Assessing solar resource and photovoltaic production in Tahiti from ground-based measurements

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Abstract. This study focuses on the solar resource available at Faaa, Tahiti (17.5°S, 149.5°W) thanks to 10 year-long solar irradiance time series. Faaa's global horizontal irradiance ranges from 14 MJ.m^{-2}.day^{-1} (June) to 21 MJ.m^{-2}.day^{-1} (November) in agreement with the sun's annual path, while clearness index ranges from 0.5 (January) to 0.67 (July), in agreement with the wet and dry seasons. The Global Solar Atlas satellite-derived dataset shows acceptable relative error when compared to Faaa in situ measurements. This product could then be used for other coastal areas of Tahiti. The annual energy output of a single PV module is 256.7 kWh, which corresponds to 7 % of the annual consumption of a typical household in Tahiti. The capacity factor reaches 22.5 %, which makes Faaa a good site for harnessing solar resource.

1 Introduction

Tahiti is a volcanic island located in the middle of the tropical Pacific (17.5°S; 149.5°W), in the Société archipelagos, French Polynesia. Figure 1 shows an elevation map of Tahiti and Moorea. The island enjoys a tropical climate, which can be divided in two seasons, the wet season from November to April and the dry season from May to October. In 2012, 69 % of French Polynesia's inhabitants lived in Tahiti. Tahiti's consumption represented 80 % of the total electricity consumption over French Polynesia [1].

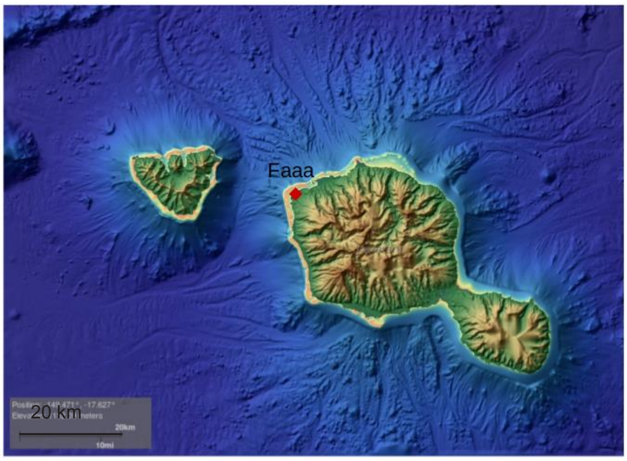

Fig. 1. Tahiti and Moorea topography and bathymetry font map retrieved from NOAA [2].

Although the part of renewable electricity production in Tahiti is relatively high (around 30 % high in 2015, [3]) the island remains heavily dependent on fossil fuel imports for power generation and transport energy needs. This makes Tahiti highly vulnerable to petroleum price volatility and supply disruptions. Nowadays, renewable energy production in Tahiti mostly comes from hydro-electric stations (25.7% of the total energy mix in 2015) and from solar panels (4.5 % in 2015). A solar map covering the whole world with 1 km resolution is made freely available at [4] by the World Bank Group. The solar radiation data is derived by Solargis algorithms from satellite images and auxiliary atmospheric datasets. In this paper, we use ground-based measurements of solar irradiation to assess the solar resource in Tahiti and compare them with satellite-derived values from the global solar atlas.

2 Data and methods

2.1. Dataset description

The Kipp and Zonen CM11 model pyranometer is installed at the meteorological station of Faaa international airport on the north-western part of Tahiti. It should be mentioned that irradiance indicates the rate of solar energy arriving at the surface per unit time and unit area, in W.m^{-2} while irradiation refers to the amount of solar energy arriving at the surface during a given period of time, in J.m^{-2}. Hourly totals of global horizontal irradiation (GHI) in J.cm^{-2} over the 2008-2017 period have been considered in this study. Reference time is the solar time. We have discarded the nighttime measurements and selected values from 08:00 to 17:00 local time to avoid the sunrise and sunset shifting issues. Also, the instrument has been installed far from any

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obstructing structure and the shading due to orography does not affect it from 08:00 to 17:00.

2.2. Basic solar energy definitions

Solar irradiance is usually depicted through three different components:

- Direct-normal Irradiance (DNI) is the amount of irradiance per unit area received by a plane perpendicular to the rays that come from the sun in a straight line
- Diffuse Horizontal Irradiance (DHI) is the amount of irradiance per unit area that does not arrive in a direct path from the sun
- Global Horizontal Radiation (GHI), or Global Horizontal Irradiance, is the total amount of irradiance falling on a horizontal unit area, i.e. the sum of direct radiations (DNI), diffuse radiation (DHI) and ground-reflected radiation (often neglected):

GHI = DHI + DNI cos θz

where θz is the solar zenith angle.

