Household Energy Consumption and Solar PV Energy Generation: A case study in Malta

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Abstract. The household energy consumption is an essential parameter to design renewable energy generation systems, to carry out demand response studies and to optimize the operation of energy management systems. Nevertheless, only few studies in literature analyze the user's electrical consumption profile in detail. Hourly data are often used and the electrical loads are typically assumed to operate at their rated power.

This paper presents a detailed analysis of the electrical consumption profile of a dwelling located in Malta. The electrical demand was monitored for over one year at a resolution of 30 seconds. Measurements of the electricity generated by a photovoltaic system installed on the roof-top of the dwelling, have also been performed and a parametric analysis has been carried out to evaluate the effect of different solar PV system sizes. Moreover, different strategies to increase the self-consumed electricity and reduce the excess electricity injected into the grid are described.

1. Introduction

Accurate electrical consumption profiles are a vital component when designing distributed renewable energy generation systems, enhancing the performance of energy management systems and to optimize demand-side management algorithms. However, hourly data and constant electrical consumption of household appliances are often used. Moreover, aggregated profiles are usually available whereby the household consumption is typically obtained by either averaging the consumption profile of several users or by averaging the electrical consumption of a single user, over a certain period of time (usually one month). Although aggregated profiles are useful to analyze the general trend and users' behavior [1], these result in a smoother electrical profile with the loss of the high frequency variability due to the After Diversity Maximum Demand effect [2].

Linssen et al. in [3] underline the importance of using individual realistic consumption profiles to design and optimize photovoltaic systems. The authors point out that the use of standard and aggregated load profiles leads to an overestimation of the self-consumption rate, i.e. the electricity produced and used directly on-site, with a consequent overestimation of the expected energy savings. However, empirical household consumptions are not easy to obtain and for this reason, several modelling strategies have been proposed to provide synthetic realistic electrical consumption profiles. A review of these different modelling techniques has been carried out by Swan and Ugursal [4]. The authors distinguish between top-down and bottom-up approaches, highlighting advantages and drawbacks of both. Top-down models only require aggragated and hystorical data as input but do not consider the individual end-user. Bottom-up models overcome this limit but detailed information is required as input. Widén J and Wäckelgård [5] proposed a bottom-up model approach. According to the authors, the elements required to accurately predict the household electrical demand are: the type and number of appliances in the building; their electrical consumption; and how they are used (i.e. the occupants behavior). Based on these considerations, Widén J and Wäckelgård [5] used the Markov chain model to generate a sequence of activities for each building occupant. Those activities were then converted into electrical demand. Beside the central role of load profiles, another element which should be considered is the temporal resolution of the available data. Wright and Firth [6] analyzed the electrical profile of eight houses, considering different temporal resolutions of 1, 5, 15 and 30 minutes. They show that the variance in the instantaneous power consumption disappears when increasing the temporal resolution above 1 minute. In addition, the estimated electricity being imported from the grid widely changes. Beck et al. [7] analyzed the effect of temporal resolutions on the self-consumption rate. They show that for a PV system without energy storage, a resolution of 15 minutes of the solar radiation data is sufficient to predict the generated electricity, while a resolution of 60 seconds is required for the electrical household consumption profile to ensure an accurate prediction of the self-consumption rate. The interval can be increased up to 15 minutes if most of the power consumption is below 2kW since this only results in a 5% error in the self-consumption rate. In this work, both the electrical energy consumption and PV production of a dwelling located in Malta have been measured and analyzed having a temporal resolution of 30 seconds. In section 2, the main characteristics of the PV system and the electrical consumption profile are described. The main system performance indicators are defined and determined in section 3. In section 4, the results of the parametric analysis carried out for different PV system sizes, are presented and discussed. Moreover, an overview of the main strategies to reduce the mismatch between electrical demand and PV generation are also described.

2. Photovoltaic System and Electrical Load Profile

Data was obtained by measuring the electrical consumption and PV generation of a dwelling located in Malta for over one year with a temporal resolution of 30s. Figure 1 and 2 show the electrical profile in a typical winter and summer day respectively.

