Energy Monitoring and Management for Homes

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

Due to increasing electricity consumption, which can jeopardise an outdated electrical grid and lead to power failures, along with the environmental problems caused by fossil fuel power plants in recent decades, it has become essential to better manage energy consumption.

From a consumer perspective, the electricity bill is a substantial portion of most people's budget. Hence, given the rise in prices over the last years, finding a way to better manage the power required from the grid while decreasing the costs of electricity is the goal to aim for.

Some concepts like load shifting and peak energy reduction are explored in this thesis, along with the usage of solar panels in order to find a way to reduce costs for the end-user while reducing electricity consumption during peak periods, that helps prevent any overload of the electrical grid.

A simulation for a home energy management system (HEMS) using these concepts is considered for the different electricity tariffs available in Portugal, using baseline scenarios with different family types and consumption patterns.

Shifting loads to off-peak periods reduce peak demand at home and allows the final consumer to potentially reduce the contracted power which will result in a lower bill amount.

Depending on the type of devices and usage in a home, we have observed a potential reduction up to 16,9% in a monthly bill.

Keywords: HEMS, Load Shifting, Peak Reduction, Bi-hourly tariffs, Contracted Power, Electricity Bill

Resumo

Devido ao aumento progressivo que se tem assistido de consumo de energia elétrica, que pode comprometer uma rede elétrica desatualizada e levar a falhas de energia, e aos problemas ambientais causados pelos combustíveis fósseis nas últimas décadas, tornou-se essencial uma melhor gestão do consumo de energia.

Do ponto de vista do consumidor, a fatura de eletricidade é ainda uma parte significativa do orçamento da maioria das pessoas. Desta maneira, dado o aumento dos preços nos últimos anos, encontrar uma maneira de gerir melhor a energia pedida à rede bem como simultaneamente reduzir os custos com a eletricidade, é o objetivo que se pretende atingir.

O sistema explora o conceito de mover cargas e redução de picos de energia, juntamente com a utilização de painéis solares, de modo a reduzir o consumo de eletricidade fora dos períodos de vazio, ajudando a evitar uma eventual sobrecarga sobre a rede.

De modo a explorar estes conceitos, foi realizada uma simulação assumindo um sistema de gestão de energia em casa (HEMS), que considera os diversos tipos de tarifação disponíveis em Portugal, usando para o efeito cenários com diversos padrões de uso de cargas.

Deslocar cargas para períodos de vazio ajuda a reduzir picos de energia em casa, permitindo uma redução da potência contratada, a qual resultará numa redução do montante da fatura elétrica.

Dependendo dos padrões de consumo e dispositivos dentro de uma casa, foi observada uma possível melhoria na fatura mensal de eletricidade até 16,9% caso o utilizador reduza efetivamente a potência contratada.

Palavras chave: HEMS, Deslocamento de carga, Redução de pico, Tarifas bi-horárias, Fatura de eletricidade, Potência contratada

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List of Abbreviations

ADENE – Agência para a Energia

BMS – Building Management System

CAV – Contribuição audiovisual

CO^2 – Carbon Dioxide

DGEG – Direção Geral de Energia e Geologia

DSM – Demand Side Management

EDA – Eletricidade dos Açores

EDP – Energias de Portugal

EEM – Empresa de Eletricidade da Madeira

ERSE – Entidade Reguladora dos Serviços Energéticos

HEMS – Home Energy Management System

HVAC – Heating, Ventilation and Air Conditioning

IEC – Imposto Especial de Consumo de Eletricidade

PV – Photovoltaic

REN – Redes Energéticas Nacionais

ToU – Time of Use

TV – Television

VAT – Value Added Tax

W_p – Watt-peak

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1 Introduction

Electrical appliances became part of our society in the 19^{th} century and, since then, we have become increasingly dependent on them for our daily activities.
In this respect, it is only natural that we monitor and manage their energy consumption, whether to save on our electricity bills or to reduce the harmful effects of climate change.
In this work, our energy consumption patterns will be explored. Then, based on their energy consumption, suggestions are made to consumers to reduce peak household consumption or shift loads to a time of day when electricity is cheaper.

1.1 Motivation

Nowadays, we live in a world where electrical energy has become a vital resource for people's daily lives, and its consumption is increasing. Moreover, the world is gradually becoming more technological, and we are witnessing an increase in the power of various electronic devices that require higher consumption.
The current grid is finding it increasingly difficult to satisfy the demand, especially in times of higher consumption. Therefore, there is a need for action at this level to save as much energy as possible, especially at peak times.
Due to these increasing demands, negative aspects and consequences are widely known, such as global warming. In this respect, it is imperative to avoid unnecessary energy consumption and move energy from peak to off-peak periods with minimal compromises.
A home energy management system (HEMS) could help perform such actions and thus, benefit the consumers and the grid.
For the grid, demand would be reduced during peak hours, reducing the risk of grid problems, while consumers could have a lower electricity bill.

1.2 Problem Definition

The load on the electrical grid varies throughout the day and seasons, but we can find some patterns to understand when to expect peak demand on the grid.
Although we can use the recent past to improve energy efficiency and electricity use, recent events have gradually changed how electricity is used.
Global warming has led to some uncertainty and fluctuations in temperatures throughout the year, which has led us to frequently use very high consumption appliances, such as air conditioners.
Although the price of electricity has risen gradually over the last decade, in recent months, we have seen a severe crisis in the energy sector, which has led to more frequent increases in the price of electricity.
Furthermore, the recent pandemic has led us to shift part of the load that was majorly used/paid in companies to their employees' homes during some time.

With this in mind, users are now more aware than ever of the need to improve efficiency and try to reduce or manage the overall consumption in their homes in a better way.

The user will then appreciate any improvement that can be done to pay as little as possible for its electricity bill.

The electrical grid may also benefit from more efficient management of energy at homes since some of the load at peak times can get reduced or even shifted to another period in which the grid is not overloaded.

In summary, it would be helpful if the user had a tool to see his/her consumption patterns and get some insights and suggestions for improvement.

1.3 Solution Objectives

The main objective is to monitor energy consumption throughout the day according to different user-profiles and seasons and based on that, shift some loads to an off-peak period which can reduce the peak demand at home.

By moving those loads to an off-peak period, the consumers may leverage the bi-hourly tariffs, in which that period is cheaper, to pay less for the electricity bill. That may possibly help reducing the contracted power, which also decreases the monthly electricity bill.

The concept of load shifting should be applied to devices that domestic users are willing to postpone to another time without affecting their well-being (e.g., postponing the washing machine from the afternoon to late evening).

Based on the consumption type, the user should define a profile according to their needs, allowing some tailoring possibilities when moving loads or defining what devices can be shut down first in an emergency case.

It is up to the user to define what compromises he/she is willing to make, and that is why each individual should have a tailored profile. For example, a user who likes to watch sports would not define a TV (Television) as a device that should be switched off to avoid peaks in the network.

Although a user cannot rely 100% on the energy produced by a solar panel, this dissertation also explores the auto-consumption at home and how can it be leveraged to reduce the energy demand from the grid.

A simulation of a home energy management system will allow us to understand the impact of the concepts above.

Instead of running an automatic logic to move loads, the system should propose new times to run a shiftable device, as the consumers may change their routines.

To test the designed algorithm with some scenarios, homes and devices will be modelled with several attributes such as the average power and runtimes.

The aim will be to objectively compare electricity consumption before and after running the designed logic and evaluate what decisions and tariffs are beneficial for the user in the long run.

The benefit must be analysed from the economic point of view of the final user and as a possibility to relieve some load from the network.

1.4 Thesis Outline

This dissertation is composed of five chapters. Chapter 1 motivates the problem and describes the main objective and structure of this dissertation. Chapter 2 reviews the main techniques in the literature.

Chapter 3 presents a new proposal that addresses the needs and challenges already mentioned and explains how the simulations and the proposed solutions are expected to work. Chapter 4 will address the simulation of the scenarios tested, along with the main takeaways. Finally, conclusions and future work are addressed in Chapter 5.

2 Related Work

This chapter initially presents a literature review of the electrical grid origin and the energy sources responsible for its supply.

Then, this dissertation explores some concepts of home energy management and its possible interaction with a smart grid and smart buildings.

Finally, this chapter will also consider the current state of tariffs and home energy management systems in the Portuguese market.

2.1 Electrical Grid

2.1.1 Origin of the electrical grid

The electrical grid is an interconnected and complex network of electric generators (i.e., power plants), along with transmission and distribution lines that respond to fluctuations in electricity supply and demand to ensure a reliable supply of electricity [1].

Its origins come back to 1882, in New York City, where Pearl Street Station has become the first central power plant [2].

It started generating electricity on the 4th of September 1882, with an initial load of 400 lamps serving 85 customers.

The station was built by the Edison Illuminating Company, which Thomas Edison headed. Initially, the power stations were dedicated to specific customers and isolated from each other. In the following decades, however, these stations were interconnected, which gradually proved to be a decisive advantage.

This led to a more reliable grid since it was then capable of sharing resources in case of a failure in the grid, equipment, or unexpected peak demand. That way, the consumers did continue to have access to electricity.

Since then, the electrical grid has progressively become more complex, and it certainly was a factor that carried the second industrial revolution in the late 1800s and early 1900s [3].

That way, it was only natural that the number of parties involved had increased over time.

2.1.2 Energy Sources

The energy sources can be classified into two types:

- Renewable;
- Non-renewable.

The renewable sources are virtually inexhaustible, meaning they are naturally replenishing but also flow-limited. The major types of renewable energy sources are biomass, geothermal, hydropower, solar and wind.

Non-renewable energy sources cannot be replenished quickly since their supplies are limited on Earth, meaning they replenish themselves slower than the rate we use them. Some examples of this kind are petroleum, natural gas, coal and nuclear energy.
Due to its adverse impacts, there has been a consensus worldwide to reduce the power supply coming from non-renewable sources.
Those sources have negative impacts on our planet, such as global warming and air and water pollution. To that extent, using them is always a significant risk to severe consequences to the environment in case a disaster happens.

Over the past decades, we have observed some examples that had an impact on the planet and may take several decades to recover:

1. **Chernobyl** – In 1986, two explosions ruptured one of the core reactors of the nuclear power plant in Chernobyl, destroying its building [4].
   This nuclear disaster was responsible for many casualties, not only in the accident/explosion, but it also increased mortality over the subsequent decades due to the radiation that has been spread.
2. **Gulf Oil Spill** – In 2010, there was an explosion and sinking of the Deepwater Horizon oil rig in the Gulf of Mexico [5].
   The oil accidentally spilt into the ocean has harmed sea creatures due to its toxic compounds. The increased pollution in the ocean also has other consequences in the ecosystem that may threaten water species or other commercial activities such as fishing.

Across our history, human being has become more aware of non-renewable sources risks. Due to that, renewable sources such as solar energy or wind have progressively been adopted in the past decades while also considering that they should not decrease society's evolution and productivity in the adoption phase.

Although we are trying to adapt society to renewable sources progressively, some challenges make it hard to abandon non-renewable sources entirely.
Renewable energy sources are not always available, and since the energy is not storable, there is always a level of uncertainty at what times they can be used.
Solar energy cannot be leveraged during the night, the wind may vary throughout the day and year, and the energy coming from waves is influenced by the moon. These examples illustrate that energy sources may not be as reliable as we wished they were, especially with increased energy demand.
The region of the world we are in also needs to be accounted for since different sources have geographical dependencies.

Some alternatives are being explored, such as fusion power, a proposed form of power generation to generate electricity by using heat from nuclear fusion reactions.

The fusion power takes advantage of atomic nuclei that combine to form a heavier nucleus while releasing energy simultaneously.
It is the opposite paradigm of classic nuclear energy, which uses nuclear fission to split atoms and leverage the energy release to transform it into electricity.

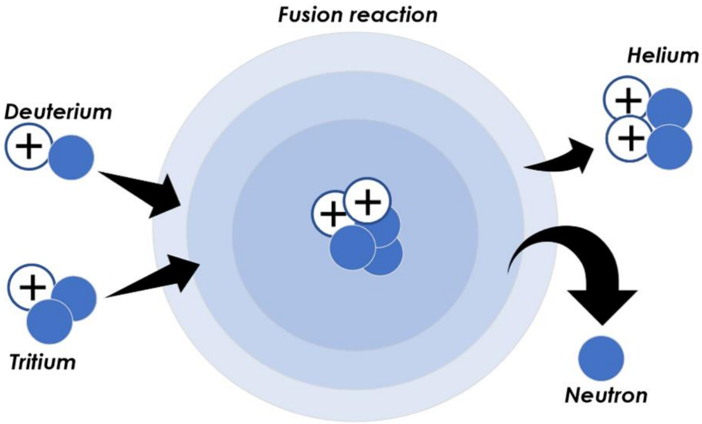


Figure 1 – Mixture of deuterium and tritium that may be used to fuel future fusion plants [6]

It is expected in the future that inside the reactor of a power plant, the collision and fusion of two of the hydrogen isotopes (deuterium and tritium) will be responsible for releasing helium and neutrons [7].
It is an auspicious process since the amount of energy produced by fusion is four times that of nuclear fission, releasing a vast amount of energy.
On top of being abundant energy, it is carbon-free and does not produce long-lived radioactive waste.

However, it is still challenging to have a fully controlled environment to reach the necessary temperature and pressure to make deuterium and tritium fuse. Similarly to the emerging of new technology, it will also be more expensive at the beginning than the fission reaction.

Although renewable sources are progressively taking over energy production, thirteen countries in 2020 have produced at least one-quarter of their electricity from nuclear energy [8].
For example, France generates around 70% of its electricity from nuclear energy, and it is not expected to decrease these numbers below 50% by 2035 [9].
It can be noted that nuclear energy production is still very significant in several parts of the world.

Although fusion power is among the most environmentally friendly sources of energy, it is only expected to be exploited and used for electricity generation in the second half of the century.
A prototype of a fusion reactor is expected to be built by 2040 [10].

2.1.3 Electricity Market in Portugal

With the growing number of parties across the time in Portugal in the past decades, the Portuguese government found that nationalising the different players would benefit the interests of the Portuguese nation.

In 1976, EDP was founded (originally Electricidade de Portugal), resulting from a merge process of 13 other companies [11].

The new company was responsible for electrification, with the existing electrical grid extension and modernisation as the primary goal.

In 1994, an in-depth restructuring happened, and the company was split into two companies, EDP (Energias de Portugal) and REN (Redes Energéticas Nacionais).

REN has later become an independent company after separating from EDP in 2000.

These have been the leading players for the electrical grid in Portugal in the last decades.

In the past years, with the appearance of the liberalised market in Portugal among the rising number of players in the electricity sector, especially on the providers' side, it is crucial to have a set of well-defined rules in the country.

In Portugal, the regulatory authority for the electricity is RSE (Entidade Reguladora dos Serviços Energéticos).

To better understand how the electricity sector in the country works [12], a high-level electricity flow starting from the production point until it reaches the consumer is presented in the figure below:

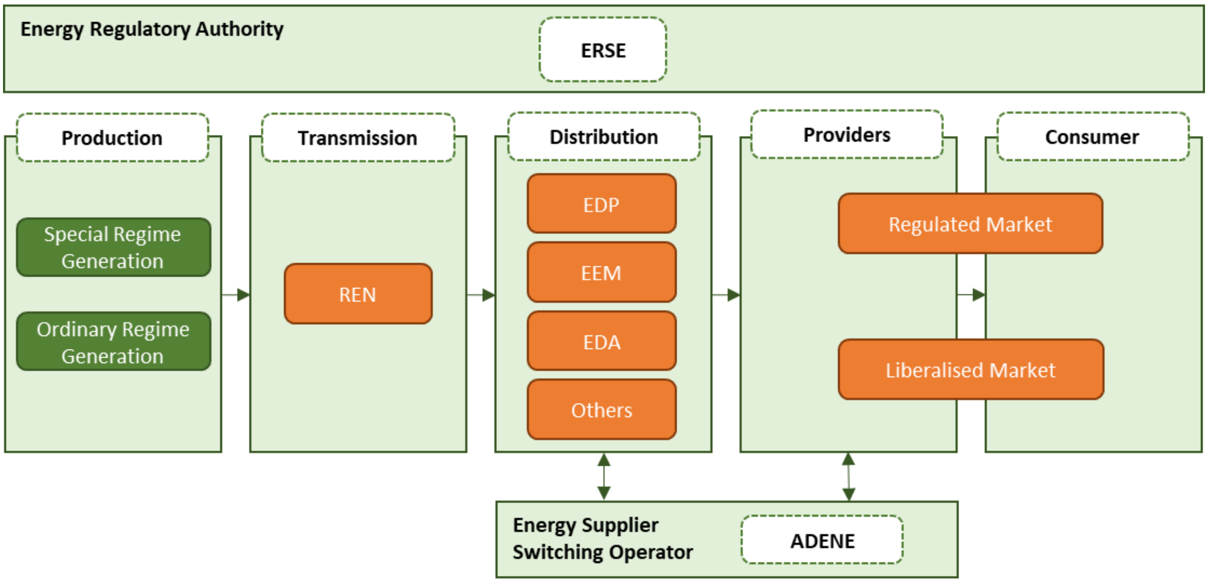


Figure 2 – High-level diagram with the main players of the electric sector in Portugal

The electricity distribution can be drilled down in the following stages:

1. **Production** – In Portugal, there are two types of electricity production:
   - **Ordinary Regime –** Applies to electricity generated from traditional and non-renewable energy sources and large hydro plants.

