22nd International Conference on Renewable Energies and Power Quality (ICREPQ'24)
Bilbao (Spain), 26th to 28th June 2024

ISBN: 978-84-09-60656-6

Algorithm for managing the consumption curve of a consumer with self-consumption photovoltaic generation

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Abstract. In the quest for sustainability, self-consumption of solar energy, facilitated by home automation and information technology, emerges as a viable solution for energy management. This paper presents an innovative algorithm designed to optimize the scheduling of electric consumption-based devices in domestic settings. The algorithm aims to align the power consumption curve with solar generation, thereby promoting efficient energy use. The algorithm's effectiveness has been validated through simulations conducted in MATLAB, using real-world data to emulate various scenarios of photovoltaic generation and consumption. The results demonstrate the potential of this approach in contributing to energy sustainability by improving the efficiency and providing flexibility to the grid, which translates in broader societal and economic benefits.

Keywords. Self-consumption, photovoltaic, sustainability, efficiency.

1. Introduction

In the contemporary discourse on sustainability, energy management practices and societal habits have gained momentum. One potential pathway to achieving energy sustainability is through self-consumption, where individuals harness renewable energy sources, such as solar power, for their personal use. This alternative, facilitated by advancements in home automation and information technology, holds promise for delivering significant social and economic benefits. Due to this reason, in the realm of electrical engineering, the pursuit of sustainability has emerged as a critical concern in recent years. Traditional efforts have concentrated on the creation of clean power generation methods, including solar, wind, and hydroelectric power.

However, this represents only one facet of the sustainability equation. While the generation of clean power is undeniably vital, a combination of several strategies must addressed for pursuing energy sustainability. In Fig. 1 the most significant strategies are summarized. Technological innovation involves the use of advanced technologies like smart grids and energy storage systems to improve energy efficiency. Demand reduction aims to decrease energy consumption through energy-efficient practices and appliances. Energy diversification reduces dependence on a single energy source, promoting a mix for energy security. The use of renewable energy sources such as solar and wind is encouraged for their sustainability and lower emissions. Self-consumption, particularly with solar photovoltaic systems, reduces the need for grid energy. Lastly, adapting consumption habits, such as using energy-efficient appliances and shifting energy use to off-peak times, can significantly reduce energy consumption. This work targets all these strategies but places a particular emphasis on the adaptation of consumption habits in order to enhance the performance of the self-consumption photovoltaic systems.

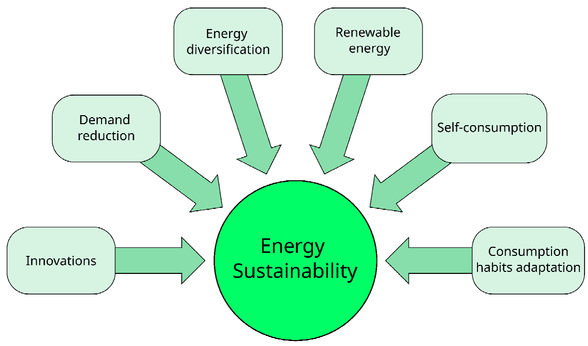

Fig. 1. Factors for energy sustainability

As depicted in Fig. 2, consumption curves do not commonly align with production curves, leading to inefficiencies, such as wasting the energy or increasing the capacity requirements of batteries when facing energy surpluses during off-peak hours. On the other hand, when the generation is lower than consumption, there is a need to consume more energy from the grid, which can lead to higher costs and increased reliance on traditional energy sources. This is particularly evident during peak hours when the demand for energy is high. Furthermore, these misalignments can lead to wear and tear on energy infrastructure [2], as the systems need to constantly adjust to the fluctuating supply and demand. This can result in increased maintenance costs and shorter lifespan of the infrastructure. These inefficiencies highlight the need for smarter energy management systems reducing wasted energy and improving the overall efficiency of the energy system.