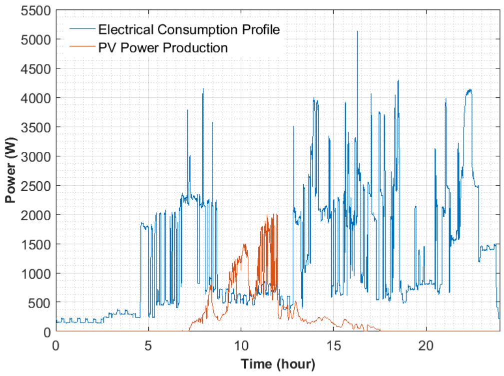

Figure 1: Electrical consumption and PV generation in a typical winter day.

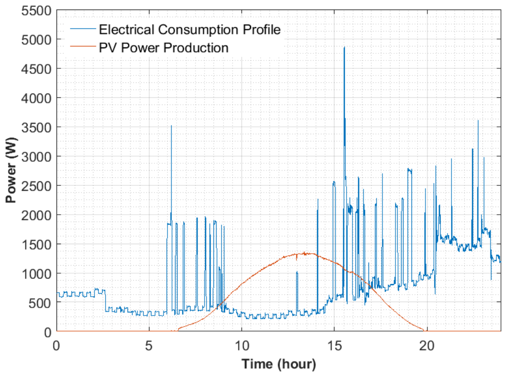

Figure 2: Electrical consumption and PV generation in a typical summer day.

The high frequency variations due to the operation of the consumer loads are evident from the analysis of figure 1 and 2. The electrical demand varies widely in the different seasons and even from day to day making accurate predictions difficult. The electrical demand can be considered to consist of two components: (1) the base load which is due to those appliances that are switched on 24 hours a day (such as fridge and freezer) and; (2) a variable load which is more difficult to forecast since it depends on several factors. These factors include weather conditions, daylight availability, type of appliances in the building, occupancy and specific user habits. It is also worth noting that the PV generation profile can be very intermittent in winter due to the more variable weather conditions. To analyze the user behavior, the mean value and standard deviation of the generated electricity and electrical consumption have been determined for the different seasons and are shown in figure 3 to 6 using a temporal resolution of 30 minutes. The error bars represent the standard deviation which provides information on how much the values tend to deviate compared to the mean value.

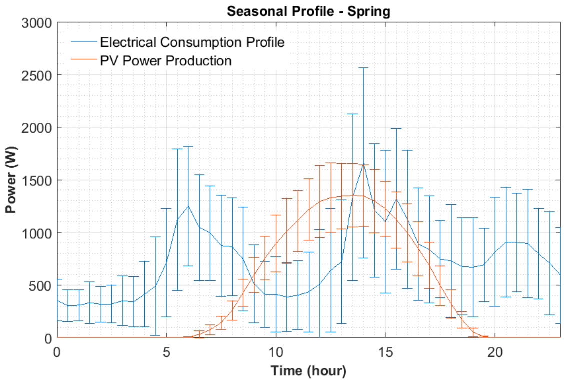

Figure 3: Spring seasonal daily profile for electrical consumption and PV generation.

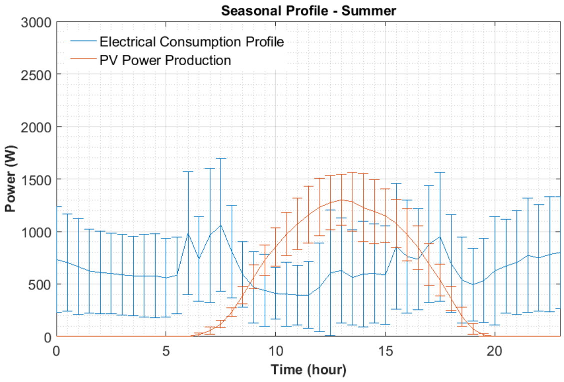

Figure 4: Summer seasonal daily profile for electrical consumption and PV generation.