- **Special Regime –** Refers to electricity generation subject to special legal regulations, such as cogeneration and endogenous resources, renewable and non-renewable sources, or micro-production.

2. **Transmission** – REN is the entity responsible for the extra-high-voltage networks;
3. **Distribution –** Management of the high, medium, and low-voltage networks:
    - EDP – Main player in the Portuguese Mainland, coexisting alongside a few minor entities that are part of small areas of the Portuguese territory, such as the Casa do Povo de Valongo do Vouga [13];
    - EEM (Empresa de Eletricidade da Madeira) – Entity responsible for the distribution in Madeira;
    - EDA (Eletricidade dos Açores) – Entity responsible for the distribution in Azores.
4. **Providers** – Energy suppliers responsible for setting a contract with the consumers, either in the regulated or liberalised market.
5. **Consumers** – End-users that will be responsible for the energy consumption and for paying the electricity bill.

Finally, ADENE (Agência para a Energia) is the entity responsible for managing the process of switching electricity suppliers.

2.1.4 Tariffs and Prices

Today, interconnected power grids serve a large number of consumers. As a result, utilities (usually in the public sector) must sell their electricity at a price that covers the costs of generation, transmission, distribution, employee salaries, interest, depreciation, and the company's targeted profit.

The price at which electricity is sold to consumers is called a tariff. It is composed of different components depending on the country.

ERSE defines the tariff regulation in the Portuguese market, regardless of the consumer being in the regulated or liberalised market.

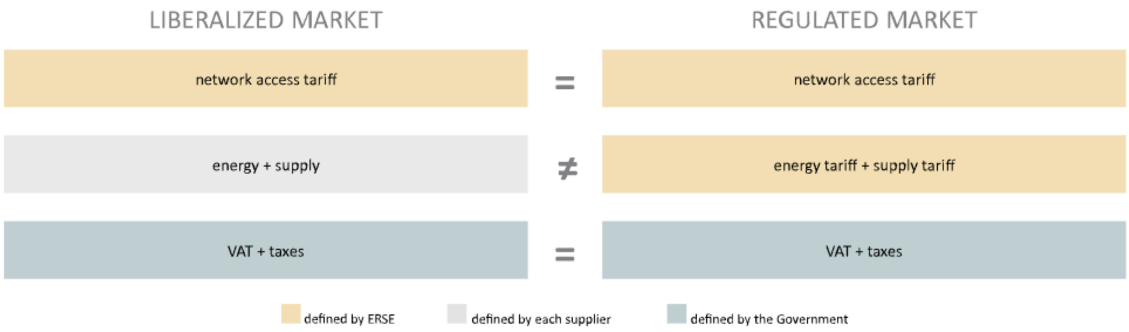


Figure 3 – Tariff Regulation in Portugal in both Liberalised and Regulated Markets, defined by ERSE [14]

As observed in the figure above, both network access tariff and “VAT + taxes” variables are defined by the same entities, ERSE and government, for both markets.
Therefore, the main difference between them falls on the energy and supply tariffs.

The access tariffs reflect the cost of infrastructures and all services used by all consumers on the network. These tariffs are defined by ERSE.

Regarding the energy and supply tariffs, the consumers will pay the tariff set by ERSE in the regulated market. In contrast, in the liberalised market, each supplier can define its values, promoting competition. These tariffs reflect the contracted power and the energy consumption.

Finally, the government defines VAT (Value Added Tax) and another set of taxes across both markets.

Although we have both markets now, it is expected that all clients in the regulated market will progressively transit to the liberalised market until the end of 2025 [15], the date from which the regulated market should not be allowed in new contracts anymore.

From a consumer point of view, network access, energy, and supply tariffs are presented altogether, so the actual costs of accessing the network are embedded in the energy and supply tariffs.

Therefore, from a consumer's perspective, there are three main components to be paid in the electricity bill [16]:

1. **Variable Component** – Part of the bill that depends directly on the amount of electricity consumed (e.g., 0,1047 €/kWh);
2. **Fixed Component** – Part that is independent of the amount of electricity consumed. It usually depends on the contracted power (€/kVA).
3. **Taxes Component** – VAT and set of Taxes defined by the government and applied on top of the first two components.

We can observe that although the amount of electricity consumed each month plays a significant role in the final amount of the electricity bill, the contracted power is also an essential factor to consider.
It is also vital to notice that the percentage of VAT may be different depending on the energy consumption during each month or on the contracted power. Hence, the consumers have a further incentive not to waste energy.

Considering all these components, choosing the right tariff is crucial to help reduce the energy bill at the end of the month.

Since the taxes component is defined by the government and relies directly on the contracted power (fixed component) and energy consumption (variable component), the user needs to be aware of its needs before deciding on the electricity contract.

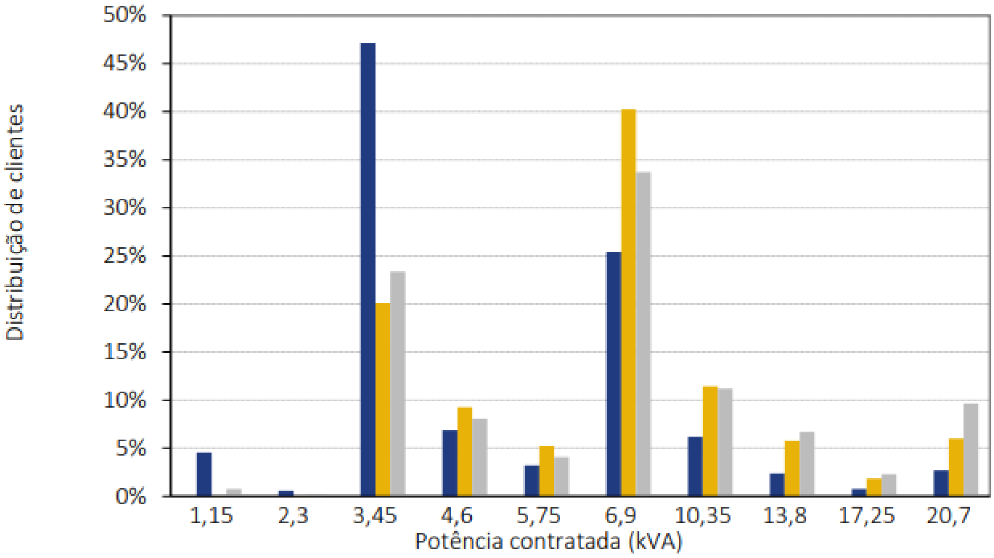
For domestic users, the most common contracted power is in the range between 3,45 kVA and 6,90 kVA [17]. The user pays a daily fixed price based on the selected power, regardless of the energy consumed.
Typically, a power of 3.45 kVA is enough for a single person, while for a family of four, it is usually short, and 6.90 kVA is a safer choice. However, the necessary power relies on the routines and appliances the consumers have.

Regarding the consumption of energy during the month, usually expressed in €/kWh, there are two main types of tariffs related to the time of the day:

1. **Single rate** - The user pays the same rate regardless of the time of the day the energy gets consumed;
2. **Time of use (ToU) –** The price of electricity changes at different times of the day. Usually, there are two rates attached to two periods:
    - **Peak** – This is the period when electricity costs the most. It usually applies in the evenings;
    - **Off-Peak** – This is when electricity is cheapest. Off-peak rates usually apply overnight.

We may have a third rate [18] for domestic ToU tariffs (regular period), an intermediate period between the peak and off-peak times and costs less than electricity during peak times.
A bi-hourly tariff is the standard ToU tariff for residential customers. For the tri-hourly tariff, peak hours are very costly but could be suitable for companies as this period is usually outside working hours. However, for specific consumers, they may be the right choice.

In the graphic below, we have the distribution of clients per type of tariff in the liberalised market in Portugal, for which the contracted power is equal to or lower than 20,7 kVA:



	1,15	2,3	3,45	4,6	5,75	6,9	10,35	13,8	17,25	20,7
BTN< Simples	4,6%	0,6%	47,2%	6,9%	3,3%	25,5%	6,2%	2,4%	0,8%	2,7%
BTN< Bi-Horária	0,0%	0,0%	20,1%	9,3%	5,2%	40,3%	11,4%	5,7%	1,9%	6,0%
BTN< Tri-Horária	0,8%	0,1%	23,4%	8,1%	4,1%	33,7%	11,2%	6,7%	2,3%	9,6%

Figure 4 – Clients distribution in the liberalised market, per tariff and contracted power (ERSE) [19]

The total number of clients per tariff is summarised in Table 1.

Table 1 – Number of clients per tariff in the liberalised market.

Type of Tariff	Number of clients
Single	4.685.230
Bi-Hourly	486.511
Tri-Hourly	48.523

The single rate is lower than the peak rates of a time-of-use tariff. Therefore, this rate is a good choice for people who usually stay the afternoon at home during weekdays and need to use high-consumption appliances (like a heater or air conditioning) during that period.

For the ToU tariffs, the consumer needs to indicate what type of cycle [20] should the tariff follow:

- **Daily** – With this option, the two daily periods are always the same during the year, meaning the winter/summer time or weekdays/weekends will not play any role;
- **Weekly** – The peak and off-peak periods are not the same in the Summer and Winter, and there are also differences between the periods at the weekends and weekdays.

The daily and weekly cycle periods are defined by ERSE [21], as per the images below:

- **Daily Cycle**

Figure 5 – Daily periods defined by ERSE for daily cycle tariffs

- **Weekly Cycle**
    - **Weekdays**

Figure 6 – Weekday periods defined by ERSE for weekly cycle tariffs

- - **Saturday (Summer time)**

Figure 7 – Saturday periods defined by ERSE for weekly cycle tariffs during summer time

- - **Saturday (Winter time)**

Figure 8 – Saturday periods defined by ERSE for weekly cycle tariffs during winter time

- - **Sunday**

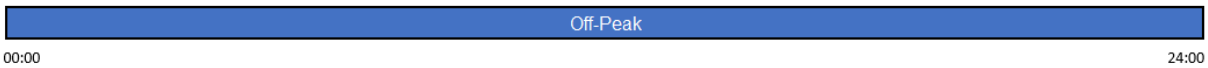


Figure 9 – Sunday periods defined by ERSE for weekly cycle tariffs

Additionally, some countries have happy hour tariffs, where electricity is free for a certain period, or dynamic tariffs, which vary according to energy demand. However, due to their uncertainty, these are mainly experimental tariffs.

2.1.4.1 Tariffs Recommendation

Nowadays, with the emerging of new players in the liberalised market, there are a lot of online tools to provide the best suppliers considering some parameters the user provides, such as the contracted power, type of tariff and number of appliances.

There is not an ideal tariff for everyone. In principle, every user should choose a tariff that suits its usage patterns.
A user that spends most of the time at home may not have any purpose or benefit in using a tariff that varies throughout the day. In contrast, someone who spends most of the day out of home and then concentrates the usage of the appliances during the evening or night and weekends should probably subscribe to a time-of-use tariff.

There are some guidelines to decide between the three types of domestic tariffs.
For example, EDP Commercial recommends on their website [22] the best usage for each one of the three main tariffs (single, bi-hourly, and tri-hourly) based on a daily cycle:

- **Single Rate** – Suitable for consumers who have less than 20% of their energy consumption between 22:00 and 8:00;

- **Bi-Hourly Rate** – Ideal for those who spend more than 40% of the overall consumption between 22:00 and 08:00;
- **Three-Hourly Rate** – Ideal for consumers under the following two conditions:
    - Spend more than 20% of the energy between 22:00 and 8:00.
    - There is no consumption between 9:00 – 10:30 and 18:00 – 20:30 since the tariff in these two periods is much higher.

Adding to the weekdays and weekends as another factor in deciding which tariff is the best, it is easy to understand that it gets trickier to make a proper recommendation. It gets even more critical to emphasise that many people do not have any routine defined on weekends.

In the last few years, it has become a standard to mix the electricity and natural gas tariffs in the same bill if the provider is the same. That may lead to a discount on the final price, but for simplicity, only the electricity tariff will be considered throughout the document for the electricity bill analysis.

2.2 Smart Grids

The power grid is a network of power lines and substations that transport electricity from power plants to homes/companies and has remained almost unchanged over the past decades.
Nowadays, the power grid is struggling, it needs to be updated, and it is running at its maximum capacity [23].
When power lines break or power plants cannot produce enough electricity, blackouts can occur, which is a problem that can lead to fatalities.
At the same time, today's power grid often relies on a single source of electricity and does not provide detailed usage information, making it difficult to manage power.
We built new power plants in the past to overcome this, but now we can work towards sustainability and reduce our dependence on fossil fuels by using a smarter grid.

The smart grid adds sensors and software to the electric grid, providing utilities and individuals with new information that helps them understand and respond quickly to changes. It is a network that allows a two-way flow of power and data.
It can be used to detect and automatically respond to problems on the power grid. For example, a tree falls on a power line, and 1000 homes are without power. With the current power grid, utility workers often must physically reroute power, which takes time.
With the smart grid, sensors and software would detect the problem and reroute power immediately, limiting the problem to fewer households [24].

The price of electricity changes throughout the day, but we cannot see it with the current meters on our homes. So, it may be expensive during peak hours and cheap late at night.

With new smart meters, the communication of readings to the Distribution Network Operator is carried out remotely and automatically, ending the estimates in electricity bills. In addition, we can set some electric devices (e.g., dishwasher) to run when power is cheap. Thus, it provides more control of the energy bill and helps prevent blackouts at peak hours.

The smart grid also means new ways to use renewable energy, and power generation can now be distributed across multiple sources, so the system is more stable and efficient.
This ability to communicate and manage electricity makes the grid more innovative and help us avoid burning more fossil fuels in the future.
The smart grid on a large scale is still a few years away [25]. However, it is a good indicator that we will manage our energy bill, help the environment, and help the economy make more informed decisions about using electricity.

Although they may be independent of each other, managing a home's energy consumption can be integrated into a smart grid. It may even allow the user to sell energy to the grid (micro-production) if it is not used or inform the user of a peak in the network.

The smart grids have several positive features that will give a direct benefit to consumers, which include [26]:

- Real-time monitoring;
- Automated outage management and faster restoration;
- Dynamic pricing mechanisms;
- Incentivise consumers to alter usage during different times of the day based on pricing signals;
- Better energy management;
- In-house displays;
- Web portals and mobile apps.

The smart grids can take the consumer experience to another level, which was impossible with the traditional grid.

Although the consumers may be the main stakeholders that can directly benefit from it, other parties, such as regulators, may also take advantage of the several benefits of deploying a smart grid, such as having increased grid visibility and self-healing grids.

2.2.1 Smart Meters

Smart meters are the next generation of gas and electricity meters that provide more information about energy supply and control over energy consumption [27].

They are gradually being installed in several countries at no upfront cost, and the goal is to bring them to as many households as possible.

Initially, the full roll-out in Portugal was supposed to be completed in 2020, but it has been postponed until 2024 [28]. However, with many of the best energy tariffs only available to customers with a smart meter, it is time to ask the supplier to install it.
The installation is taking place all over the country. So this is an opportunity for every consumer to check whether the smart meter is already available in his/her residential area if it is not yet installed at home.

They are called smart meters since they have two-way communication instead of the old-style electricity meters they are replacing:

- **Automatic meter reads** – Smart meters send up-to-date information to the supplier automatically, so no more dark cupboards and spiderwebs;
- **Pay only for power consumption -** As consumption data is automatically transmitted, the provider will never charge the user for an estimate. The user pays for exactly what was consumed;
- **Smart data display** – The user gets an in-home display, a gadget that monitors the usage and costs, giving accurate readings in euros and kilowatt-hours.

2.2.2 Smart Buildings

Although not the focus of this dissertation, it is worth noting that smart buildings are becoming increasingly popular. They can help reduce energy bills by automating some processes and giving building owners/managers relevant insights into overall consumption and how to reduce it.

Smart buildings use the Internet of Things (IoT) to monitor various building characteristics, analyse the data, and provide insights into usage patterns and trends that can be used to optimise the building environment and operations [29]. However, it is more than applying new technology to an existing building.
To get a clear picture of what smart building technology is, here is an example comparing it to a traditional building management system (BMS):

- **Traditional Approach** – A BMS can be programmed to turn the building's heating, ventilation and air conditioning (HVAC) system on and off at specific times based on predefined temperature values;
- **Smart Building Approach** – It provides more control over how the HVAC system is operated. It can measure carbon dioxide (CO^2) levels in real-time and turn the HVAC system on and off based on those levels. For example, when the CO^2 levels approach the limit, additional outside air is supplied.

This type of control over the HVAC system can help save energy and money without sacrificing comfort.

2.3 Home Energy Management System

It is estimated that buildings in Europe are responsible for 40% of our energy consumption [30]. Unsurprisingly, home energy management systems (HEMS) are rapidly gaining popularity worldwide as their technology improves and small solar panels become more viable [31].

However, when defining and using these systems, there are conflicting descriptions and confusion among people.

Essentially, a home energy management system consists of hardware and software that allows the user to monitor energy consumption and generation and manually/automatically control energy use in a home.