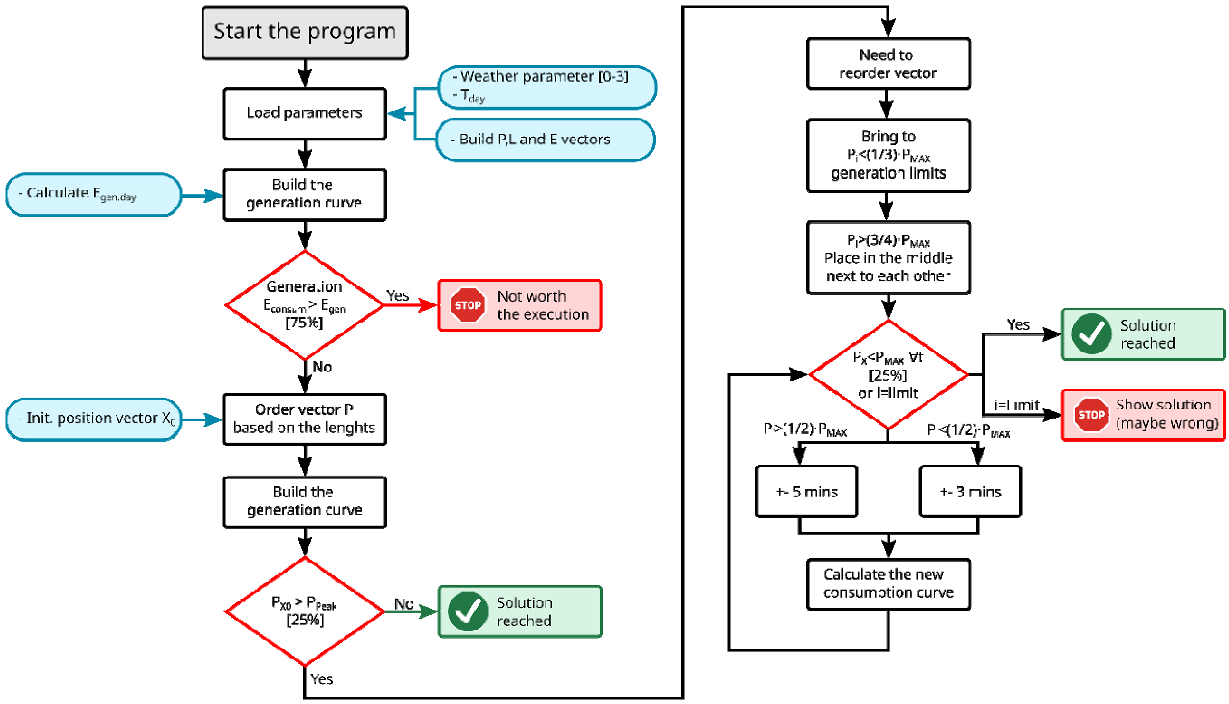

Fig. 3. Flow chart of the developed algorithm

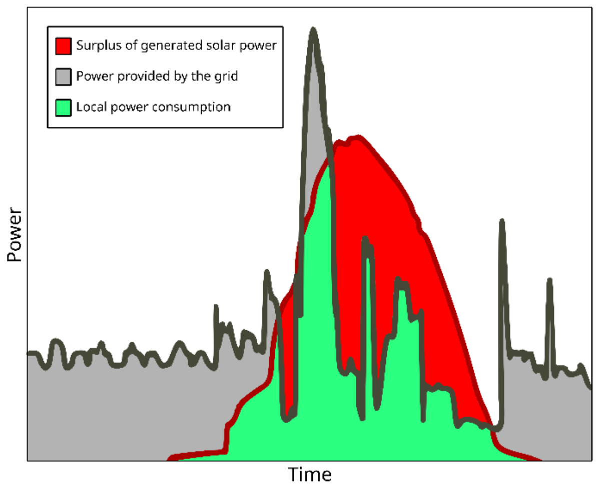

Fig. 2. Example of photovoltaic production profiles and consumption in a single-family residential building [1]

The electrical energy consumption management enhances grid flexibility by allowing for modifications in generation and consumption patterns [3]. This flexibility, coupled with new technologies and market structures, enables to dynamically balance the resources and to smooth out the discrepancies between production and consumption curves. This leads to more efficient and sustainable energy use, thereby modernizing the power grid and increasing its resilience [4].

Given the complexities and implications of the issues discussed, there is a number of researches in the literature dedicated to this topic, such as [5-10]. This underscores the significance and urgency of finding effective solutions in consumption management for self-consumption systems.

In the field of consumption demand management, the primary objective often emphasized in most studies is the reduction of economic costs. These alternatives are commonly designed to respond to a non-linear optimization problem, that is, setting several conditional functions (which can also be non-linear) when looking for a minimum of an objective function. The optimal solution hinges on the precise calibration of the load, specifically, the consumption programming that minimizes the objective function.

This issue could lead to numerous solutions, suggesting the presence of multiple local optimal points that may vary considerably from the absolute optimum. Meta-heuristic algorithms have been used to find the solution, such as genetic algorithms [11-12] or compromise algorithms [13], but other different algorithms are also used in other areas related to the field [14-16]. These algorithms guarantee greater flexibility compared to traditional ones, but the complexity also increases due to inaccuracies.

