV production and electricity consumption, the expected need for electricity production will be greater. As the only type of electricity production with variable installed capacity, the power required from photovoltaics increases over time, until almost all of the island's potential has to be reached, for temperatures equivalent to those predicted in the 2090 (3) scenario. Only the three short-term scenarios show no difference between them. Indeed, it was shown earlier that temperature trends up to 2030 still show few distinctions between the scenarios. In addition, it can be seen that there is no need for storage at this time horizon, as the system is sized so that the 3 batteries currently connected to the grid are sufficient (total of 19.3 MWh).

The results also show a growing need for storage, due to the increasing percentage of intermittent energy sources over the long term with the development of PV. Regarding power lines, only two lines would need to be reinforced in all scenarios, in line with the growth in storage requirements. These reinforcements remain reasonable, with the most affected line expected to reach 63 MVA in the 2090 (3) scenario.

Lastly, the results show that by restraining electricity consumption, the demand can be met despite the rise in temperature. On the other hand, although electric vehicles were considered in this study in the medium and long term, the trend is towards electrification, and other forms of mobility such as aviation and shipping were not modelled. Therefore, if electricity consumption were to increase more than forecasted here, local production might not be sufficient.

4 Discussion

To take this last point further, the estimates in this study have been made using current technological data. Indeed, the PV production estimation models were obtained from historical data. It is therefore possible that new panels will be installed in the future, which will be less subject to a drop in yield as temperatures rise [21]. It is also possible that the trend in electricity consumption linked to changes in temperature will also evolve. Air conditioning is a very popular subject of study, and new innovations are regularly being developed. It is therefore possible that, as technologies evolve - a parameter that is difficult to predict - different results will be observed in the future. It should also be remembered that the results obtained here depend entirely on the data used, in particular the temperature and irradiance data. A different evolution of these data will lead to different results.

Climate change will not only impact electricity consumption and PV production. In fact, the biomass sector will also be affected, with overall drops in rainfall, droughts, increase in forest fires, rising temperatures, flooding, etc. However, the articles dealing with this subject in the literature come to divergent conclusions, making the subject uncertain [22]. Local literature does, however, suggest a downward trend in yields [23]. Climate change will also have an impact on hydroelectric production. Rainfall data has also been collected as part of the BRIO project. These data show that, in the future, while an annual fall in rainfall may be observed depending on the scenario, it is above all the disparity between zones and the alternation of dry and wet periods that will be more marked. This impact on hydroelectricity production has not been studied here because, once again, it is difficult to quantify (several production technologies, lack of historical data, dispatch according to demand, etc.). On a more positive note, the increase in average temperature could have a positive impact on OTEC production, due to the increase in surface temperature and a greater temperature difference with deep waters. Finally, rising temperatures will also have an impact on the electricity grid itself: reduced capacity of substations and transformers [24], overheating of underground lines, increased capacity losses [25], and so on. However, estimating these parameters requires a certain amount of historical data, which is not available for the case study.

These impacts have therefore not been taken into account.

Last element raised by the BRIO project, is the impact of the tropical cyclones. Located in a cyclonic area, the island can be hit by up to eight cyclones per decade [26], usually causing some damage but no casualties. In the future, fewer cyclones could appear, but with greater intensity and with the maximum intensity shifting towards Reunion Island. This will have a knock-on impact on the electricity system, with possible impacts on electricity transmission and distribution lines, as well as on generation facilities.

5 Conclusion

The impact of climate change on the development of photovoltaic resources and storage requirements has been assessed in the case study of Reunion Island. Especially, data on temperature trends up to 2100 and according to three scenarios were analysed. The expected drop in photovoltaic production was estimated, remaining negligible over the long term. At the same time, the increase in electricity consumption linked to the rise in temperature has also been assessed, and although negligible in the medium term, could become problematic if temperatures were to rise more than forecast. In addition, consumption peaks during hot spells could pose problems for the electricity network. Finally, the overall impact of these changes on the grid has been assessed. While power lines would be less affected by changes in electricity production and consumption, more and more PV would be needed to compensate for lower plant efficiency and higher consumption, followed by an increase in storage requirements. These forecasts on high storage needs should allow local actors to prepare, whether in terms of recycling, skills, supply chains, or the choice of these storage means. If batteries have been modeled here, other means, such as hydrogen, are possible.

It was not possible to assess all the impacts of global warming in this study. Moreover, complete energy autonomy has not been modelled, since consumption in the maritime and air sectors has not been considered. Future work should be able to fill these gaps, in order to obtain a global vision of the impact of climate change. In addition, works like this should be updated regularly, taking into account the evolution of the island's electricity system as well as new climate forecasts.

As shown here, power consumption, the nerve centre of the electricity grid, will be impacted by the increase in temperature. Each sector therefore needs to prepare itself to anticipate future changes and ensure that electricity demand is always met. Concrete solutions could be put in place to reduce electricity consumption in the future: demand management, reduction in the use of private cars, development of high energy efficiency technologies, etc. As the island is rather small and not connected to the mainland, electricity production has its limits in terms of local resources and installation potential. Electricity demand will therefore have a key role to play in the future.

Acknowledgements

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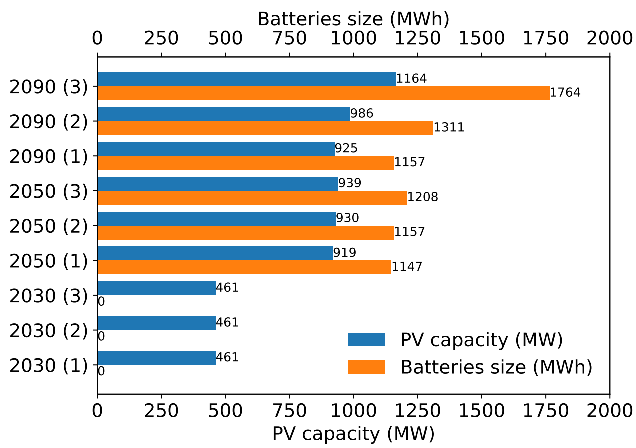

Figure 5: Sizing of PV installations and batteries requirements for the different scenarios.