The hardware consists of a "hub" device, which is responsible for mediating communications between the users and, in some cases, local utilities or power retailers. This communication will include usage patterns and consumption of home users.

The software moderates the incoming and outgoing data and communications.

From the user's perspective, the software is the interface that provides access to the system's monitoring data and control functions. The interface is usually accessed through an app or a web portal.

The main goal of HEMS' software is to increase energy efficiency while other systems are usually designed to control devices remotely or automatically for convenience or security reasons.

From the user's point of view, we can divide the HEMS software into two primary purposes, monitoring and control:

- Monitoring:
  - Device data – What devices are on/off and how much energy each is consuming. The user can see the current information in real-time or check the history;
  - Insights – The system can warn the user of specific problems or send tips to increase energy efficiency.
- Control:
  - Turn devices on/off remotely:
  - Set devices to operate on specific schedules;
  - Set up conditional rules for devices operation;
  - Manage the flow of energy coming from solar panels or other generators;
  - Use machine learning to run the system automatically.

All the above advantages and uses of a HEMS system should be user-tailored according to the needs and goals.

We can say that HEMS is responsible for managing four main aspects of home energy [32]:

1. **Electricity** – The core functionality of a versatile home energy management system begins with electricity in the home.
   A HEMS should allow the user to monitor what devices are doing and access them remotely to turn them on or off or change their operation (e.g., lower the thermostat temperature of an air conditioner).
   Since one of the main goals of HEMS is to save the user some money, the management of electricity consumption takes into account, among other things, the grid's electricity rates, whether the customer bills based on consumption, and whether solar energy or batteries are available on site.
   Critical considerations in power consumption management include electricity rates and whether solar power or batteries are available on site.
   A HEMS can also operate in an off-grid scenario. In this case, it is even more critical that the energy is used effectively and consistently available when needed.

2. **Solar Photovoltaic** – Solar PV (Photovoltaic System) systems are now widespread in many countries and allow households to generate some of their electricity locally.
   Depending on the situation and incentive structure, it may be a priority for the owner of a PV system to directly "self-consume" their solar electricity or export it to the grid as much as possible.
   A HEMS can show the user how much solar power they generate, consume, and feed to the grid [32]. With this information, the user can change its energy usage patterns at home to get the most out of its solar panel system.
   The presence of solar battery storage adds complexity to the equation, making a home energy management system an even more attractive option than a home without its micro-production system.

3. **Battery Storage** – Battery storage is the next step in the home energy supply. They are a step towards greater energy self-sufficiency and lower electricity prices - not to mention the future of our electricity infrastructure itself. However, to maximise the value of battery storage, it is helpful to have a smart management system that can take into account multiple variables, such as whether we have a time-limited flat rate or whether we have an incentive to sell the stored energy to the grid.

4. **Solar Thermal Panels** – It is a popular technology that uses the sun's power to heat water in a home. Solar hot water systems often operate largely independently of the rest of a home's electrical appliances. However, a good HEMS with the proper connectivity and monitoring capabilities can further enhance their value.

Users typically use only one or two of the above aspects, and this dissertation will focus on electricity and solar PV, the most common in HEMS.

2.3.1 Electricity

As explained earlier, managing electricity is the core function of a HEMS and is the focus of this dissertation.

Although users can make their own decisions that reduce electricity costs at the end of the month, the idea of HEMS is to provide consumers with insights and detailed data that help them get ahead in saving money.

Providing real-time data and energy usage history in a household can make consumers more aware of their energy behaviour and improve it.

Nevertheless, monitoring a household's energy use is not the only input HEMS users can take advantage of at home. The system can also suggest what can be improved in the home.

In addition, there are some control options, such as shifting consumption to a time when energy is cheaper or the grid is not overloaded.

This shift can either be scheduled by the user (e.g., the user can set the washing machine to start working at 11 p.m.), or the system can automatically detect, based on user preferences, that a particular load can be shifted to a less costly time.

If a household is part of a building with a central intelligent hub, all homes may have a scheduling process to avoid overlap in scheduling loads that run during off-peak periods.

For example, in a building with eight households where each owner has scheduled its washing machine for an off-peak period (typically between 10:00 p.m. and 08:00 a.m.) and considering a washing program that lasts 2 hours, the building's smart centre could allocate the following time slots:

1. 10 p.m. – 12 a.m. – Houses 1 and 2;
2. 12 a.m. – 2 a.m. – Houses 3 and 4;
3. 2 a.m. – 4 a.m. – Houses 5 and 6;
4. 4 a.m. – 6 a.m. – Houses 7 and 8.

The system could also adjust the time window for all these devices to operate using machine learning algorithms, depending on the energy consumption patterns of the occupants and the time of the year or day of the week.

For example, residents are likely to use more energy on Fridays and Saturdays so that washing machines could run later (e.g., at 11 p.m.).

In some tariffs, energy is cheaper on weekends, so the algorithm should adapt according to the day.

It must be remembered that this presupposes that the consumer has already prepared everything in the washing machine to run it automatically at night.

Shifting loads may be the most efficient way to save money on the electricity bill, but the user should aim to reduce the overall expenditure on electricity. That would benefit the user financially and help the overall grid by reducing possible peaks and blackouts.

Of course, consumer welfare needs to be prioritised and should not be affected when performing automated decisions.

Before achieving a monitoring and control approach, the central system needs to know what devices will be controlled in a home.

To this end, smart plugs are typically installed to detect the type of devices that will be managed. These smart plugs then communicate with a local controller, which is usually connected to a supply controller. The supply controller is responsible for requesting power from a power source. It is usually the electrical grid but can also come from a micro-production system such as a solar panel or battery connected to the home/building.

2.3.2 Solar PV

There are three types of solar panels:

- Photovoltaic, which generate electricity to power homes;
- Thermal, which is installed on houses to receive sunlight directly;
- Thermodynamic, which work in different weather conditions, such as at night, when it rains, or when it is cloudy.

The focus will be on the photovoltaic solar panels since they are the most adopted ones, especially for micro-production at home.

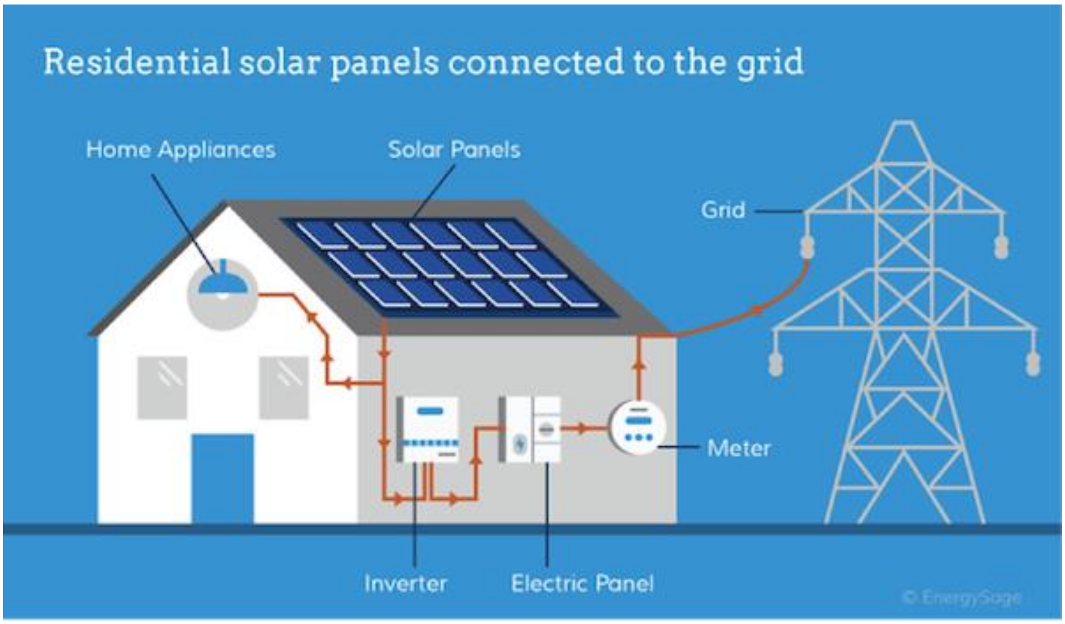


Figure 10 - Set of photovoltaic solar panels in a home [33]

Photovoltaic solar energy or PV solar energy converts sunlight directly into electricity using technology based on the photovoltaic effect.

When sunlight hits one of the surfaces of a solar photoelectric cell (of which there are many, forming a solar panel), it produces an electric voltage differential between both faces that makes the electrons flow between one to the other, generating an electric current [34].

In the early days of photovoltaic technology, it was used to power satellites. However, the development of photovoltaic panels accelerated in 1950 [34] and today has become an alternative to the use of fossil fuels.

Today, renewable energy sources are cheaper than conventional sources in most parts of the world. More than two-thirds of the world's population live in countries where solar and wind power are already the most competitive energy sources. Moreover, when the environmental and social costs of energy sources are internalised and accounted for, renewables are the most competitive energy sources in the world.
In the last ten years, the cost of photovoltaic modules has fallen by 94%.

Modern photovoltaic panels are becoming more and more efficient. However, under standard conditions, the time it takes a panel to generate the energy used for its production is calculated at about two years. It corresponds to a useful life of more than 25 years, during which it will continue to produce energy using sunlight as the only fuel that is clean, free and inexhaustible.

In photovoltaic solar panels, peak capacity refers to the amount of kW installed, and nominal capacity refers to the capacity of the inverter (the electrical equipment that converts the electricity generated by the panels so consumers can use it).

In principle, nominal capacity defines the limit of the plant (one cannot produce more than the inverter can convert). Nevertheless, photovoltaic facilities usually install a more significant peak capacity than the nominal (more panels) to ensure 100% of the inverter capacity is used.

Since 2020, any consumer that wants to install a solar panel until 350 W, does not need to communicate it to DGEG (Direção Geral de Energia e Geologia) anymore [35].

Now it is only required for installations above 350 W, although its capacity is limited by the contracted power at home.

If there is a surplus of energy generated by a solar PV system aimed for self-consumption, this surplus can be sold to the grid at a price agreed upon with a supplier.
It is worth noting that the tariff is usually much lower than the standard prices charged to the end consumer.

2.3.3 HEMS in Portugal

The applications available in Portugal give the consumer an overall consumption of a house, which it can be leveraged to perform some decisions, such as understanding if it worth to change from a single to a bi-hourly tariff.

The most popular solution is EDP Re:dy [36] which is offered to EDP customers that have solar PVs.

It allows the user to perform the following activities:

- Monitor energy consumption to the home and to electric cars;
- Monitor energy production from solar PVs;
- Access a mobile app to see real-time energy consumption and production;
- Alerts and notifications about failures on the grid, solar PVs, and home.

3 Proposal

This chapter will present a thorough explanation of the proposed solution to manage energy at home.

3.1 Proposed Solution

The aim of this master thesis is to investigate some mechanisms for energy management in households.

These mechanisms not only allow to reduce the overall load on the electrical grid and minimise the occurrence of problems but can also reduce to a large extent the need to ask other entities for energy. In Portugal, for example, it is necessary to ask Spain for energy at certain times of the year [37].

Although this management is scalable and can work with multiple homes connected through a central device, the focus is on studying energy management in a single home.

Most people have their routines, but there are always periods when they want to do something different and temporarily change their priorities and routines. For this reason, people will not necessarily welcome a fully automated system that decides everything for them when it comes to turning off devices or moving loads, even if they have set their preferences.

Therefore, some assumptions were made for the proposed solution:

1. Each load is connected to a smart plug so that HEMS can detect which device is connected;
2. Instead of a fully automated solution, the system should make suggestions to the user. The main objective is to understand what the impact is if the user follows the recommendations.

For example, suppose that a user tries to start an intensive washing machine programme. In this case, the system could pause the operation for 5 minutes, notify the user via mobile app, and recommend starting the programme later, depending on the number of appliances turned on.

The HEMS will focus on three main factors to achieve better energy management:

1. **Reduction of energy peaks** – Any peaks that residents have during the day should be reduced to avoid home outages and reduce the load on the grid.
2. **Load shifting**
    a. Off-peak – This time is usually cheaper, so the user can use it to reduce both the electricity bill and electricity consumption at peak times;
3. **Solar panel –** This can significantly reduce the energy drawn from the grid and potentially shift some loads from other peak times.

These three factors will be explored to understand their actual impact on energy peaks and electricity bills.
Since each house has a different number of consumers and routines, different scenarios will be explored in this thesis to understand better who can benefit from any of the already mentioned strategies.

The different scenarios will include the characterisation of the following:

- **Family characteristics** – Characteristics of the family, such as the number of elements living in the house;
- **Consumer devices** – Includes any device that can consume energy at home;
- **Consumer routines** – It will list the periods that each device is powered on or is on standby. It is the characterisation of a typical day in a family when it takes to turn on/off the appliances at home;
- **User Preferences** – List of preferences the consumers in a house have set to help the system to suggest some actions or perform decisions.

These characteristics will be further detailed across this chapter in individual sub-sections.

Although some benefits of home energy management are difficult to quantify, such as the contribution to reducing the overall load on the electricity grid at peak times, there is always one crucial factor that worries consumers every month: the electricity bill.
Consumers are always on the lookout for ways to save money, and the electricity bill cannot be overlooked, especially considering that electricity is now a part of the civilised world.
Therefore, the amount consumers have to pay for their electricity at the end of the month is one of the critical factors considered in the results.
On the other hand, consumers have a contracted power that can easily be exceeded if many appliances with high consumption are turned on simultaneously.
We may say the total instant power throughout the day inside a home will be one of the main factors determining the outcomes of the analysis.

In conclusion, we can say that the tariff also plays a vital role to get results since we need to consider two critical factors to calculate the final electricity bill amount:

- **Contracted power** – Each day, a fixed amount is charged to the consumer according to the maximum power it has been defined in the contract;
- **Power Consumption** – The amount of power consumed in a house is subject to a given rate expressed in kWh that depends on the type of tariff (single, bi-hourly or tri-hourly) and time of the day, in case it is a ToU tariff.

3.1.1 Consumer Role

Consumers have different patterns when it comes to using energy throughout the day. There are some common points, such as having the fridge turned on the whole day, but most of the power consumption may come from different sources at different times.

From the three components of the electricity bill, only the taxes are not subject to consumers' routines. As a result, the consumer should leverage its routines, choose a lower contracted power, and shift loads to cheaper periods.

Before the contracted power may be reduced, it is vital to understand the risk of exceeding that power throughout the day according to the number of appliances usually used.
Below are two examples of when the contracted power may be exceeded:

1. **Several air conditioners powered on:**
    - It is not uncommon for a family or group of workers living together to run the air conditioner in several rooms during summer days, even at night;
    - Since air conditioners may be very high consuming, this is not a scenario for which a lower contracted power, such as 3.45 kVA, is recommended.
2. **Standard family with multiple high-power devices powered on:**
    - If the parents of a family are in the living room with a more powerful air conditioner and the two sons are also in the bedroom playing video games or watching a movie with the air conditioner on, we may end up with a tremendous peak;
    - Suppose the parents also decide to start the dishwasher or washing machine for a standard program (that is not intensive or eco). In that case, the scenario becomes even more evident from a total electricity consumption perspective.

While in the first scenario, there is no way for the users to move any loads since it would affect their wellbeing, in the second scenario, it may be vital for the family to use the load shifting strategy.
Through HEMS, the user may allow shifting the load (washing machine) from a period when there are already too many devices running simultaneously and potentially lowers the electricity bill by shifting it to a period when electricity is cheaper.

Electricity consumption is also not the same all year round. For example, air conditioners and heaters, usually the appliances with the highest consumption per month, are not used as often in spring and autumn.

We will explore some scenarios that depend on the following factors:

1. **Season** – Summer, Autumn/Spring or Winter;
2. **Work Location** – Onsite or Offsite;

3. **Family type** – Composition of the family, including the number of members, single, couple with two children, among others.
4. **Day of the week** – Weekends or Week Days – This is more important for weekly cycles, for which the tariff periods are not the same.

Since in Portugal cold temperatures are more common during the Winter and hot temperatures in the Summer, the scenarios on these two seasons will have more usage of high-consumption devices that regulate the temperature. It naturally impacts the final amount of the bill, so it is worth exploring the difference between them and a mild season.

The place of work is also significant, as the choice of the tariff may be different if the user works inside or outside the home. With the pandemic, working remotely from home has become more common. Therefore, using appliances such as the oven or air conditioner in the regular work schedule had significant impacts on the payment of electricity bills.

Finally, the number of people in the household also has a major influence on total consumption, as it can lead to the washing machine or dishwasher being used more often.

A composition of different scenarios has then been made to investigate the different factors further when it comes to energy consumption.

Table 2 – Summary of the scenarios to be used in the simulation

Scenario ID	Family Type	Work Location	Season	Solar Panel
1	Single	Onsite	Summer	No
2	Couple	Onsite	Autumn	No
3	Couple with Children	Offsite	Spring	Yes

It is not explicitly mentioned in the table, but both weekdays and weekends are examined in the scenarios, as both are needed to obtain the estimated invoice amount for a given month.
These scenarios are based on Portugal's three most common family types [38], and an example of consumption use is considered. The usage pattern, which is detailed in the analysis of the different scenarios in chapter 4, includes the time windows when each device in the house is switched on.