For this reason, in this work, a traditional algorithm will be sought, which is more rigid but lighter in terms of computational work. Consequently, the goal of this work has been too develop an algorithm designed to establish a specific load consumption schedule, aligning it with the generation curve in a solar energy-based self-consumption system.

2. Proposed algorithm

This section describes the developed algorithm, shown in Fig 3, which aims to optimize the scheduling of electric consumption-based devices in domestic settings, thereby aligning the power consumption curve with solar generation. This scheduling process seeks to optimize energy usage, ensuring that the available solar power will be utilized in an efficient manner.

Once the program has been launched, in a first step, the solar source parameters are loaded to create the generation curve. In the next step, the user introduces the electric energy consumption to create the data base of the devices to be used, including the power ratings and hours of use. With this information, the consumption curve is built, placing all electrical consumption at midday hours. At this point, it will be verified that the total energy consumption is not 1.5 times greater than the total energy production. If so, the program will enter the restructuring function, otherwise it will indicate that it is not worth doing through the consumption management algorithm.

The scheduling function has been designed as a waterfall structure that follows the bell-shape of the generation curve. Then, in each iteration, it gradually moves the consumption of each device distancing it from the centre until the optimal solution has been reached. The first step of the scheduling is to sort the matrix of peaks according to powers by classifying them. For instance, peaks very close to Pmax (4/5) are considered high power, while those far from Pmax (1/3) are low power.

The scheduling algorithm aims to balance the operation of high-consumption and low-consumption devices throughout the day to optimize energy use. During the scheduling process, the calculation of the areas of each of the curves (generation and consumption) is carried out using the trapezoidal integration method. In this process, high-consumption devices are used near the peak of the generation curve, while low-consumption devices are more likely to be used simultaneously at the ends of the curve, that is, in the mornings and at dusk, likely when overall energy demand is lower. The remaining equipment is placed after performing further classifications (peaks above and below $0.5 \times P_{max}$). Hence, they will be moved left-right through different iterations, displacing the medium-low powers by 5 minutes in each iteration and the medium-high ones by 3 minutes. This iteration has two limits: while the first and main limit aims to obtain $P_{\text{consumption\_}max} < 1.25\ P_{\text{generation\_}max}$ relation, the second limit is used to avoid entering into an infinite loop. This is carried out by limiting the iterations in the programming loop. This limit depends on the number of devices to be scheduled.

After obtaining a satisfactory result with an optimal schedule, the algorithm provides the results, including a graph that contrasts the final generation energy with the final consumption energy management. In addition, a table with the data for each day is displayed.

3. Validation

The validation process of the proposed approach has been conducted using the MATLAB R2021a software, with the various modules of the algorithm designed to operate within this environment. The first module calculates the electric generation of the photovoltaic system by processing historical irradiance data. Subsequently, a consumption profile is constructed based on the list of appliances provided by the user. With the data gathered from these steps, the developed algorithm performs the processing to derive an optimized consumption schedule.

The algorithm also provides the results of two parameters: self-sufficiency ratio and self-consumption ratio.

The electrical self-sufficiency ratio (1) indicates the percentage of electrical consumption provided by photovoltaic installations. This parameter not only quantifies the photovoltaic installation's contribution to energy consumption, but also serves as an index of the restriction on energy derived from the electrical grid. Consequently, it mirrors the potential for economic savings. In a scenario of complete self-sufficiency (100%), the consumer is exempt from the variable component of the electricity bill, indicating maximum cost efficiency.

$$\boldsymbol{self\ sufficiency}(\%) = \mathbf{100} \cdot \frac{\boldsymbol{Local\ P.Consum.}}{\boldsymbol{Local\ P.Consum.+Grid\ P.}} \quad (1)$$

Self-consumption (2) indicates the percentage of photovoltaic production that is consumed on-site. The ratio is at its peak (100%) when all the production is consumed. A low ratio value could be due to incorrect installation sizing (excessive production for the existing consumption) or consumption deviating from production times. This has different economic implications depending on what is done with the surplus electricity. In this case, since no batteries are used, this surplus energy is not considered. The aim of this work is to create an algorithm that maximizes this ratio by reducing surplus energy.

$$\boldsymbol{self\ consumption}(\%) = \mathbf{100} \cdot \frac{\boldsymbol{Local\ P.Consum.}}{\boldsymbol{Local\ P.Consum.+Surplus\ gen.}} \quad (2)$$

Finally, the algorithm simulates the results using the calculated data, enabling user to visualize the potential impact of distinct strategies. This feature positions the algorithm as a potent tool for energy management, offering users tangible and comprehensible results.