We define the clearness sky index (k_t), or effective global horizontal transmittance, as the ratio of measured GHI at the Earth's surface to the extra-terrestrial GHI (GHI_0):

$$k_t = \frac{GHI}{GHI_0} = \frac{GHI}{DNI_0 cos\theta_z}$$

Where θz is the solar zenith angle and DNI_0 is the extra-terrestrial DNI.

The extraterrestrial solar irradiance on a horizontal surface GHI_0 is calculated as a function of the solar constant S_0 = 1367 W.m^{-2}, eccentricity correction factor of the Earth's orbit E_0, local latitude Φ, solar declination δ and hour angle ha according to the expression :

$$GHI_0 = S_0 E_0 cos\theta_z$$

where

$$E_0 = 1 + 0.033cos\left(2\pi\frac{j}{365}\right)$$

with j being the sequential day of the year and θz, the solar zenith angle defined by:

$$cos\theta_z = sin\phi sin\delta + cos\phi cos\delta cosha$$

We also define the direct beam transmittance k_b, which is the ratio of DNI reaching the Earth's surface to DNI_0:

$$k_b = \frac{DNI}{DNI_0}$$

These equations would be used to derive the energy output and capacity factor of a residential photovoltaic system.

3 Results

3.1 Daily and monthly variability of solar irradiation

Figure 2 shows the monthly daily average of GHI (in MJ.m^{-2}.day^{-1}) and k_t. The lowest value of 14.9 MJ.m^{-2}.day^{-1} is reached in June whereas November has the highest value of 21.0 MJ.m^{-2}.day^{-1}.

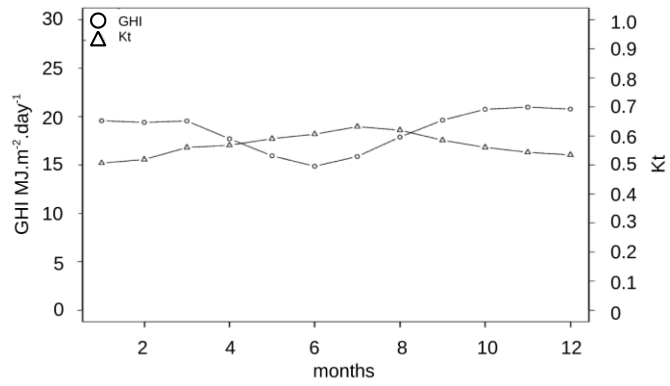

Fig. 2. Monthly variations of GHI and k_t.

This contrast is related to the apparent path of the sun along the year. The monthly values of k_t, vary between 0.5 in January and 0.63 in July. These results are in agreement with the seasonal variations of cloudiness. Indeed, cloudiness is reduced during the dry season and enhanced during the wet season. Therefore, GHI and k_t have opposite variations. The frequency histogram of k_t plotted on figure 3 shows that k_t is comprised between 0.65 and 0.75 about 30% of the daytime.

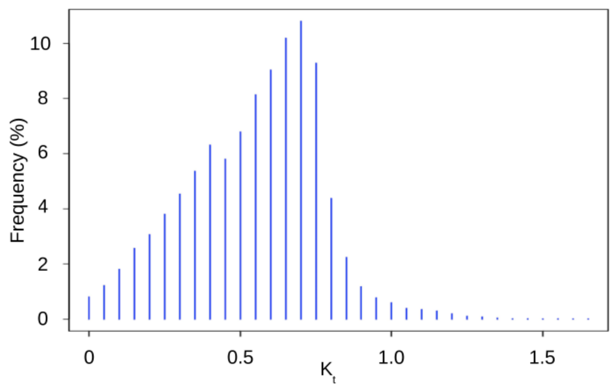

Fig. 3. Histogram of frequency of the hourly k_t (2008-2017).

Faaa has an annual GHI of 1882.6 kWh.m^{-2} based on monthly mean GHI values multiplied by the number of daytime hours in a year. Figure 4 indicates a value of 2000 kWh.m^{-2} near Faaa estimated by the global solar atlas mentionned in section 1.

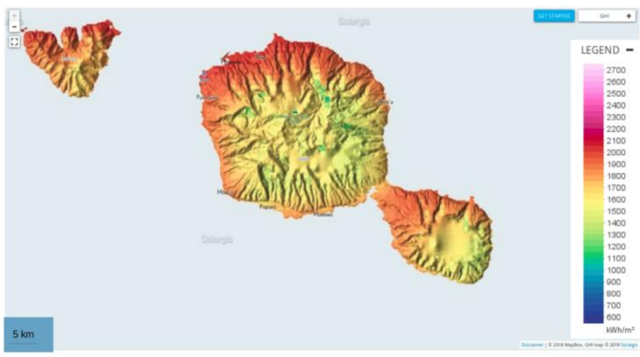

Fig. 4. Annual GHI in kWh/m² retrieved from Global Solar Atlas.