More details on types of devices and their preferences are described in section 3.1.5.

Although all the logic is applicable in any country, the analysed consumption patterns may differ in other countries.
For example, solar panels may not be very efficient in countries like Scotland, especially in the Winter, as solar energy is quite different.

Other high-consumption appliances such as a tumble dryer or an electric heater for clothes are rare in Portugal but very common in the Nordic countries.
This means that the results found in this document may not match those of an analysis of typical households in another country. In addition, different cultures may also have different effects on the time and appliances people use during the day.

It is important to note that the device that has a different pattern of use between seasons is a climate-related appliance:

- Air Conditioner.

It will be assumed to be both a cooling and heating device since nowadays the air conditioners can also heat rooms.

3.1.2 Power Demand

It is essential to reduce energy consumption at peak times, especially if there is any risk of surpassing the contracted power, leading to an outage. However, consumer wellness needs to be prioritised before turning off any appliances for this purpose.

We can reduce peak demand in two main ways:

1. Shift loads that can be moved to another time (e.g., washing machine or dishwasher).
2. Switch off an appliance to immediately reduce the total electricity consumption.

The first point is discussed in more detail in the next section (3.1.3), while this section focuses on describing the second point.

The second approach is suitable for devices the user considers as non-shiftable.
For example, if a user wants to switch on the air conditioner because he feels hot, the system should not try to avoid it.

Instead, the system analyses and checks other devices that are not relevant for the user and suggest turning them off.

At this point, user preferences are fundamental in systems of this type. The consumer must specify which devices can be shifted and which should not.

It is then necessary to classify devices according to a specific priority:

- **Low (L)** – These devices are not very important and therefore can be shut down when needed, i.e., when the network is overloaded, these devices are the first to be shut down;
- **Medium (M)** – These devices can be shut down but only under certain circumstances, which the user always needs to approve.

- **High (H)** – The devices with this priority cannot be switched off under any circumstances, so they will not be considered in any case.

The low priority devices, which the user does not rely upon most of the time, will be the first devices that HEMS will suggest turning off if that is enough to avoid a power outage.

High priority devices must not be turned off under any circumstances. Otherwise, the overall satisfaction of the users will be affected. A standard example of this is television. If users watch TV, they will not want it turned off because that was their primary activity.
HEMS will not suggest that the users turn off any of these devices as they consider them vital.

The medium priority devices are the ones that the user may be willing to turn off, depending on some conditions.
For example, an oven may be switched off if it has already reached the desired temperature (e.g., 220º C) or if foods are almost cooked already.
It may require a thermometer to communicate with the home energy management system in a real case scenario to provide more insight for the user to decide. However, as part of this solution, the system will make the recommendations based on the priority only.

In summary, before a device is powered on, the system will analyse if that device compromises the house's power consumption, possibly causing an outage.

A system of this kind monitors the total power of all devices (n) using electricity in real-time:

$$Total\ Power\ (W) = \sum_{1}^{n} Device\ Power\ (W) \tag{3.1}$$

Whenever a new device is switched on, HEMS will sum the new device's power with the current total power and further analyse if it will surpass the contracted power.
However, the system will consider 95% of the contracted power as the threshold amount to avoid further risks.

We will assume an optimal energy factor based on the contracted power, which means for a home with a contracted power of 6,9 kVA, the instant power can go until 6,9 kW. However, in order to have a safe margin to avoid additional risks if an additional appliance is switched on, the system will instead consider 95% of 6,9 kW as a threshold.

$$Total\ Power\ (W) + New\ Device\ Power\ (W)\ > 0{,}95\ \times Contracted\ Power \tag{3.2}$$

If this condition is met, the system will put the device on hold before turning it back on.

Then the system will suggest that the user turn off some devices according to the priority set.

If the user does not accept any of the suggestions and therefore no devices are shut down, there may be a power outage in the household.

3.1.3 Load Shifting

While there are some patterns to electricity consumption throughout the day, the routine of consumers can vary drastically, especially now that remote work has gained popularity.
However, some high-consumption appliances are used during hours (e.g., dinner) that could be shifted to another time when the grid is not under too much stress (off-peak hours) and the rate is cheaper.
The HEMS can provide helpful information to the user about which devices they should move to another time.

These devices are marked as shiftable in the device properties. Thus, if the user decides to turn on these devices, the system can advise the user to defer them later and rely on the user to decide whether to run them immediately.
This advice would be given in a HEMS app accessed via the web or mobile app in real-time.

The focus of the solution is to find a period for which that device should run, based on the tariff, and let the user confirm it.

Having this logic at home can reduce power consumption, resulting in the consumer reducing the contracted power (from 6.9 kVA to 5.75 kVA), which may lead to a lower electricity bill amount at the end of each month.

In order to find the proper period to reschedule a shiftable load, six additional parameters will be defined by the user:

- **Bedtime** – Time for which the user usually goes to bed;
- **Wake-up Time** – Time that the user usually gets up;
- **Laundry/Dishes Schedule** – Preferred time for the user to get the laundry/dishes done, it can be Morning or Night;
- **Predefined schedule** – This preference indicates if the consumer has set any predefined runtimes for the shiftable devices before the day starts, in order for the system to anticipate the best period right away. The idea is to leverage the sunlight to anticipate the start time for the houses that have a solar PV. It can be either yes or no.
- **Housekeeping Period (in minutes)** – The period for which the system still allows the user some time to hang up the laundry or dry the dishes in the evening. It is also used to calculate how many minutes before the wakeup time the washing machine/dishwasher should complete its programme;
- **Off-Peak Time**: Period for which the HEMS should suggest moving the loads. It can suggest periods based on a daily, weekly cycle or a custom period for a single rate tariff:

- **Bi-Hourly (Daily)**;
- **Bi-Hourly (Weekly)**;
- **Custom** – Start Time and End Time.

In case the tariff is not the single rate, then the off-peak time is automatically selected according to the respective tariff.

3.1.4 Solar Panel

To further analyse the impact of solar panels in HEMS, some samples of the solar power throughout the day will be considered.

These samples are meant for the Portuguese weather, and four significant samples to represent the different seasons will be used (Summer, Winter and Autumn/Spring).

The values of the sample will represent the power supplied to the house throughout the day.

In order to have a sample that fits the analysis, a specialised tool for photovoltaic panel systems, PGIS (Photovoltaic Geographical Information System), was used [39].

The following data was assumed in that tool in order to obtain a simple yet accurate model:

- Installed peak PV power – 340 W_p;
- System loss – 14%;
- Slope and Azimuth angles – 33º and 4º.
- Location – Lisbon;
- Year: 2016.

The slope and azimuth angles are optimised to have the maximum power and were automatically calculated by the simulation tool.

An export of all year's data has been executed. In addition, the average power of all days belonging to each season has been considered to model the solar panel power through a typical day each season.

The following graphics will be considered for the simulation:

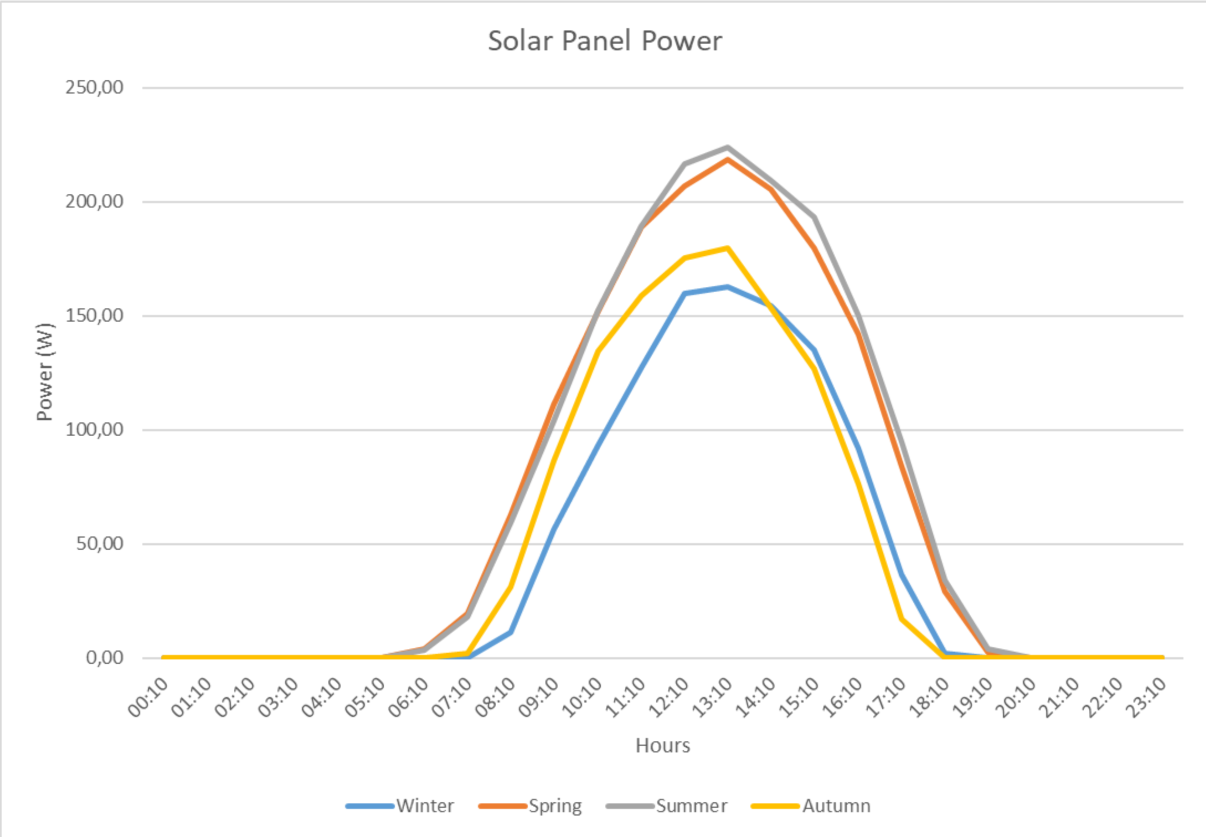


Figure 11 – Solar Panel Samples to be used in each season

Finally, it is common today for some consumers to use solar panels to reduce the power consumption from the grid through micro-production and perhaps shift some loads when the sun provides enough power to run them.

In conjunction with a load shifting strategy, it can also be a powerful tool for harnessing the energy generated during the day, rather than moving a device to an hour for which it requires power from the grid.

3.1.5 Consumer Devices

Based on the previous sections, the devices will have a set of characteristics and user preferences that the HEMS algorithm will use.
The following set of fields characterises each device:

- **Load ID** – Identifier of the load for a given home;
- **Load Type/Description** – Type of device that identifies a load (e.g., Refrigerator);
- **Start Time:** Time that indicates the first minute the device will run;
- **End Time**: Time indicates the last minute the device will run;
- **Priority** – Indicates the importance of the load for the user. It can be low, medium or high;

- **Shiftability** – Indicates if the load can be shifted to another time. It can be classified as "Yes" and "No".

By default, some loads will already have pre-defaulted values (e.g., washing machine and dishwasher are shiftable by default) according to their type. However, some of the values will need to be indicated by the user.

Some shiftable devices, such as a fast phone charger or hairdryer, can be shifted, but the user needs to see if he/she is willing to do it. For example, the user may be okay with not charging the phone before dinner if the battery is greater than 40%, or he/she could be willing to dry the hair one or two hours later.
These devices are harder to predict if they should be moved or not, strengthening the idea of user intervention for such cases.

Below is an example of what a list of devices can look like for a home

Table 3 - List of Devices – Example of what could be a list of devices for a single home

Load ID	Load Type	Start Time	End Time	Priority	Shiftability
1	Light Bulb	07:00	07:59	H	No
2	Light Bulb	20:00	22:59	H	No
3	Refrigerator	00:00	23:59	H	No
4	Oven	20:00	20:44	M	No
5	Dishwasher	21:15	22:09	H	Yes
6	Coffee Machine	07:50	07:51	L	No
7	Toaster	07:45	07:48	L	No
8	TV	20:20	22:59	M	No
9	Washing Machine	00:00	01:19	H	Yes
10	Phone (Charger)	23:00	23:44	L	Yes

As already mentioned in subsection 3.1.2, the priority can be low (L), medium (M) or high (H).

A set of predefined devices have been considered to be included in the tested scenarios. The complete list of devices can be found in Table 4.

Table 4 – List of possible devices and their power specifications

Device Type	Load Type ID	Average Power (W)	Peak Power (W)	Special Pattern	Runtime
Air Conditioner (Living Room)	1	1050	1500	Yes	-
Air Conditioner (Bedroom)	2	620	900	Yes	-
Blender	3	350	500	No	-
Coffee Machine	4	1050	1050	No	-
Cooker Hood	5	170	300	No	-
Desktop (Computer)	6	220	550	No	-
Dishwasher	7	1400	2200	Yes	55 min
Hair Dryer	8	1600	2000	No	-
Hair Straightening Brush	9	100	100	No	-
Iron	10	1800	3000	No	-
Kitchen Robot	11	1000	1500	No	-
Laptop	12	80	120	No	-
Light Bulb	13	12	15	No	-
Microwave	14	1200	1500	No	-
Monitor	15	105	160	No	-
Oven	16	1600	3500	No	-
Phone (Fast Charging)	17	50	60	No	-
Phone (Regular Charging)	18	15	15	No	-
PlayStation 5	19	180	220	No	-
Refrigerator	20	100	200	No	-
Stove Burner	21	1000	1500	No	-
Toaster	22	950	950	No	-
Tumble dryer	23	800	800	Yes	45 min
TV	24	100	120	No	-
TV Box	25	11,3	11,5	No	-
Vacuum Cleaner	26	1300	1500	No	-
Washing Machine	27	450	2300	Yes	1 h 20 min
Water Heater	28	1020	4000	No	-
Wi-Fi Router	29	15	15	No	-

Some devices do not have a regular power consumption (e.g., washing machine), meaning they do not always consume the same power and are therefore marked with a special pattern.

For the appliances without a specific pattern, it was assumed that the power consumption is always the same during the use of the appliance. Therefore, the average power was assumed for these cases.

For the appliances that always run for a certain time (dishwasher, tumble dryer and washing machine), a running time was given for their programmes.

At last, the peak power is the maximum power that the devices with a special pattern can achieve.

3.1.5.1 Air Conditioner

For air conditioners, a model with inverter technology was considered. They are the best-selling type of air conditioner in Portugal today and are also more energy-efficient [40].

When they are switched on, they run at full speed until the desired temperature is reached. Then the inverter adjusts the operating frequency of the compressor to maintain the temperature without using too much electricity.

This contrasts with conventional air conditioning systems where the compressor is either off or on. This means that the conventional air conditioner operates at its full capacity.
It was assumed that the air conditioner modelled in this work takes about 15 minutes to reach the desired temperature and then stabilises at a lower frequency until the user no longer wants the air conditioner, which is usually around sunset.

The use of air conditioning varies depending on the scenario, but a typical use [40] during the day in summer may look similar to the following graphic:

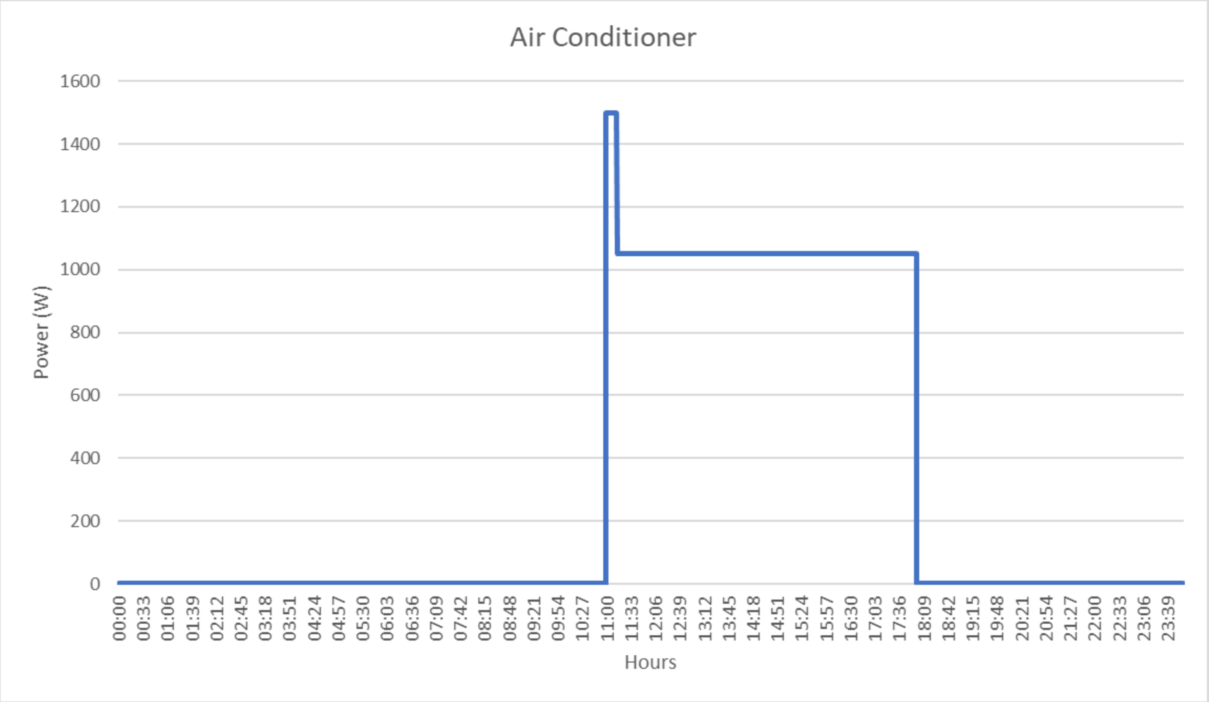


Figure 12 – Air Conditioner typical usage (with inverter technology)

After the first moments when the air conditioner is operating at its peak capacity, the average power of the air conditioner is assumed after the temperature in the room has stabilised.