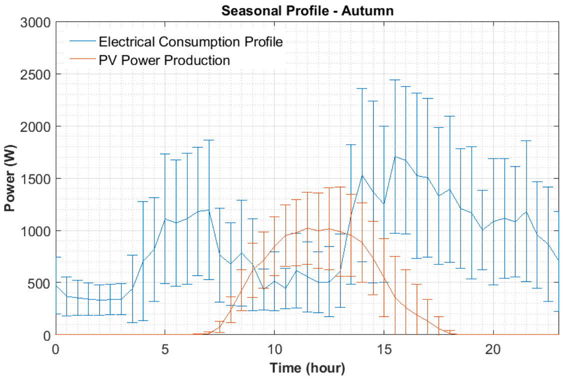

Figure 5: Autumn seasonal daily profile for electrical consumption and PV generation.

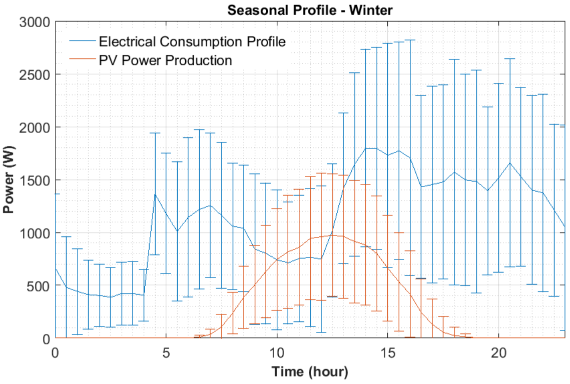

Figure 6: Winter seasonal daily profile for electrical consumption and PV generation.

The variation of the PV production is more pronounced in autumn and especially in winter, as it would be expected, considering the higher frequency of cloudy days. On the other hand, the electrical consumption profile shows high values of standard deviation in all seasons, confirming its high variability and the difficulties in forecasting the household electrical consumption. However, the analysis of figures 3 to 6 allows to identify some general trends. The average daily electrical consumption is higher in winter (26.8 kWh/day) when compared to the summer season (15.74 kWh/day). Such a difference might be due to several reasons, the reduced need for lighting in summer and the reduced use of domestic hot water. Moreover, it is worth noticing that in all seasons, power consumption peaks mainly occur in the morning when people are preparing to go to work/school, and in the afternoon/evening when they are back home. The electrical demand is lower during periods of high solar PV generation, in particular during the spring and summer season.

3. Performance Indicators

In order to evaluate the performance of a photovoltaic system, some parameters are taken into consideration: Self-Sufficiency Ratio (SSR) and Self-Consumption Ratio (SCR).

The Self-Sufficiency Ratio is defined as the ratio between the electricity directly consumed on-site by the user ($E_{PV_{cons}}$) and the overall electrical demand (E_{LOAD}). It represents the percentage of the building electrical consumption provided by the PV system.

$$SSR = \frac{E_{PV_{cons}}}{E_{LOAD}} \cdot 100 = \frac{\int P_{PV_{cons}}(t)}{\int P_{LOAD}(t)} \cdot 100$$

P_{LOAD} is the instantaneous power consumption and $P_{PV_{cons}}$ is the instantaneous power produced by the PV system and directly consumed by the user. The latter is determined as shown by the flowchart in figure 7. At each time-step, generation is compared with the load consumption. If the generation exceeds the demand it means that only part of the PV generated electricity is used (P_{LOAD}) while the remaining amount ($P_{PV} - P_{LOAD}$) is injected into the grid. If the power production is lower than the load, then all the electricity produced by the photovoltaic system is directly used by the user (P_{PV}) and any additional electricity ($P_{LOAD} - P_{PV}$) is imported from the grid.