The versatility of the algorithm has been tested across various scenarios by varying data inputs and distinct parameters. For the lack of simplicity, the consumption items, represented by household consumption devices, have been maintained constant as a reference. The fluctuating factors in these situations relate to the generation curve, particularly the weather conditions and the length of daylight hours. Distinct measurements have been conducted corresponding to distinct time durations. In each of these cases, the algorithm accounted for varying weather conditions, thereby demonstrating its adaptability and robustness in diverse environments.

The performed simulationw shown that the algorithm is effective and adaptable but also user-friendly, making it a promising solution for managing energy consumption and generation in households.

Results

This section includes the results and the simulation graphs of four of the studied cases in Matlab.

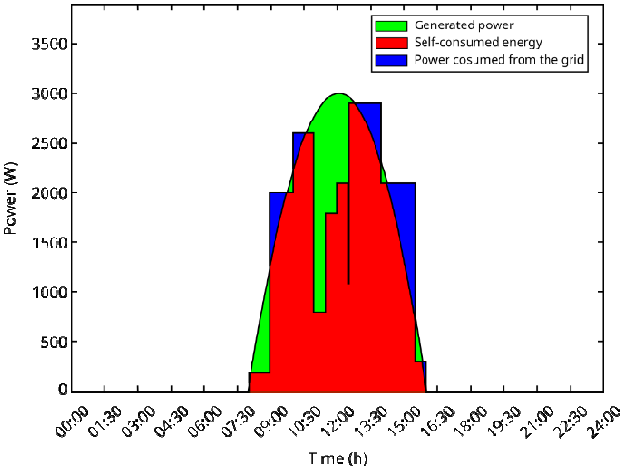

Fig. 4. Case A results: 8h and maximum power of 3 kW

Table I. – Case A results: 8h and maximum power of 3 kW

DEVICE	POWER	LENGTH	POSITION	ENERGY
Laptop	200 W	2	08:00	400
Dryer	1800 W	2	08:57	3600
PC	800 W	4	10:00	3200
Vacuum c.	1000 W	1	11:30	1000
TV	300 W	4	12:00	1200
Washing m.	1800 W	3	12:33	5400
Solution obtained Number of iterations: 287 Self-consumption ratio: 82.0183% Self-sufficiency ratio: 88.6684%				

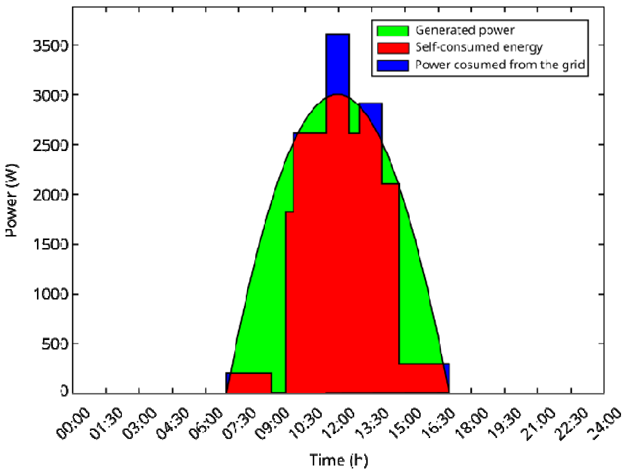

Fig. 5. Case B results: 10h and maximum power of 3 kW

Table II. – Case B results: 10h and maximum power of 3 kW

DEVICE	POWER	LENGTH	POSITION	ENERGY
Laptop	200 W	2	07:00	400
Dryer	1800 W	2	09:42	3600
PC	800 W	4	10:00	3200
Vacuum c.	1000 W	1	11:30	1000
Washing m.	1800 W	3	11:45	5400
TV	300 W	4	13:00	1200
Solution obtained Number of iterations: 180 Self-consumption ratio: 69.7797% Self-sufficiency ratio: 94.2969%				