These devices have heating properties as well, so they will be considered for the winter as well.

3.1.5.2 Dishwasher

A standard programme with a temperature of 65 ºC was adopted for the dishwasher [41], as they are becoming more efficient nowadays.

The usage of a dishwasher would then look like the following pattern:

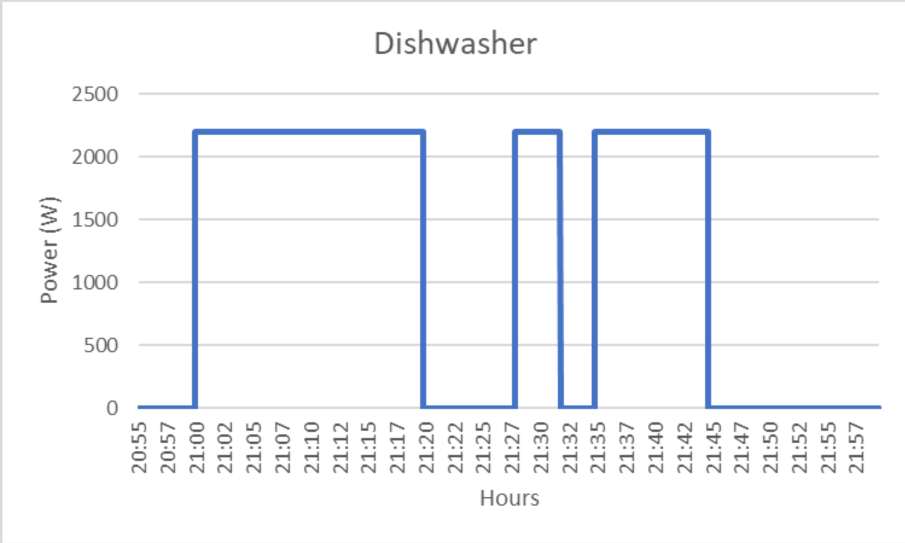


Figure 13 – Dishwasher typical usage pattern for a standard 65º programme, starting at 10:55 p.m.

3.1.5.3 Washing Machine

There are multiple programs in a washing machine that can be used. Although each manufacturer has different programmes with different power consumption patterns, a standard mixed washing programme at 40º C [41] was used as a reference to demonstrate the results.

A typical and simplified pattern is represented in the figure below.

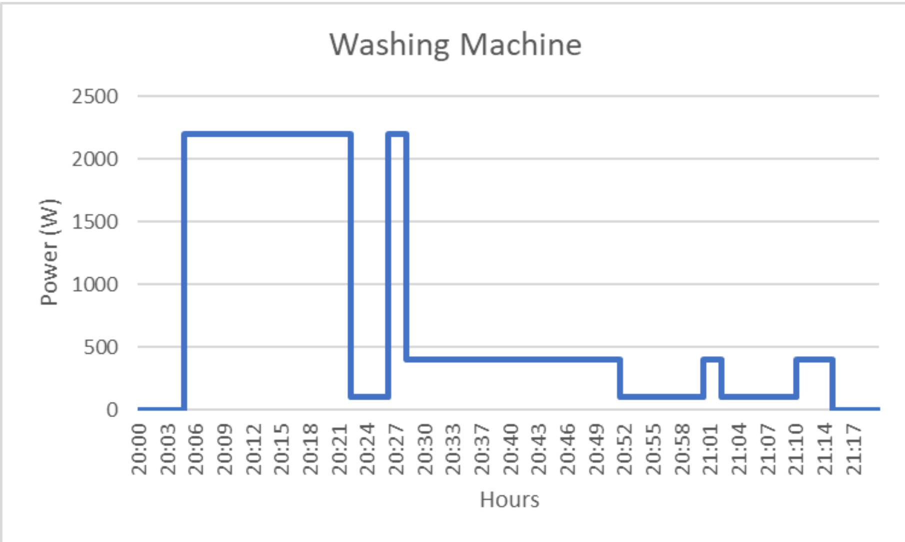


Figure 14 – Washing machine typical usage pattern for a 40º C programme, starting at 08:00 p.m.

3.1.6 Tariffs

In order to take full advantage of load shifting, tariffs based on the time of use will need to be considered.

Load shifting can be used for single-rate tariffs since it can reduce the peaks at home, and therefore the consumer may be able to reduce the contracted power, saving money that way.

Nevertheless, to take full advantage of the load shifting approach, the user should consider tariffs based on the time of use.

To that extent, an extended tariff provided by EDP Comercial was used as a reference [42], for which the contracted power may vary from 3,45 kVA to 10,35 kVA, the most common in Portugal.

Three main components are considered:

- **Power Tariff** (Fixed charge) – Related with the contracted power;
- **Consumption Tariff** (Variable charge) – Related with the electricity consumption;
- **Taxes**.

In order to make a fair comparison and understand whether the user profile fits this type of solution, the single rate tariff is also used for some scenarios to precisely see the monetary difference between the tariff types and determine whether the ToU tariffs are worthwhile.

Table 5 – Single Tariff

Contracted Power	Network Access Tariff	Power Tariff	Consumption Tariff
3,45 kVA	0,1585 €/Day	0,2474 €/Day	0,1389 €/kWh
4,60 kVA	0,2114 €/Day	0,3144 €/Day	0,1441 €/kWh
5,75 kVA	0,2640 €/Day	0,3753 €/Day	0,1453 €/kWh
6,90 kVA	0,3169 €/Day	0,4312 €/Day	0,1445 €/kWh
10,35 kVA	0,4754 €/Day	0,6027 €/Day	0,1441 €/kWh

Table 6 – Bi-Hourly Tariff (Daily or Weekly Cycle)

Contracted Power	Network Access Tariff	Power Tariff	Peak Time Consumption Tariff	Off-Peak Time Consumption Tariff
3,45 kVA	0,1585 €/Day	0,2643 €/Day	0,1827 €/kWh	0,0920 €/kWh
4,60 kVA	0,2114 €/Day	0,3251 €/Day	0,1833 €/kWh	0,0923 €/kWh
5,75 kVA	0,2640 €/Day	0,3847 €/Day	0,1834 €/kWh	0,0924 €/kWh
6,90 kVA	0,3169 €/Day	0,4448 €/Day	0,1836 €/kWh	0,0924 €/kWh
10,35 kVA	0,4754 €/Day	0,6209 €/Day	0,1829 €/kWh	0,0922 €/kWh

These are the standard tariffs that will be considered for the scenarios to be explored across the document.

The power tariff refers to the power contractually agreed, which is charged to the customer based on a fixed daily rate and already includes the network access tariff. The network access fees are listed since they may have a different applicable VAT depending on the contracted power.

The consumption tariff depends on the energy consumed and time of use at home.

In addition to these two components, taxes also need to be taken into consideration [43]:

- **DGEG** – A fee of 0,07€ per month;
- **IEC (Imposto Especial de Consumo de Eletricidade)** – This is a special rate introduced for environmental purposes, and it is defined as 0,001€ per kWh plus VAT;

- **CAV (Contribuição audiovisual)** – An audio-visual monthly fee contribution of 2,85€ plus VAT that finances the public broadcasting and television service. The consumer is not charged if its annual power consumption is lower than 400 kWh.
- **VAT** – A tax applied on top of the contracted power, energy consumption tariffs, CAV and IEC amounts. It can vary between 6% and 23%, depending on the contracted power or the energy consumed within a month.

  More details on how VAT is calculated according to different percentages on the fixed, variable and taxes components can be found below [44]:

  1. VAT on fixed and variable components:

Table 7 – VAT that applies to fixed and variable components of the bill, per contracted power

	Contracted Power	≤ 3,45 kVA	4,6 kVA – 6,9 kVA	≥ 10,35 kVA
Fixed Component	Network Access Fees	6%	23%	23%
	Remaining Fees	23%	23%	23%
Variable Component	Until 100 kWh	13%	13%	23%
	After 100 kWh	23%	23%	23%

  2. **VAT on remaining fee rates:**
     - **Tax of 6%:**
       - CAV fees.
     - **Tax of 23%:**
       - DGEG and IEC fees.

For families with at least five members, the variable component is 150 kWh instead of just 100 kWh. These taxes are applicable in the mainland of Portugal, and therefore they are different in Azores and Madeira.

It is also relevant to know that nowadays, the 100 kWh is split for the bi-hourly tariffs:

- **Peak** – 60 kWh;
- **Off-peak** – 40 kWh.

From 1st December 2021 onwards, these limits will vary proportionally according to the actual consumption. Suppose the following consumption in a month for a bi-hourly tariff:

- **Peak period** – 170 kWh;
- **Off-peak** – 80 kWh;

Then, proportionally the first 68 kWh and 32 kWh of the peak and off-peak periods, respectively, will be charged only 13% of the VAT in case the contracted power does not exceed 6,9 kVA.

There is also an additional charge (CIEG - Custo de interesse económico geral) related to network access. As explained in Chapter 2, the network access fees are already included in the commercial fees table related to contracted power and energy consumption, so the consumer does not need to consider this additional amount when looking for a new supplier.

However, these charges do appear in the breakdown of the electricity bill.

Two invoices from EDP Comercial [45] and Endesa [46] are shown in figures the below:

ELETRICIDADE | FATURA Nº 10064138046 | DE: 2 de setembro 2016 | VALOR: 51,13 €

10

escrição	Quantidade	x	Preço	=	Valor	Desconto	Total s/IVA	IVA
Consumo Real Simples 16 jul a 15 set	210 kWh		0,1587 €		33,33 €	2% (-0,67 €)	**32,66 €**	23%
A 15 de setembro recebemos uma leitura de 31900. Antes desta, tinhamos uma leitura de 31690 a 15 de julho. Assim, o seu consumo real entre estas datas foi de 210 kWh (31900 - 31690).								
Consumo estimado Simples 16 set a 30 set	63 kWh		0,1587 €		10,00 €	2% (-0,20 €)	**9,80 €**	23%
A 30 de setembro estimamos que o seu contador marcaria 31963. Antes desta, tinhamos uma leitura de 31900 a 15 de setembro. Assim, o seu consumo estimado entre estas datas foi de 63 kWh (31963 - 31900).								
11 **batimentos** 16 jul a 30 jul							**-10,57 €**	23%
A 15 de setembro recebemos uma leitura. Assim, estamos a abater a faturação dos consumos estimados entre 16 de julho e 30 de julho.								
Potência (3,45 kVA) 31 jul a 30 set	62 dias		0,1561 €		9,68 €	2% (-0,20 €)	**9,48 €**	23%
						TOTAL	**41,37 €**	sem IVA

XAS E IMPOSTOS

12

crição	Quantidade	x	Preço	=	Valor	Abatimentos	Total s/IVA	IVA
IEC 16 jul a 30 set	273 kWh		0,001 €		0,27 €	-0,07 €	**0,20 €**	23 %
A 15 de setembro recebemos uma leitura. Assim, estamos a abater o valor estimado do IEC entre 16 de julho e 30 de julho.								
IVA (41,37 € + 0,20 €)	41,57 €		23 %		9,56 €			
						TOTAL	**9,76 €**	

13

a de Qualidade de Serviço - A
O preço da eletricidade inclui o valor de 28,23 € (sem IVA) correspondente às tarifas de acesso às redes, que contêm o valor dos Custos de Interesse Económico Geral (CIEG) no valor de 17,50 €. Estes valores são independentes do comercializador.

ONTRIBUIÇÃO AUDIOVISUAL | FATURA Nº 30043466008 | DE: 2 de setembro 2016 | VALOR: 6,04 €

14

escrição	Quantidade	x	Preço	=	Valor	Abatimentos	Total s/IVA	IVA
Contribuição Audiovisual	2 meses		2,85 €		5,70 €		**5,70 €**	6%
IVA (5,70 €)	5,70 €		6 %		0,34 €			
						TOTAL	**6,04 €**	

Figure 15 – Electricity Bill from EDP Comercial that includes all components the consumer has to pay, such as power consumption, contracted power and taxes. This example does not include the latest tax rules introduced in December of 2020.

LUZ	Fatura: FAC xxxxxxxxxx/xxxxxxxxxx		Data: 01 jul 2020	Período de Faturação: 01 jun 2020 a 01 jul 2020		
escrição	Quantidade X	Preço =	Valor -	Desconto* =	Total **	IVA
Luz (Consumo)						
Termo de Energia (Real) 01 jun a 01 jul * Desconto 1 Ano (18,68 € x 6,00%) + Desconto (18,68 € x 3,00%)	112 kWh	0,166823 €	18,68 €	**-1,68 €**	17,00 €	23% (c)
Termo de Potência (6.90 kVA) 01 jun a 01 jul * Desconto 1 Ano (2,59 € x 6,00%) + Desconto (2,59 € x 3,00%)	31 dias	0,083500 €	2,59 €	**-0,24 €**	2,35 €	23% (c)
Termo Fixo Acesso às Redes 01 jun a 01 jul * Desconto 1 Ano (9,17 € x 6,00%) + Desconto (9,17 € x 3,00%)	31 dias	0,295900 €	9,17 €	**-0,83 €**	8,34 €	23% (c)
				TOTAL Luz (Consumo)	**27,69 €**	
Taxas e Impostos						
ontribuição Audiovisual 01 jun a 01 jul	1,0164 meses	2,850000 €	2,90 €		2,90 €	6% (b)
axa Exploração DGEG (DL-4/93) 01 jun a 01 jul ** 1,0164 meses x 0,07 €/mês	1,0164 meses	0,070000 €	0,07 €		0,07 €	23% (c)
posto Especial Consumo (Real) 1 jun a 01 jul	112 kWh	0,001000 €	0,11 €		0,11 €	23% (c)
A 1 jun a 01 jul						
(c) IVA 23%	27,87 €		6,41 €		6,41 €	
(b) IVA 6%	2,90 €		0,17 €		0,17 €	
				TOTAL Taxas e Impostos	**9,66 €**	
				TOTAL DA FATURA DE LUZ	**37,35 €**	

HCFo - Processado por programa certificado n.º 2516

Por ter optado pela tarifa Endesa, paga pelo seu consumo de eletricidade 1.29€ comparativamente à tarifa regulada (não incluindo taxas e mpostos).
Lembre-se que com a Endesa os seus amigos podem ajudá-lo a poupar. Por cada amigo que contrate com a Endesa, recebem os dois 1€ de desconto por mês na fatura.
Zona de Qualidade de Serviço - C.
Pegada ecológica CO2 : 23,66 kg
O valor da fatura inclui o valor de 17,33€ sem IVA correspondente às tarifas de acesso a redes, onde se inclui o valor dos Custos de Interesse Económico Geral (CIEG) no valor de 11,26€.

Movimentos de Conta

escrição	Número	Data de Emissão	Total
Saldo Anterior			0,00 €
Faturação de Ciclo	FAC xxxxxxxxxx/xxxxxxxxxx	04 jul 2020	37,35 €
		SALDO ATUAL	**37,35 €**

Dados da Conta

Nome: XXXXXX XXXXXXX
NIF: xxxxxxxxx
Morada de fornecimento: xxx xxx xxxxxxxxxxx x x xxx
Código Plano Amigo: xxxxxxxxx
Plano: Quero+ Luz

CPE (Código Ponto Entrega)	Potência	Ciclo horário
PT xxxx xxxx xxxx xxxx xx	6,90 kVA	Sem ciclo

Figure 16 – Electricity Bill from ENDESA, which includes a breakdown of the network access fees. This example does not include the latest tax rules introduced in December of 2020.