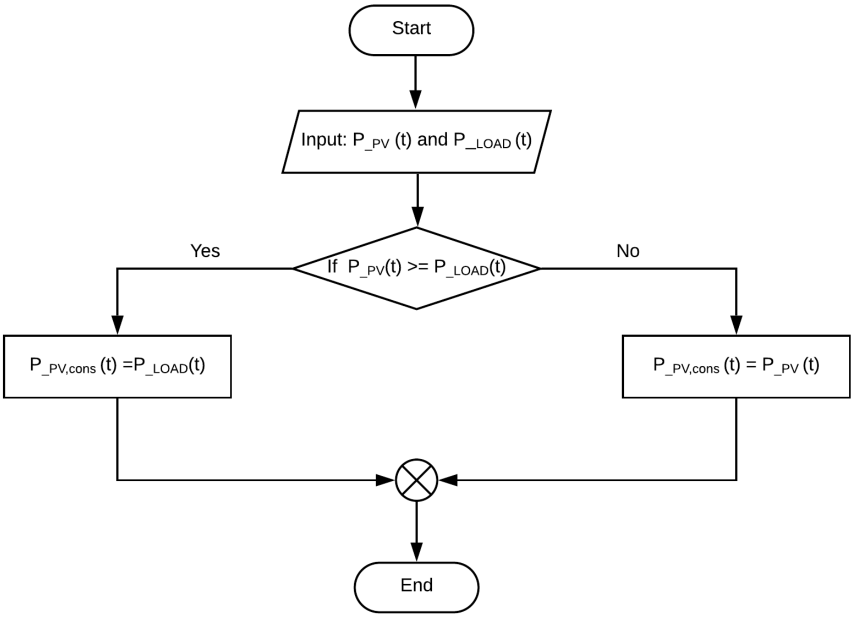

Figure 7: Flowchart of the algorithm used to determine the self-consumed PV power production ($P_{PV_{cons}}$)

The Self-Consumption Ratio represents the percentage of self-consumed electricity with respect to the overall PV production ($E_{PV_{tot}}$).

$$SCR = \frac{E_{PV_{cons}}}{E_{PV_{tot}}} \cdot 100 = \frac{\int P_{PV_{cons}}(t)}{\int P_{PV_{tot}}(t)} \cdot 100$$

where $P_{PV_{tot}}$ is the instantaneous PV power production.

The Self-Consumption Ratio and the Self-Sufficiency Ratio have been determined for the 2 kW peak photovoltaic system under analysis. The overall electrical PV production is of 2976 kWh/yr while the electrical consumption is 7535 kWh/yr. The Self-Sufficiency Ratio is 21.13%, while the Self-Consumption Ratio is 53.5%, i.e. 53.5% of the electricity produced by the PV system is directly used while the remaining 46.5% is injected into the grid. The considerable amount of electricity exported to the grid is due to the mismatch between PV generation and electrical demand. In areas where there is a large concentration of PV systems, with large amount of electricity injected into the grid, this will cause reverse power flows in the distribution system with the consequence that consumers experience voltage rises which could possibly disconnect the PV generation system and even other equipment to avoid damage [8]. This highlights the need to increase self-consumption, which is usually obtained coupling the solar PV with a storage system. It is also worth noticing that the above mentioned values for the Self-Consumption Ratio and Self-Sufficiency Ratio have been obtained using a temporal resolution of 30 seconds. However, a Self-Sufficiency Ratio of 27.79% and Self-Consumption Ratio of 70.37% would be obtained using monthly profiles, obtained by averaging the data over a month. This confirms the results of Linssen et al. [3]. The use of aggregate profiles in this case would overestimate Self-Consumption by 16.87%.

4. Parametric Analysis and Discussion of the Results

To evaluate the effect of different PV system sizing on the Self-Consumption and Self-Sufficiency Ratio, a parametric analysis has been performed. Considering the electrical load described in section 2, the PV size has been varied in the range from 0 to 6 kW. Figure 8 shows the electrical load and the power production of different PV systems (2, 4 and 6 kW peak) for the winter season. The comparison is based on the assumption that all photovoltaic systems have the same type of panels, inclination and orientation, the only difference is the number of panels.