Relative error is 6% which is acceptable. The solar atlas could be used in other coastal areas of Tahiti where irradiance measurements are not available to have an overview of the annual GHI. The inner part of Tahiti is mountainous, clouds tend to develop in this area due to orographic ascent, consequently the amount of GHI is lower.

3.2 Direct normal irradiation

In this subsection, we derive direct normal irradiation from global horizontal irradiation using the empirical model of [5]. The authors developed an empirical correlation model using global and direct irradiance data registered at Ajaccio, France, between October 1983 and June 1985. Hourly values of the clearness index k_t are used to estimate the direct transmittance k_b, using the following relationship:

$$k_b = -10.626k_t^5 + 15.304k_t^4 - 5.205k_t^3 + 0.994k_t^2 - 0.059k_t$$

The calculation of extra-terrestrial irradiance GHI_0 and DNI_0 is presented in section 2. Then, k_t is derived using computed GHI_0 time series and GHI observed records. Finally, hourly DNI data is computed from k_t thanks to the Louche et al relationship.

3.3 Photovoltaic power production

3.3.1 Effective global irradiation on a tilted plane

Global Horizontal Irradiation represents the amount of radiation that a fixed horizontal surface can collect. If the PV plate is fixed non-horizontal (e.g. tilted at latitude) or is tracking the sun, then solar irradiation will vary. In this section, we derive the effective global irradiance G_{eff} incident on a tilted surface. Tilt angle β is the angle between the horizontal and the array surface. Optimal tilt angle varies with the season, but we will consider in our study that the PV array is tilted at latitude (17,5° for Tahiti). Array azimuth angle is the horizontal angle between a reference direction (North) and the direction that the array surface faces. By convention, it is expressed in degrees East of North (i.e. North = 0°, East = 90°, South = 180°). In the Southern hemisphere, azimuth angle is optimal when the array is due North. G_{eff} has three components (direct, diffuse and ground reflected) and depends on tilt angle β [6]:

$$G_{eff} = DNIR_{direct}K_{direct} + DHIK_{diffuse}\frac{1+cos\beta}{2} + \rho GHIK_{global}\frac{1-cos\beta}{2}$$

Where β is the angle of incidence of the sun rays on the tilted plane, $R_{direct} = \frac{cos\theta}{cos\theta_z}$ is the ratio of direct radiation on the tilted surface to that on a horizontal surface, ρ is the foreground albedo.

K_{direct}, $K_{diffuse}$ and K_{global} are the incidence angle modifiers. These parameters model the increase in reflected radiation on the solar panel with incidence angle. According to [6], those parameters only have noticeable effects at incidence angles 65° and higher. Therefore, their effect will be neglected in the rest of our study and they will be considered equal to 1.

The incidence angle θ between the surface and the beam of the sun depends on tilt and azimuth pointing angles (β and α_{surf}), and on solar zenith and azimuth angles (θ_z and α):

$$cos\theta = cos\theta_z cos\beta + sin\theta_z sin\beta cos(\alpha - \alpha_{surf})$$

DHI data is derived from GHI and DNI (computed using the [6] method) using the relationship:

$$DHI = GHI - DNIcos\theta_z$$

Ground reflectance ρ varies depending on the type of surroundings where the solar panel is located. In our study, we consider the example of building integrated PV facilities. We chose ρ equal to 0.20. This value is based on the work of [7], for a residential roof.

3.3.2 Monthly and annually energy output and capacity factor

The energy output from a PV module strongly depends on the solar radiation intensity, the cell temperature, the panel's orientation, and its size, among others. In this section, we will give a simple estimate of the energy output that a typical multi-crystalline silicon panel installed on a roof could annually produce, based on our previous calculations. The panel is oriented in the North direction and tilted at latitude (17.5°). We can estimate the energy output of a PV system by using the simple formula:

$$E = A\eta G_{eff}PR$$

where E is the annual electrical energy production (kWh/year), A is the total solar panel area (= 0.81 m^2), η is the module's nominal efficiency, G_{eff} is the yearly incoming effective irradiance and PR is the performance ratio. The module's nominal efficiency η represents the portion of photon energy that can be converted into electrical power via the photovoltaics technology of the cell. For current multi-crystalline silicon technologies, nominal efficiency typically varies between 18.5 and 21 % at standard test conditions [8]. For our calculations, we fix the value η = 20 %. The performance ratio of a PV system PR is defined as the ratio between the annual production of electricity at AC and the target yield (i.e. theoretical annual only considering the incoming irradiation and the module's nominal efficiency). It represents the total losses in the system and it is independent from the irradiation. Typical losses are pre-conversion losses (shading, dirt on the panel...), system losses (wiring, inverter...), or thermal losses (temperature dependence of the solar module). It usually ranges between 70 and 80 % [9]. For our calculations, we set the value PR = 0.75.