3.2 Solution Design

3.2.1 Overall Solution Design

To achieve a generic solution that will gather the coexistence of the load shifting, solar panel and peak reduction strategies, then an overall algorithm/diagram is found below with the processes/steps that should be followed:

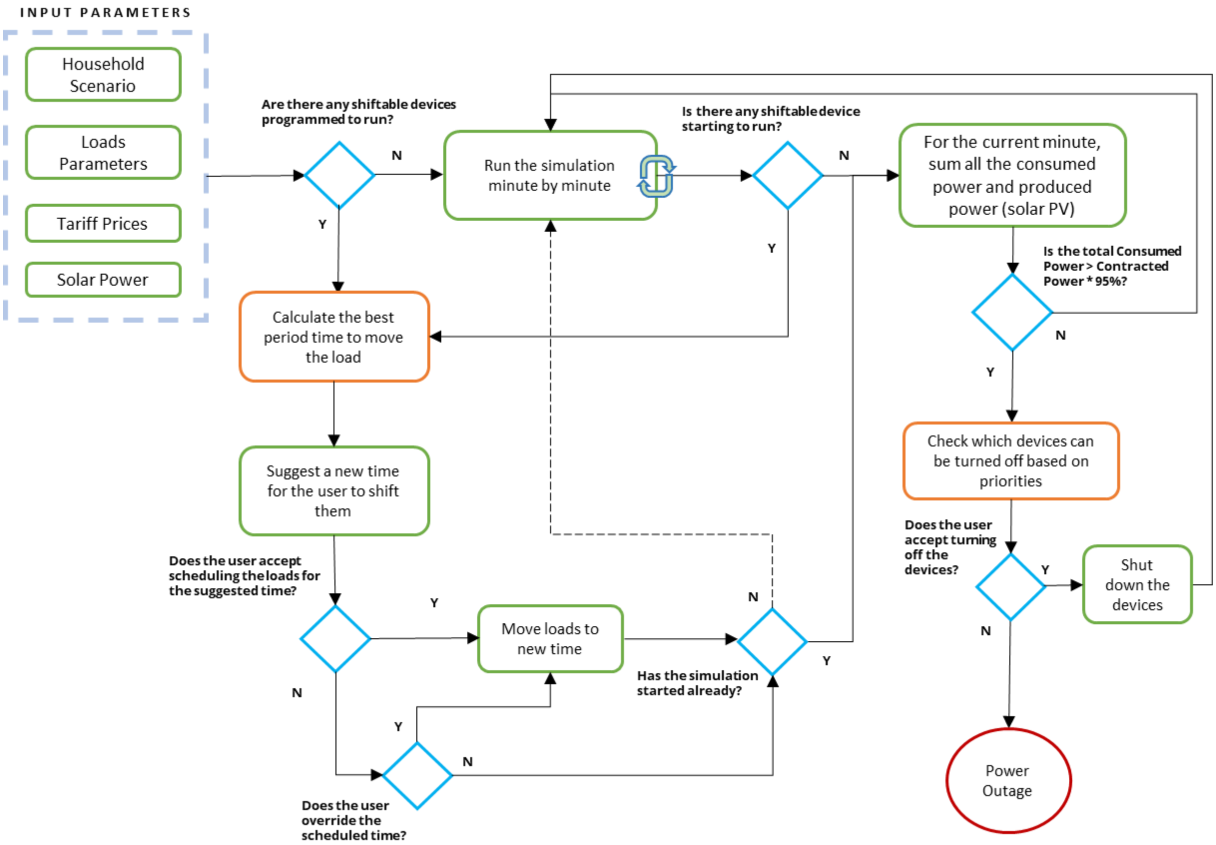


Figure 17 – Flowchart of the overall solution

Different input parameters need to be established to understand the potential improvements from using load shifting, solar panel and peak reduction:

1. **Loads parameters** – Specifies the default values that are pre-defined for each type of load;
2. **Household Scenario** – List of all loads in a house, including their times of use and consumer preferences;
3. **Tariff prices** – Prices of the tariff for the system to know when electricity is cheaper and to calculate the cost of the electricity bill;
4. **Solar Power** – The power of a solar panel(s) installed in the house.

In the first step, the system checks the time each device will run (in case a pre-defined schedule was set). Then, if a shiftable device is programmed to run during a peak time, the user will be prompted with a new suggested time to move the device.

If the user agrees or decides to postpone the load to another time, the device's start and end times are updated according to user selection.

It is assumed that users can indicate in the day before which devices they intend to use.
This logic is introduced mainly to shift loads to a period when the consumer can use the solar panel. Otherwise, it might be too late already, as the load cannot be shifted back in time.

In case the system detects that a shiftable appliance starts running and that minute does not fall in an off-peak period, the system calculates the best period for switching the appliance and suggests it to the user. In the meantime, that load will not start running until the user has made a decision.
The user can accept the proposal, postpone it to another period or reject it, which moves the process to the next step.

If the shiftable unit starts at an off-peak time, the system moves to the next step and does not attempt to reschedule it.

For each minute, the system adds up the power consumption of the devices switched on and any possible new devices that will be added shortly, i.e. devices that the user has just switched on.

In case there is a possibility that the total consumption power with the new device will exceed the contracted capacity, the system puts it on hold.

Based on the priorities set by the user, the system proposes to switch off some devices. Finally, the user selects one or more devices whose switch-off is sufficient to avoid a power failure, and the simulation continues in the next minute.

In the worst case, the consumer does not see a notification in the app or does not want to switch anything off, and a power failure occurs.

It is important to know that when the solar panel is placed in a house, the energy it generates is added to the contracted power throughout the logic.

3.2.2 Calculate the period for shifting a load

Following the diagram in the previous section, which included a step in calculating the best period to shift a load, the figure below explains in more detail how HEMS does this.

This time is the HEMS suggestion for which the user should move a shiftable device.

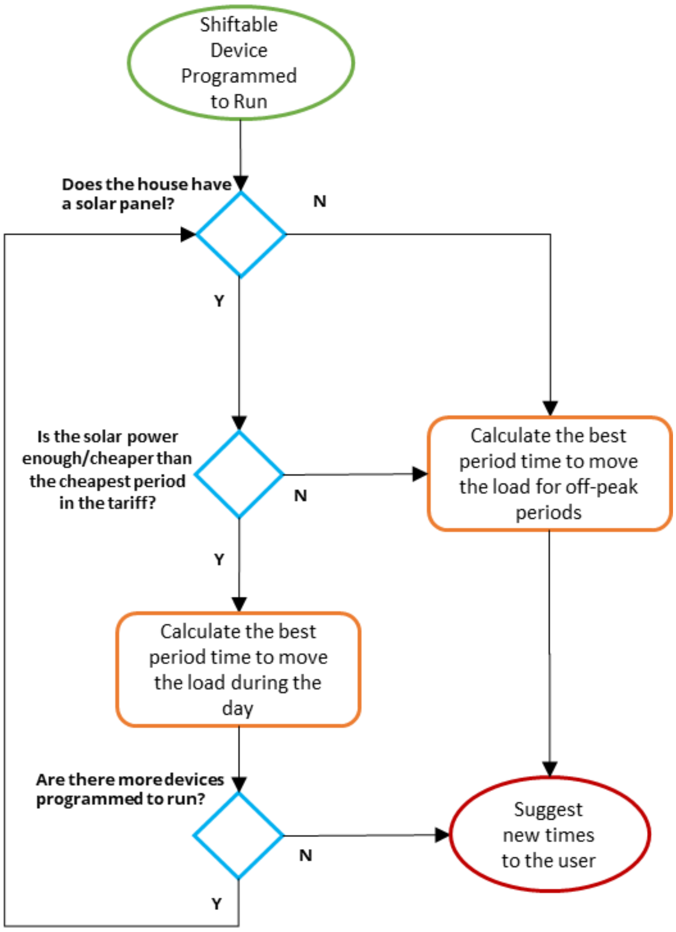


Figure 18 – Flowchart for new load shifting times ending with a time suggestion for users.

When HEMS detects that a shiftable device is programmed to operate, whether at the beginning of the day or when the user turns on a device, it starts looking for a new time to shift that load. First, the system checks if there are solar panels in the house. If there are not, it checks if there is a better time in an off-peak period to shift the load. If there is a better period, it suggests a new time to the user.

If there is a solar panel in the house, the system checks if the solar power predicted for that day is sufficient to handle the load.
It then compares the shifting of this device against an off-peak period (regardless of the time of day) and compares the corresponding tariff to justify a possible shift of this load during the day.

It is important to notice that even if a load is scheduled to run in a different period than initially predicted, the system will recheck the new period before the load starts effectively running. That is especially important because the user may have switched on several appliances in the meantime that the system cannot predict.

3.2.2.1 Calculate the best period to leverage the solar panel power

As soon as the system detects a solar panel in the house, it checks whether the energy it generates is sufficient to shift the load to that period, instead of shifting it later to an off-peak period for which the grid is needed.

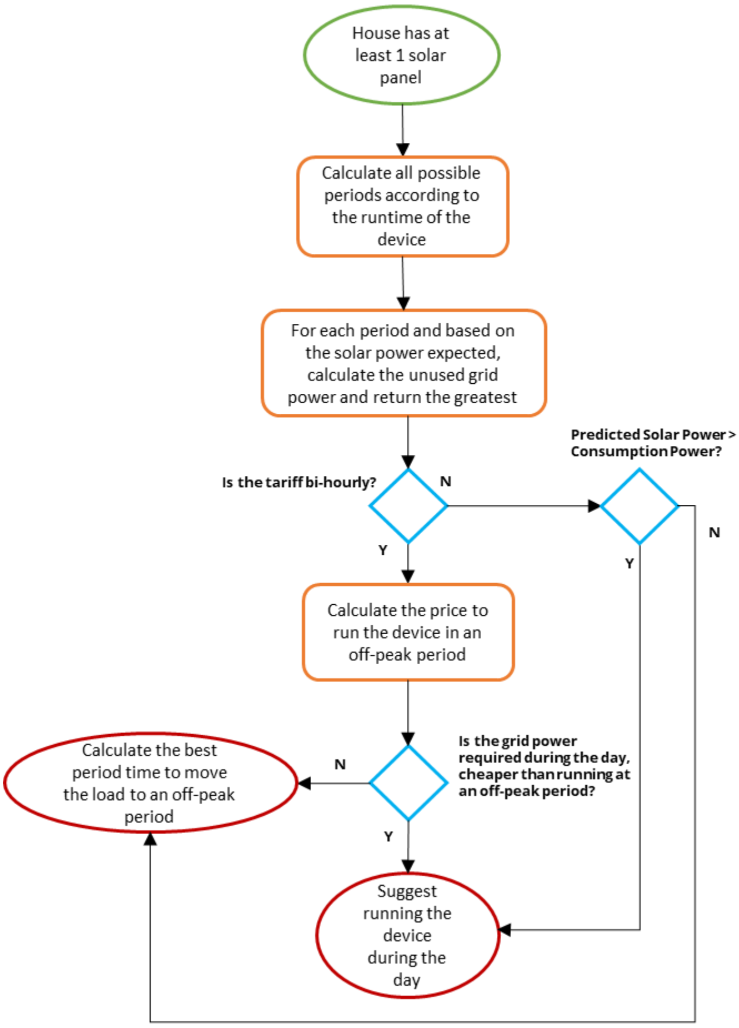


Figure 19 – Flowchart for calculating the time period for shifting a load when the house has a solar panel.

Based on the expected runtime (e.g., 40 minutes) of the scheduled device, the system searches all possible time windows and checks the following metrics for each time window:

1. Device consumption required;
2. Expected solar PV energy;
3. Required energy from the grid, based on the difference between the two values above.

Then, based on the runtime, it determines the period when the available solar energy will be the greatest during the day.

After determining this period, the system checks whether the house still needs more energy from the grid to operate such an appliance.

If this is not the case, the system automatically suggests running the appliance at this time. Otherwise, HEMS performs calculations to determine whether the electricity needed from the grid is cheaper than moving the appliance to an off-peak time.

For single rate tariffs, the load will only be moved in case the energy from the solar PV covers entirely the energy consumption of the device.

3.2.2.2 Shifting the load to off-peak periods

Suppose the house does not have any solar panels. In that case, HEMS will verify a new period to shift the device based on the user's preferences regarding the defined bedtime/wake-up time and if it prefers to do the laundry/dishes at night or in the morning.

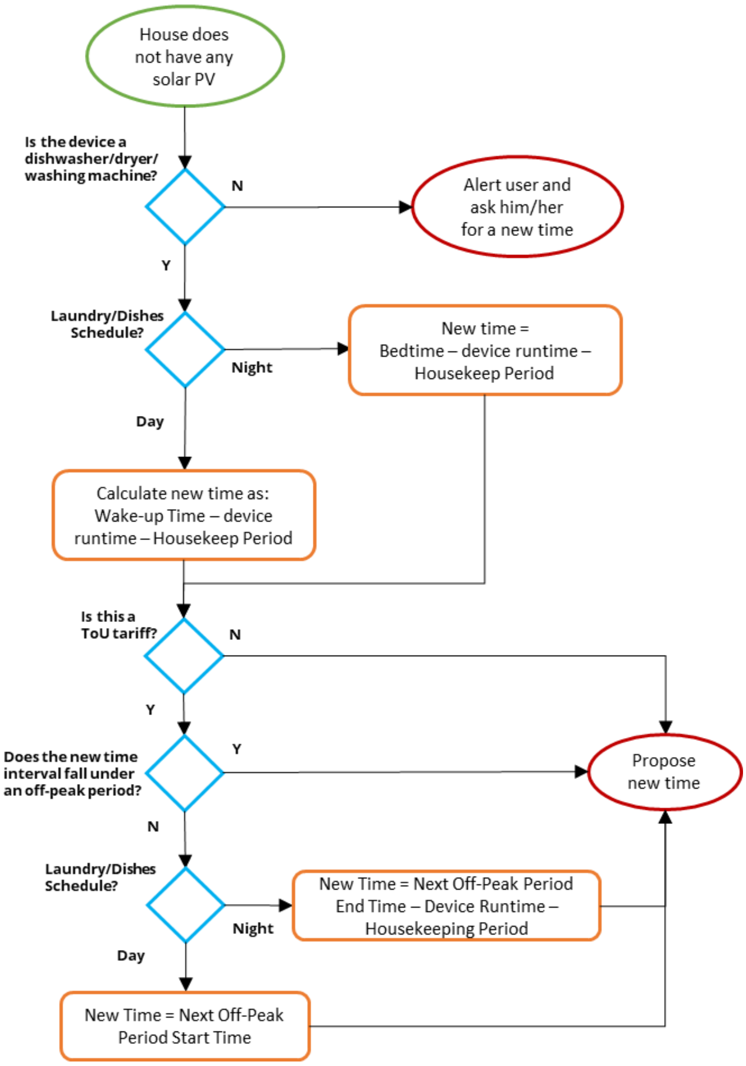


Figure 20 – Flowchart for calculating the time period for shifting a load to an off-peak period

If the user prefers to do the laundry or dishes in the morning, the system will propose a new time to reschedule it for the period before the consumer may wake up.

Given the programme duration of the machine, the system will consider it to end just before the consumers are supposed to wake up. This way, either laundry or dishes will be ready to be picked up in the morning.

Otherwise, if consumers prefer to do it at night, the system will also consider the bedtime defined. This is relevant because in case the consumer does not have a bi-hourly rate, the system will suggest a new time based on these preferences, and not entirely on off-peak times.

HEMS also need to consider some time for the users to hang clothes, put them on the tumble dryer or even take out the dishes from the machine. This is something parametrised by the user as well.

Considering an example with the following characteristics:

1. Single rate tariff;
2. Bedtime – 23:45;
3. Washing machine programme runtime – 80 minutes;
4. Housekeeping period – 20 minutes.

In the above case, the system adds the time from parameters 3 and 4, giving a total time of 100 minutes, and subtracts it from bedtime.

This means that the washing machine would start running at 10:05 p.m.

In the case of bi-hourly rates, it is not so simple, as the user may not have enough time between the start of the off-peak period and the time when he/she goes to sleep. In such cases, the system prompts the user to move the unit to a period of his choice.

The calculated time is therefore only a suggestion, and the user can set their own instead.

For Saturdays on a weekly cycle, there will be more than one off-peak period, and the system will check the next available off-peak period as the one to do the logic.

4 Results and Discussion

In order to understand the impact HEMS can have on reducing electricity peaks and potentially reducing contracted power, leveraging periods when the price of electricity is cheaper, three different scenarios were created.

Table 8 – Summary description of the scenarios used

Scenario ID	Description	Solar Panel
Scenario 1	A single person working in the office during Summer	No
Scenario 2	A married couple working in the office, and usually doing their domestic activities on weekends	No
Scenario 3	A family of four (Couple with two children), with parents working at home	Yes

Three different families that fit the description above were asked to describe their usual daily consumption patterns across the week. For each scenario, different daily consumption patterns are used to provide a more reliable basis for calculating the monthly electricity bill each family has to pay.

For each day, a set of devices with their respective usage time is defined to obtain the simulation results.
User preferences are also described for each scenario and with a more detailed description of each family routine.
In summary, each scenario contains the following daily consumption patterns:

- Saturday;
- Sunday;
- Two different weekday patterns.

This gives a total of four different patterns to extrapolate the monthly electricity costs.
At the end, a table is presented with the monthly amounts with the following values:

- Contracted power;
- Electricity consumption;
- Taxes;
- Total amount.

These results are displayed before and after applying the HEMS logic to understand the actual impact of the algorithm.

The simulation of the proposed algorithm was implemented in the Microsoft Excel application.
As this was the tool chosen, it was also leveraged to calculate the invoice amounts and all the graphs related to the results obtained.

The input parameters that define the information for a specific day are detailed as per below:

Input Parameters

Day of the Week	Thursday
Season	Spring
No Solar Panels (340 Wp)	0
Contracted Power	6,90 kVA
Bedtime	23:45:00
Wake up Time (Weekdays)	07:00:00
Wake up Time (Weekends)	08:30:00
Laundry Schedule	Night
Dishes Schedule	Night
Housekeeping Period	00:15
Tariff	Single
Cycle	Daily

Daily Consumption

Total Consumption	5,41 kWh
Grid Energy	5,41 kWh
Total Solar Energy	0,00 kWh
Solar Energy Wasted	0,00 kWh

Tariff	Daily Costs (Energy Consumption)	Peak Costs	Off-Peak Costs
Single	0,78 €	-	-
Bi-Hourly (Daily)	0,87 €	0,75 €	0,12 €
Bi-Hourly (Weekly)	0,76 €	0,53 €	0,24 €

HEMS Suggestions

Next User's notification	Device	Time Suggestion	
Please reschedule the following device	Washing Machine	22:10:00	23:29:00

At risk of power failure
No

Figure 21 – Simulation Tool – Excel Spreadsheet with the input parameters that simulate a day.