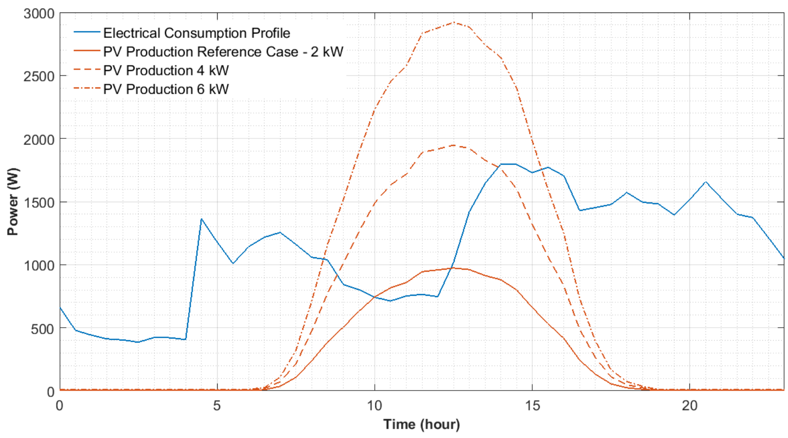

Figure 8: Winter seasonal electrical consumption profile and PV production for different PV size of 2, 4 and 6 kW

The Self-Sufficiency Ratio, Self-Consumption Ratio and the electricity exported to the grid with respect to the overall electrical load have been determined for the different PV sizes. The graph reported in figure 9 shows on the y-axis the values of these three parameters while on the x-axis the PV size has been plotted with respect to the reference PV system of 2 kW. A temporal resolution of 30 seconds was used in the calculations.

Figure 9 highlights that the self-consumed electricity only slightly increases, while the surplus of electricity injected into the grid grows at a faster rate. Its value increases from 18.4% to 50% doubling the PV system size and up to 85.6% with a PV system three times bigger. Hence, it is evident that an oversized PV system will cause a large amount of electricity to be injected into the grid. In high market penetration scenarios of solar PV, this will possibly incur curtailment and

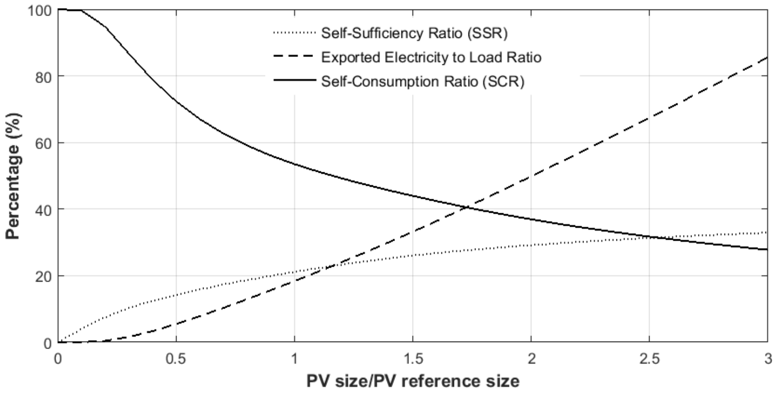

Figure 9: Self-Sufficiency Ratio, Self-Consumption Ratio and the electricity exported to the grid with respect to the overall electrical load for different PV size

jeopardize the grid stability and reliability. Increasing on-site power consumption can increase the market penetration of renewable energies and ensure a better integration. Nevertheless, it should be considered that the self-consumption potential of a PV system alone is limited. As shown in figure 9, the SSR curve is an asymptotic curve. The Self-Sufficiency Ratio increases from a value of 21.13% to 29.16% with an increment of 8.03% and to 32.91% with an additional increment of 3.75% for a PV system 2 and 3 times bigger respectively. The already small increment of the Self-Sufficiency Ratio strongly reduces for higher PV sizes.