Figure 5 illustrates the potential energy that a PV system could annually produce. Minimum is 20.4 kWh in February and maximum is 30.2 kWh in May. The 0.81 m² PV module produces 308.5 kWh per year, it represents 8.8% of the annual electricity consumption per household in Tahiti, which was around 3 500 kWh in 2008 [1]. Installing 10 PV modules (8.1 m²) could cover 88% of a household.

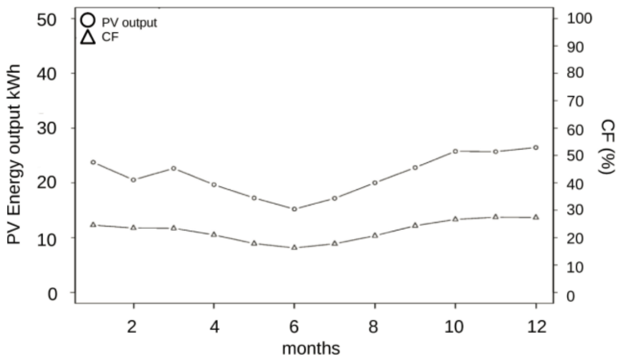

Fig. 5. Monthly variations of PV output and capacity factor.

The Capacity Factor (CF) is the ratio of the actual annual output of a PV module E on its potential output if it had operated at full nominal capacity throughout the year.

$$CF = \frac{E}{P_{rate}T}$$

where P_{rate} is the rated power of the PV module (equal to 130 W in our study) and T is the number of hours in a year. The capacity factor is 27.1 % and its monthly variation is plotted on figure 5. The lowest value is 22.7 % in January and the highest value is 31.2 % in May. Capacity factors for PV are typically in the range of 10% to 25% for fixed tilt systems which makes Faaa a good site for harnessing solar resource.

4 Conclusions

This study addressed the solar resource available in Faaa, Tahiti, thanks to long records of in situ measurements. Global horizontal irradiation is above 14 $MJ.m^{-2}.day^{-1}$ each month. The highest value of 21 $MJ.m^{-2}.day^{-1}$ is reached during the wet season as the sun is in the Southern Hemisphere during this period of the year. Clearness index, on the contrary, is minimal during the wet season, when cloud cover is abundant and maximal in the dry season, when cloud cover is reduced. The photovoltaic energy output in Faaa has also been estimated. The energy that could be produced using a single fixed PV module due North and tilted at the latitude reaches 308.5 kWh/yr. Ten PV modules representing 8.1 m² of roof top could cover 88% of a typical Tahitian household's annual electricity needs. The capacity factor is 27.1 % confirms the economic viability of a residential PV central. Future work would focus on how to manage the intermittency of the solar resource.

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References

1. Service de l'Energie et des Mines (2009). Bilan prévisionnel équilibre offre demande d'électricité à Tahiti, Service de l'Energie et des Mines, 2009, available at: http://www.service-energie.pf/telechargement/BILAN%20PREVISIONNEL%20ELECTRICITE%20OFFRE%20DEMANDE%20TAHITI.pdf.
2. https://www.noaa.gov/.
3. EDT Engie available at : http://www.edt.pf/a-propos-dedt/.
4. World Bank Group. Global Solar Atlas available at: https://globalsolaratlas.info.
5. A. Louche, G. Notton, P. Poggi, & G. Simonnot. Solar Energy, **46**(4), 261-266 (1991).
6. W. De Soto, S. A. Klein, & W. A. Beckman. Solar energy, **80**(1), 78-88 (2006).
7. H. Akbari, S. Menon, & A. Rosenfeld. (2008).Climatic Change **94**(3-4), 275-286 (2009).
8. M. A. Green, K. Emery, Y. Hishikawa, W. Warta, & E. D. Dunlop, (2015). Progress in photovoltaics: research and applications, **23**(1), 1-9 (2015).
9. N. Aste, C. Del Pero, F. Leonforte, & M. Manfren. Energy, **59**, 503-512 (2013).