This information along with the parametrisation of the different daily scenarios (Figure 22) is used to perform the intermediate steps and calculations in auxiliary tables/spreadsheets, according to the proposed logic/algorithm.

Load Type ID	Load Type	Monday		Tuesday		Wednesday		Thursday		Friday		Saturday		Sunday	
		Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
1	Air Conditioner (Living Room)	21:00	21:29	21:00	21:29	-	-	21:00	21:29	-	-	-	-	21:00	21:29
2	Air Conditioner (Bedroom)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	Blender	-	-	-	-	07:50	07:52	-	-	07:50	07:52	09:15	09:18	-	-
4	Coffee Machine	08:00	08:01	08:00	08:01	08:00	08:01	08:00	08:01	08:00	08:01	-	-	10:00	10:02
4	Coffee Machine	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	Cooker Hood	19:30	20:09	19:30	20:09	-	-	19:30	20:09	-	-	-	-	-	-
6	Desktop (Computer)	21:00	22:39	21:00	22:39	-	-	21:00	22:39	-	-	-	-	13:30	16:49
7	Dishwasher	21:00	21:54	21:00	21:54	-	-	21:00	21:54	-	-	-	-	-	-
8	Hair Dryer	07:50	07:54	07:50	07:54	07:50	07:54	07:50	07:54	07:50	07:54	-	-	-	-
9	Hair Straightening Brush	-	-	-	-	-	-	-	-	-	-	12:00	12:09	-	-
10	Iron	-	-	-	-	-	-	-	-	-	-	-	-	0,667	0,708
11	Kitchen Robot	0,813	0,843	0,813	0,843	-	-	0,813	0,843	-	-	-	-	-	-
12	Laptop	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	Laptop	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	Light Bulb	07:30	07:59	07:30	07:59	07:30	07:59	07:30	07:59	07:30	07:59	23:30	23:59	19:00	23:59
13	Light Bulb	19:00	23:59	19:00	23:59	23:00	23:59	19:00	23:59	23:00	23:59	-	-	-	-
14	Microwave	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	Monitor	21:00	23:39	21:00	23:39	-	-	21:00	23:39	-	-	-	-	13:30	16:49
16	Oven	-	-	-	-	-	-	-	-	-	-	-	-	19:00	19:59
17	Phone (Fast Charging)	00:00	00:40	00:00	00:40	00:00	00:40	00:00	00:40	00:00	00:40	00:00	00:40	00:00	00:40
18	Phone (Regular Charging)	00:00	01:30	00:00	01:30	00:00	01:30	00:00	01:30	00:00	01:30	00:00	01:30	00:00	01:30
19	Playstation 5	-	-	-	-	-	-	-	-	-	-	10:00	11:29	17:00	18:59
20	Refrigerator	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59
21	Stove Burner	19:30	20:09	19:30	20:09	-	-	19:30	20:09	-	-	-	-	-	-
22	Toaster	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	Tumble dryer	-	-	-	-	-	-	-	-	-	-	12:30	13:14	12:30	13:14
24	TV	21:00	23:39	21:00	23:39	23:00	23:49	21:00	23:39	23:00	23:49	09:30	14:09	10:30	22:59
25	TV Box	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59
26	Vacuum Cleaner	-	-	-	-	-	-	-	-	-	-	-	-	15:20	15:49
27	Washing Machine	-	-	-	-	-	-	-	-	-	-	11:00	12:19	11:00	12:19
28	Water Heater	-	-	-	-	-	-	-	-	-	-	-	-	-	-
29	Wi-Fi Router	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59

Figure 22 – Simulation Tool – Excel Spreadsheet that defines start and end times for each device in the tested scenario.

Based on the given suggestion, which may not be accepted, the user will override a similar table as in Figure 22 with the new times, which will be used to check the results with the proposed time changes.

A separate spreadsheet will contain the breakdown of all the amounts that are calculated in the tested scenarios.

Monthly Costs

Power (kVA)	Tariff	Electricity Consumption	Peak Consumption	Off-Peak Consumption	Contracted Power	DGEG	IEC	CAV	VAT	Total Taxes	Total Amount
6,90	Single	29,66 €	0,00 €	0,00 €	12,94 €	0,07 €	0,21 €	2,85 €	8,59 €	11,71 €	54,31 €
6,90	Bi-Hourly (Daily) - Before HEMS	33,02 €	28,28 €	4,74 €	13,34 €	0,07 €	0,21 €	2,85 €	9,43 €	12,55 €	58,91 €
6,90	Bi-Hourly (Weekly) - Before HEMS	30,45 €	23,11 €	7,34 €	13,34 €	0,07 €	0,21 €	2,85 €	8,84 €	11,96 €	55,75 €
6,90	Bi-Hourly (Daily) - After HEMS	29,55 €	21,30 €	8,25 €	13,34 €	0,07 €	0,21 €	2,85 €	8,63 €	11,75 €	54,65 €
6,90	Bi-Hourly (Weekly) - After HEMS	28,27 €	18,73 €	9,54 €	13,34 €	0,07 €	0,21 €	2,85 €	8,34 €	11,46 €	53,08 €
5,75	Single	29,83 €	0,00 €	0,00 €	11,26 €	0,07 €	0,21 €	2,85 €	8,23 €	11,36 €	52,44 €
5,75	Bi-Hourly (Daily)	29,52 €	21,27 €	8,25 €	11,54 €	0,07 €	0,21 €	2,85 €	8,21 €	11,33 €	52,40 €
5,75	Bi-Hourly (Weekly)	28,25 €	18,71 €	9,54 €	11,54 €	0,07 €	0,21 €	2,85 €	7,92 €	11,04 €	50,84 €
4,60	Single	29,58 €	0,00 €	0,00 €	9,43 €	0,07 €	0,21 €	2,85 €	7,77 €	10,89 €	49,91 €
4,60	Bi-Hourly (Daily)	29,50 €	21,26 €	8,24 €	9,75 €	0,07 €	0,21 €	2,85 €	7,79 €	10,92 €	50,18 €
4,60	Bi-Hourly (Weekly)	28,23 €	18,70 €	9,53 €	9,75 €	0,07 €	0,21 €	2,85 €	7,50 €	10,63 €	48,61 €
3,45	Single	28,51 €	0,00 €	0,00 €	7,42 €	0,07 €	0,21 €	2,85 €	5,43 €	8,56 €	44,50 €
3,45	Bi-Hourly (Daily)	29,41 €	21,19 €	8,21 €	7,93 €	0,07 €	0,21 €	2,85 €	5,56 €	8,69 €	46,03 €
3,45	Bi-Hourly (Weekly)	28,14 €	18,64 €	9,50 €	7,93 €	0,07 €	0,21 €	2,85 €	5,27 €	8,40 €	44,47 €

Figure 23 – Simulation Tool – Excel Spreadsheet that provides the monthly costs from to each tariff

4.1 Results

4.1.1 Scenario 1

The first scenario is the characterisation of a single person working in an office with a single rate tariff and a contracted power of 6,9 kVA.

In terms of user preferences, the following parameters were set:

- **Bedtime** – 11:45 p.m.;
- **Wake-up time**:
    - 07:00 a.m. (on weekdays);
    - 08:30 a.m. (on weekends).
- **Laundry/Dishes Schedule** – Night;
- **Housekeeping Period** – 15 minutes;
- **Tariff –** Single**;**
- **Off-Peak Time Period –** Bi-Hourly (Daily)**;**
- **Predefined schedule** – No.

In the simulation of this scenario, the off-peak time is based on a daily cycle, which means that HEMS primarily proposes to move the loads to a period after 10 p.m.

In the following table, a predefined set of appliances with a scheduled time has been defined to simulate the consumer's consumption pattern during the day.

Table 9 – Scenario 1 – Devices consumption pattern across the week during the summer

ID	Load Type	Wednesday		Other Weekdays		Saturday		Sunday	
		Start	End	Start	End	Start	End	Start	End
1	Refrigerator	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59
2	Wi-Fi Router	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59
3	TV Box	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59
4	Light Bulb	07:00	07:29	07:00	07:29	-	-	-	-
5	Iron	-	-	-	-	-	-	18:00	18:29
6	Microwave	07:42	07:46	07:42	07:46	09:42	09:46	09:42	09:46
7	Toaster	07:43	07:45	07:43	07:45	09:43	09:45	09:43	09:45
8	Coffee Machine	07:45	07:46	07:45	07:46	09:45	09:46	09:45	09:46
9	Air Conditioner (Living Room)	19:00	19:29	19:00	19:29	11:00	11:59	18:00	19:29
10	Washing Machine (*)	18:50	20:09	-	-	-	-	11:00	12:19
11	Dishwasher (*)	21:00	21:54	-	-	10:00	10:54	21:00	21:54
12	Light Bulb	21:00	23:44	21:00	23:44	23:00	23:44	21:00	23:44
13	TV	19:00	22:29	19:00	22:29	-	-	18:30	22:29
14	Oven	19:15	19:59	19:15	19:59	-	-	19:15	19:59
15	Playstation 5	21:00	22:29	21:00	22:29	-	-	18:30	22:29
16	Phone (Fast Charging)	23:45	00:29	23:45	00:29	23:45	00:29	23:45	00:29

The only appliances marked as shiftable (with an asterisk) were the washing machine and the dishwasher, as the user did not want other devices to be moved.
It was assumed that the consumer washes the dishes in the dishwasher on Wednesday, Saturday and Sunday, while the washing machine is used twice a week.

The consumption pattern for Wednesday looks like the following figure:

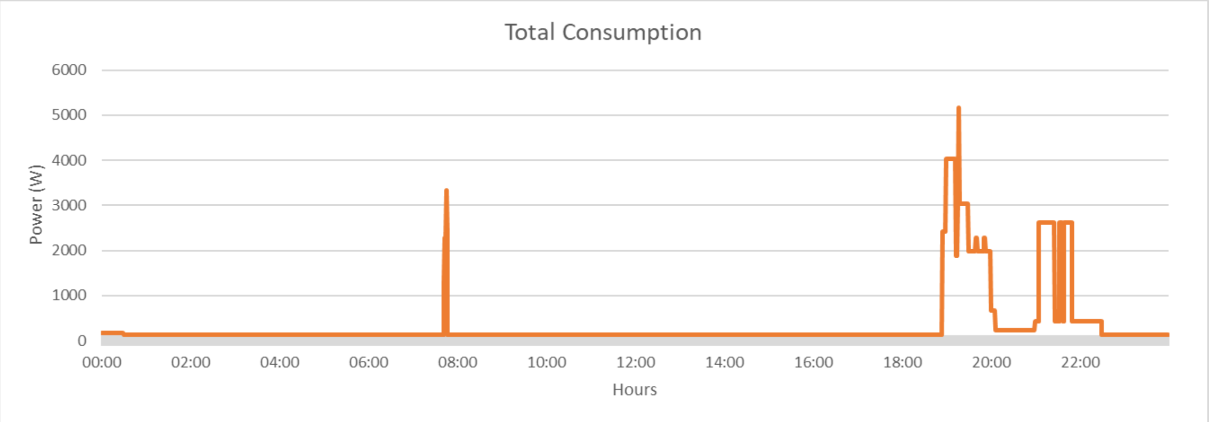


Figure 24 – Scenario 1 – Daily electricity consumption for Wednesday before HEMS.

This is a typical pattern for someone who works away from home in the summer and, when he gets home, turns on the air conditioning while he prepares dinner and sorts the dirty laundry.
As observed, there is a peak of about 5,2 kW which could be avoided if the washing machine was started later than 10:00 p.m.
If the contracted power is 6,9 or 5,75 kVA, the consumer should not have any problem, while there may be a power cut if the contracted power is less.

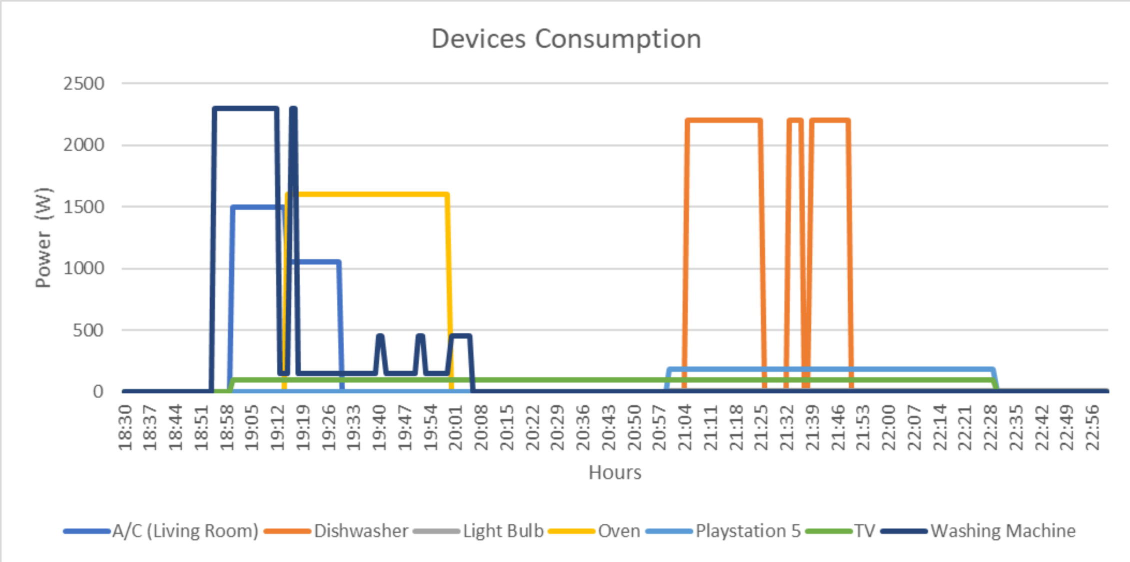


Figure 25 – Consumption of all devices that are switched on after the user arrives home

If we look more closely at the consumption of devices since the consumer entered the house, we find that we could avoid running some appliances at the same time.

While it is understandable to turn on the washing machine after arriving home to hang it up or dry it that day, there is not much leeway if the user wants to turn on another high-consumption appliance in the meantime.

So, assuming that the consumer has a HEMS at home, the system starts executing the algorithm until it finds a time when a switchable appliance is turned on or a peak that could exceed the contracted power.

Table 10 – User notification to move a switchable appliance (washing machine) to 10:10 p.m.

User Notification	Device	Time Suggestion
Please reschedule the following device	Washing Machine	10:10 p.m.

The system notifies the user that the washing machine should be postponed to a later time. Based on the user's defined bedtime and preferred schedule, 10:10 p.m. is the new suggested time to run the washing machine.

While with the single tariff the usual peak and off-peak times have no influence on the amount of the bill, the consumer can reduce the contracted power and thus the electricity bill by reducing the peak load.

Just by switching the washing machine, we can already see a reduction in peak consumption.

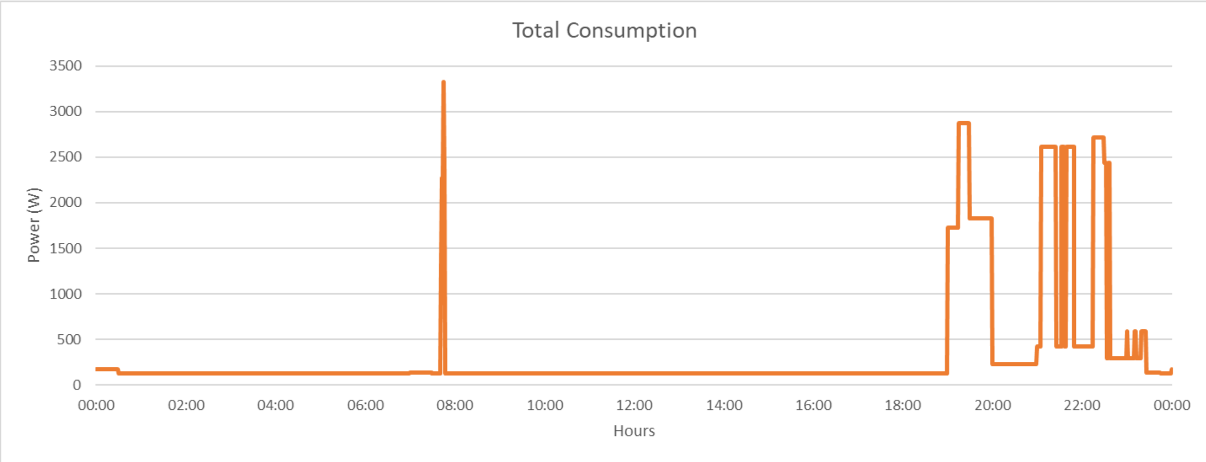


Figure 26 – Scenario 1 – Power consumption on Wednesday after the relocation of the washing machine.

Since the dishwasher is also put into operation before an off-peak time, it is also postponed. This has no direct effect on the highest peak, which is still reached at 7:15 p.m.