To overcome this limit of photovoltaic installations, the possibility to couple PV with energy storage has been widely considered in literature [9]. Electrical and thermal storage represent the most typical options. In the first case, the excess of electricity is stored in batteries in the second case, electricity is converted by a heat pump into thermal energy and stored in tanks. Another option to increase self-consumption is the use of demand-side management systems (DSM). Several authors have suggested different demand side management techniques to determine the optimal schedule of household appliances [10] [11]. A review of DSM concept, terminology and methodologies has been carried out by Fattahi Meyabadi and Deihimi [12]. In this context, it is also evident the central role of the end-users who have to modify their habits shifting as much as possible their electrical consumption during the peak of energy generation. This result can be obtained by switching on deferrable appliances (such as dishwasher, washing machine and dryer) during periods of high solar radiation to minimize the electricity injected into the grid.

5. Conclusions

In this paper the electrical energy consumption of a typical residential building located in Malta and the electricity produced by a grid-connected photovoltaic system, installed on the roof-top of the dwelling, have been analyzed. The Self-Sufficiency Ratio and Self-Consumption Ratio have been determined using data with a resolution of 30 seconds. The photovoltaic system provides 21.13% of the building electrical consumption, 53.5% of the electricity produced by the PV system is directly used while the remaining 46.5% is injected into the grid.

The parametric analysis has shown that increasing the PV size, the amount of electricity injected into the grid will rapidly increase. In areas with large concentration of PV installations, this will cause voltage rises. To limit this risk some considerations should be taken into account

- an accurate design is needed to avoid oversized PV system installations;
- demand side management algorithms together with the development of different user habits, can be useful to reduce the excess of electricity injected into the grid, shifting the electrical consumption in periods of high solar PV generation;
- suitable energy storage solutions, such as batteries and thermal storage, should be

implemented.

Another aspect highlighted in this paper is the importance of accurate electrical profiles. The use of data averaged over a month would have overpredicted Self-Consumption by 16.87%. This factor should be duly considered when designing a PV system and economic analysis are performed.

References

[1] Bedir M, Kara E C 2017 Behavioral patterns and profiles of electricity consumption in dutch dwellings *Energ Buildings* vol **150** 339–52

[2] Jenkins D P, Patidar S and Simpson S A 2014 Synthesising electrical demand profiles for UK dwellings *Energ Buildings* vol **76** 605–14

[3] Linssen J, Stenzel P and Fleer J 2017 Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles *Appl. Energy* vol **185** 2019–25

[4] Swan L G, Ugursal V I 2009 Modeling of end-use energy consumption in the residential sector: A review of modeling techniques *Renewable and Sustainable Energy Reviews* vol **13** 1819–35

[5] Widén J, Wäckelgård E 2010 A high-resolution stochastic model of domestic activity patterns and electricity demand *Appl. Energy* vol **87** 1880–962

[6] Wright A, Firth S 2007 The nature of domestic electricity-loads and effects of time averaging on statistics and on-site generation calculations *Appl. Energy* vol **84** 389–403

[7] Beck T, Kondziella H, Huard G and Bruckner T 2016 Assessing the influence of the temporal resolution of electrical load and PV generation profiles on self-consumption and sizing of PV-battery systems *Appl. Energy* vol **1** 320–31

[8] Von Appen J, Braun M, Stetz T, Diwold K and Geibel D 2012 Time in the Sun: The Challenge of High PV Penetration in the German Electric Grid *IEEE Power Energy Mag.* 55–64

[9] Settino J, Sant T, Micallef C, Farrugia M, Spiteri Staines C, Licari J and Micallef A 2018 Overview of solar technologies for electricity, heating and cooling production *Renewable and Sustainable Energy Reviews* vol **90** 892–909

[10] Mohsenian-Rad A, Wong V W S, Jatskevich J, Schober R, Leon-Garcia A 2010 Autonomous Demand Side Management Based on Game-Theoretic Energy Consumption Scheduling for the Future Smart Grid *IEEE Transaction on Smart Grid* vol 331–42

[11] Di Giorgio A, Pimpinella L 2012 An event driven Smart Home Controller enabling consumer economic saving and automated Demand Side Management *Appl. Energy* vol **96** 92–103

[12] Fattahi Meyabadi A, Deihimi M H 2017 A review of demand-side management: Reconsidering theoretical framework *Renewable and Sustainable Energy Reviews* vol **80** 367–379