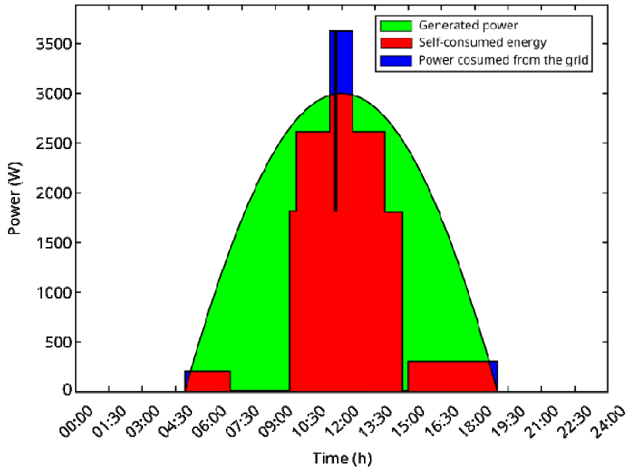

Fig. 6. Case C results: 14h and maximum power of 3 kW

Table III. – Case C results: 14h and maximum power of 3 kW

DEVICE	POWER	LENGTH	POSITION	ENERGY
Laptop	200 W	2	05:00	400
Dryer	1800 W	2	09:42	3600
PC	800 W	4	10:00	3200
Vacuum c.	1000 W	1	11:30	1000
Washing m.	1800 w	3	11:45	5400
TV	300 W	4	15:00	1200
Solution obtained Number of iterations: 180 Self-consumption ratio: 50.4473% Self-sufficiency ratio: 95.4408%				

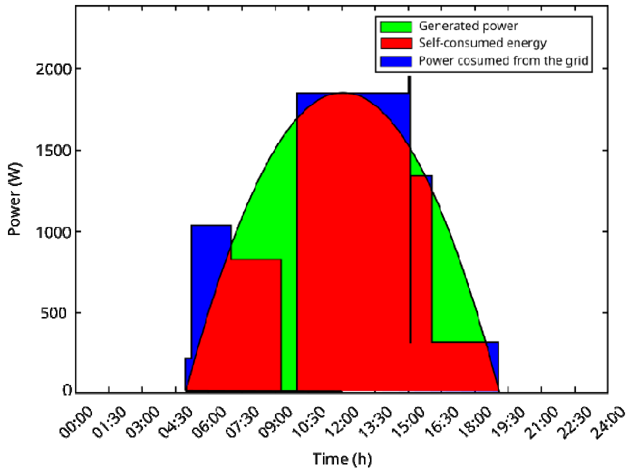

Fig. 7. Case D results: 14h and maximum power of 1.8 kW

Table IV. – Case D results: 14h and maximum power of 1.8 kW

DEVICE	POWER	LENGTH	POSITION	ENERGY
Laptop	200 W	2	05:00	400
PC	800 W	4	05:16	3200
Dryer	1800 W	2	10:00	3600
Washing m.	1800 W	3	12:01	5400
TV	300 W	4	15:00	1200
Vacuum c.	1000 W	1	15:03	1000
Solution obtained Number of iterations: 355 Self-consumption ratio: 79.5828% Self-sufficiency ratio: 90.3372%				

The results obtained from the tests demonstrate the attainment of valid solutions. It is important to note that the interaction count fluctuates considerably across different cases. The results are subject to the specific attributes of each case, leading to a variable range of outcomes. Generally, the application yields favourable self-consumption ratios, obtaining even better self-sufficiency ratios.

Finally, the program has been executed relatively fast in all the studied cases (between 1 and 3 seconds). It must be remarked that the majority of the processing time has been used draw graphs (for example, in a case where the total execution time was 2.435 s, the algorithm's execution only used 0.112 s). While these results are not conclusive due to their dependence on the specific hardware and software used, they provide a valuable benchmark for assessing that can be useful in gauging the algorithm's efficiency and responsiveness.

4. Conclusion

The proposed approach fosters efficient energy utilization, thereby contributing to the overarching objective of energy sustainability. The algorithm's effectiveness has been substantiated through comprehensive simulations in MATLAB, leveraging real-world data to simulate diverse scenarios of photovoltaic generation and consumption.

The algorithm offers multiple advantages. Primarily, it aids in optimizing energy consumption, facilitating a quicker return on investment for the installation. This promotes the adoption of self-consumption solutions, empowering consumers and aiding in the reduction of reliance on traditional energy sources. Another significant advantage is the algorithm's capacity to improve energy management, thereby helping to extend the time that households could be disconnected from the primary network. In addition, the approach provides potential to increase the flexibility and contributes to grid stability, enhancing its resilience against fluctuations and potential disruptions.

In terms of future work, there are several promising avenues for enhancing the application. One potential improvement could be to equip the algorithm with the capability to prioritize specific time slots for certain consumptions, thereby offering users greater control and customization. The inclusion of the battery in the analysis would be another interesting aspect for improvement. Additionally, the development of a user-friendly interface or a hardware implementation, such as a mobile application, could significantly enhance the user experience and accessibility of the system. These enhancements could further optimize energy consumption scheduling and contribute to the broader goal of sustainable energy management.

Acknowledgement

This work was supported by the Grant TED2021-129930A-I00 funded by MICIU/AEI/10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR"; by the Grant PID2021-125881OB-I00 funded by MICIU/AEI/10.13039/501100011033 and by "ERDF A way of making Europe; and by the Basque Government under the Grant IT1647-22 (ELEKTRIKER research group).

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