The system suggests moving it to 11:45 p.m., fifteen minutes (housekeeping period) after the washing machine has finished its programme.

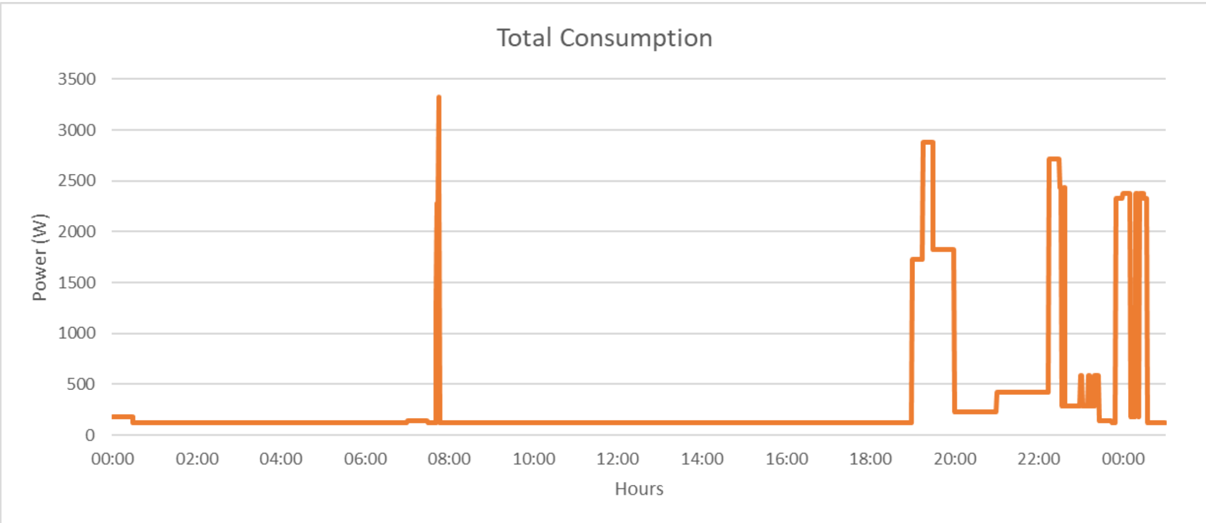


Figure 27 – Scenario 1 – Power consumption for Wednesday after HEMS

With this consumption pattern, the consumer may eventually seek a reduced contracted power as the highest peak (3,33 kW) has dropped significantly.

In case a weekly cycle was being considered for a bi-hourly rate instead, then the new scheduled times would have the period between 12:00 a.m. and 07:00 a.m. into consideration:

- New washing machine time: 12:00 a.m.;
- New dishwasher time: 01:35 a.m.

Considering a period of 24 hours (from 01:00 a.m. to 01:00 a.m.), the total consumption was 8,00 kWh, and the daily cost of energy consumption (assuming a contracted power of 6,9 kVA) is summarised in the table below, according to each tariff.

Table 11 – Costs associated with energy consumption in a day when HEMS has defined a daily cycle.

Tariff	Before HEMS	After HEMS
Single	1,16 €	1,16 €
Bi-Hourly (Daily)	1,32 €	1,11 €
Bi-Hourly (Weekly)	1,39 €	1,18 €

We can conclude that using HEMS on a day when the consumer uses both the dishwasher and the washing machine, benefits the bi-hourly tariff. It reduces the cost of the daily bi-hourly tariff by about 16%.

The bi-hourly (weekly) rate is the most expensive tariff for this case, which is not surprising given that weekly cycles usually benefit from focused weekend usage.

Although it is important to verify the results and impact of HEMS in a full day, the consumer does not always have the same usage pattern, and therefore the dishwasher and washing machines are not used every day.

Since this was a case for a summer day, if we consider an entire month (July 2021) based on the Table 9, then the monthly costs per contracted power and tariff can be summarised in Table 12.

Table 12 – Monthly Costs during July 2021 for scenario 1

Contracted Power (kVA)	Tariff	Consumed Power Amount	Contracted Power Amount	Taxes + VAT	Total Bill Amount
6,90	Single	30,76 €	13,37 €	12,07 €	56,20 €
	Bi-Hourly (Daily) - Before HEMS	34,67 €	13,79 €	13,04 €	61,50 €
	Bi-Hourly (Weekly) – Before HEMS	31,80 €	13,79 €	12,38 €	57,97 €
	Bi-Hourly (Daily) - After HEMS	32,42 €	13,79 €	12,53 €	58,73 €
	Bi-Hourly (Weekly) - After HEMS	30,37 €	13,79 €	12,05 €	56,21 €
5,75	Single	30,93 €	11,63 €	11,71 €	54,27 €
	Bi-Hourly (Daily)	32,39 €	11,93 €	12,09 €	56,41 €
	Bi-Hourly (Weekly)	30,35 €	11,93 €	11,62 €	53,89 €
4,60	Single	30,67 €	9,75 €	11,22 €	51,65 €
	Bi-Hourly (Daily)	32,37 €	10,08 €	11,66 €	54,11 €
	Bi-Hourly (Weekly)	30,32 €	10,08 €	11,19 €	51,59 €
3,45	Single	29,57 €	7,67 €	8,81 €	46,05 €
	Bi-Hourly (Daily)	32,26 €	8,19 €	9,36 €	49,81 €
	Bi-Hourly (Weekly)	30,23 €	8,19 €	8,89 €	47,30 €

Each bi-hourly tariff was considered with the off-peak time selection optimised.

Whenever not indicated, the results assume the bi-hourly rates after the algorithm runs, since before they were all more expensive than a single rate.

As observed, the consumer can potentially reduce its electricity bill at the end of the month if he/she is willing to reduce the contracted power.

Although not fully explored in the first scenario since a contracted power of 6,9 kVA was assumed, if the consumer wants to have a contracted power of 3,45 kVA instead, he/she can leverage the logic in HEMS to avoid any possible power outage.

For such a case, considering the consumer currently has a contracted power of 6,90 kVA and a single tariff, he/she can save 10,15€ for a month like this using HEMS in case it subscribes:

- Single rate tariff;

- Contracted power of 3,45 kVA.

In the whole week, the highest peak is 4,86 kW due to the iron usage on Sunday.

In case the user is willing to change the time of use of the iron, leveraging for that the logic in HEMS to avoid any possible power outage, then it can potentially save 18,1% in the final bill when compared to the original amount (56,20 €).

If we consider a more conservative approach and that the user had originally a contracted power of 5,75 kW, which was enough for him/her, then the potential save is 15,1%.

In theory, the summer is the season in Portugal for which the cooling/heating devices are more used, along with some possible peaks in the Winter.

Therefore, it is not expected that the user surpasses even more the peak power in the remaining seasons.

We can see that because the user does not regularly use the shiftable devices, so there would be no improvement in changing to a bi-hourly rate for a 3,45 kVA contract power.

4.1.2 Scenario 2

The second scenario is the characterisation of a married couple who work in an office and usually do their domestic activities at the weekend. For this scenario, the month of November was considered and therefore the respective peak and off-peak times of the weekly cycle are taken into account.

They are currently on a single tariff but would like to explore other options as they may fit in the type of users that should have a bi-hourly tariff.
In terms of user preferences, the following parameters were set:

- **Bedtime** – 12:00 a.m.;
- **Wake-up time**:
  - 07:30 a.m. (on weekdays);
  - 09:00 a.m. (on weekends).
- **Laundry/Dishes Schedule** – Day;
- **Housekeeping Period** – 35 minutes;
- **Tariff & Off-Peak Time Period –** Bi-Hourly (weekly)**;**
- **Predefined schedule** – No.

The simulation of this scenario is based on a weekly cycle (bi-hourly tariff), i.e. HEMS primarily proposes to shift loads to the period between 12:00 a.m. and 7:00 a.m. during the weekdays and according to Figure 8 on Saturdays.

However, on Sundays, since the whole day has a cheaper tariff, the system only recommends shifting/powering off devices in case there is a risk of a power outage.

This option is adopted for the cases where the consumer has a uniform tariff.

In the following table, a predefined set of devices with the scheduling time has been defined to simulate the consumer's consumption pattern during the day:

Table 13 –Devices consumption pattern across the week during autumn.

ID	Load Type	Wednesday/Friday		Other Weekdays		Saturday		Sunday	
		Start	End	Start	End	Start	End	Start	End
1	Air Conditioner (Living Room)	-	-	21:00	21:29	-	-	21:00	21:29
2	Air Conditioner (Bedroom)	-	-	-	-	-	-	-	-
3	Blender	07:50	07:52	-	-	09:15	09:18	-	-
4	Coffee Machine	08:00	08:01	08:00	08:01	-	-	10:00	10:02
5	Cooker Hood	-	-	19:30	20:09	-	-	-	-
6	Desktop (Computer)	-	-	21:00	22:39	-	-	13:30	16:49
7	Dishwasher (*)	-	-	21:00	21:54	-	-	-	-
8	Hair Dryer	07:50	07:54	07:50	07:54	-	-	-	-
9	Hair Straightening Brush	-	-	-	-	12:00	12:09	-	-
10	Iron	-	-	-	-	-	-	16:00	16:59
11	Kitchen Robot	-	-	19:30	20:14	-	-	-	-
12	Light Bulb	07:30	07:59	07:30	07:59	23:30	23:59	19:00	23:59
13	Light Bulb	23:00	23:59	19:00	23:59	-	-	-	-
14	Monitor	-	-	21:00	23:39	-	-	13:30	16:49
15	Oven	-	-	-	-	-	-	19:00	19:59
16	Phone (Fast Charging)	00:00	00:40	00:00	00:40	00:00	00:40	00:00	00:40
17	Phone (Regular Charging)	00:00	01:30	00:00	01:30	00:00	01:30	00:00	01:30
18	Playstation 5	-	-	-	-	10:00	11:29	17:00	18:59
19	Refrigerator	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59
20	Stove Burner	-	-	19:30	20:09	-	-	-	-
21	Tumble dryer (*)	-	-	-	-	12:30	13:14	12:30	13:14
22	TV	23:00	23:49	21:00	23:39	09:30	14:09	10:30	22:59
23	TV Box	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59
24	Vacuum Cleaner	-	-	-	-	-	-	15:20	15:49
25	Washing Machine (*)	-	-	-	-	11:00	12:19	11:00	12:19
26	Wi-Fi Router	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59

The devices marked with an asterisk were defined as shiftable.

This couple uses the dishwasher three times a week while having all the remaining housekeeping activities during the weekend, mainly on Sunday.

They also eat dinner away from home on Wednesdays and Fridays, so they do not spend much time at home during the week.

Since this scenario seems to be leaning towards the bi-hourly (weekly cycle) tariff, that will be the focus of the analysis. The differences between the other two tariffs will also be part of the comparison results.

Starting with the consumption power on Wednesday/Friday, the couple barely has any since it spends most of the day out of the home.

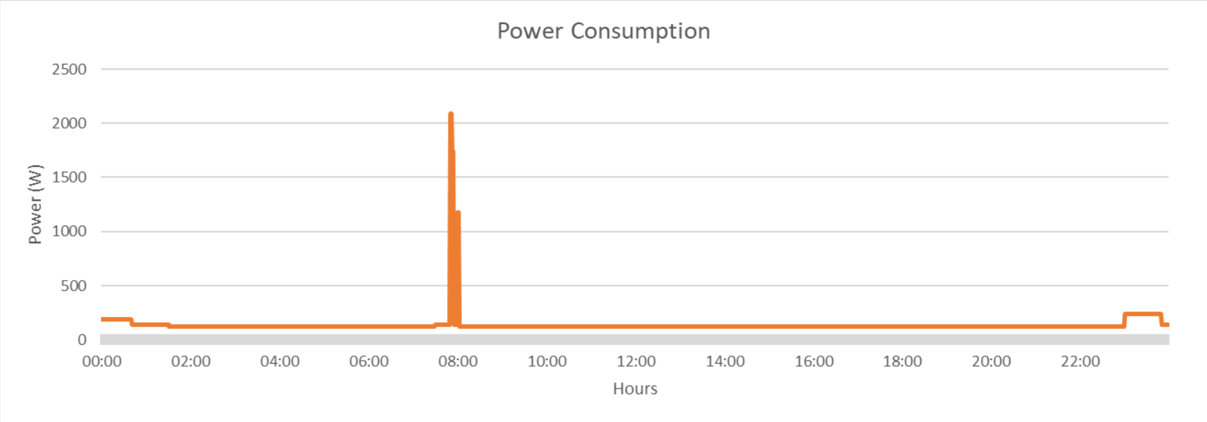


Figure 28 – Scenario 2 – Daily power consumption for Wednesday/Friday

For this case, HEMS does not have any suggestions. Therefore, everything remains unchanged.

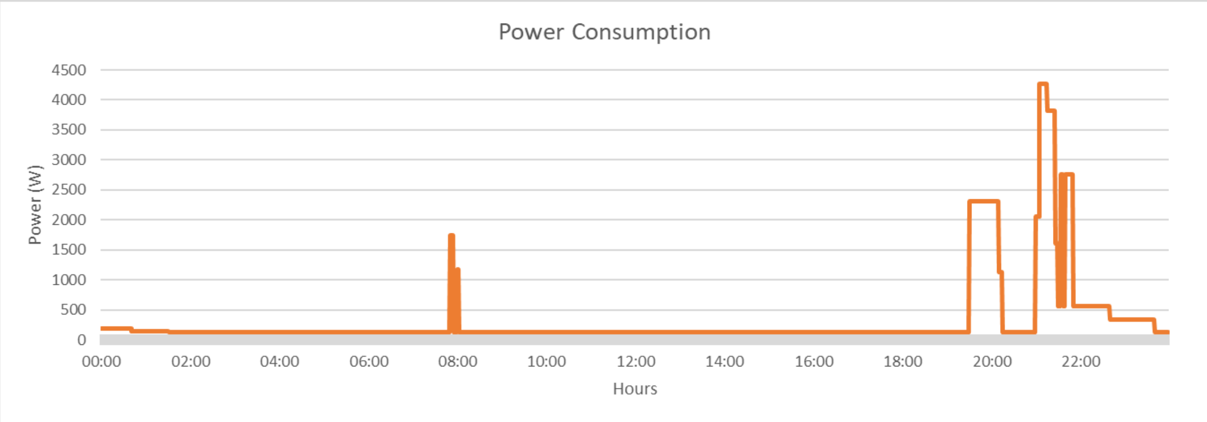


Figure 29 – Scenario 2 – Daily power consumption for remaining weekdays before HEMS

For the remaining weekdays, HEMS suggests only moving the dishwasher.
With the defined user preferences, the system verifies that the dishwasher needs to finish 35 minutes before the wake-up time, so it needs to finish before 06:55 a.m.

Considering the dishwasher programme's running time, the appliance is rescheduled from 06:00 a.m. until 06:54 a.m.

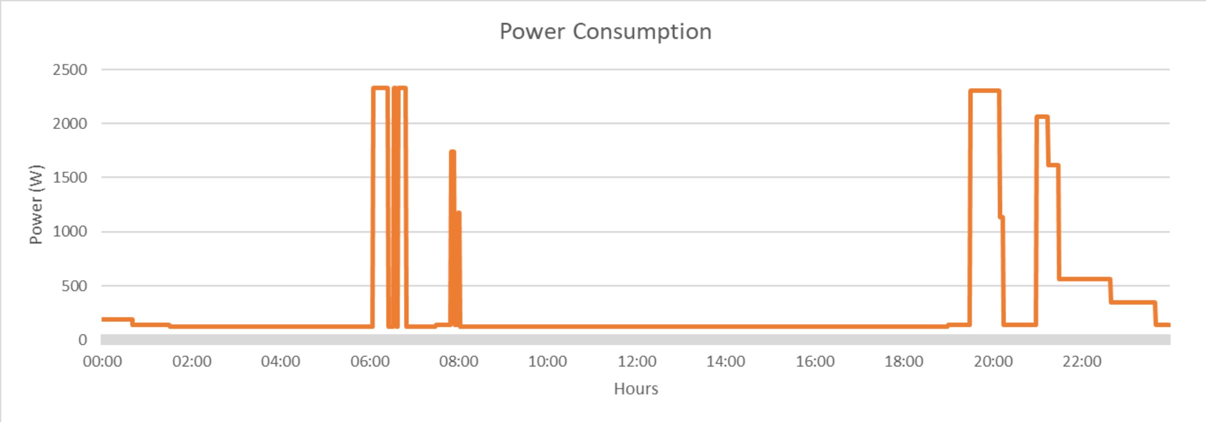


Figure 30 – Scenario 2 – Daily power consumption for remaining weekdays after HEMS

The previous peak has successfully been reduced, and the new scheduled time falls under the off-peak period of both bi-hourly tariffs.

The total consumption of that day was 7,72 kWh, and the costs per tariff and period are summarised below.

Table 14 – Summarised amounts per tariff for Monday/Tuesday/Thursday, before and after HEMS, considering a contracted power of 6,9 kVA

Before/After HEMS	Tariff	Daily Costs (Consumed Power)	Peak Costs	Off-Peak Costs
-	Single	1,12 €	-	-
Before	Bi-Hourly (Daily)	1,24 €	1,06 €	0,18 €
Before	Bi-Hourly (Weekly)	1,33 €	1,25 €	0,09 €
After	Bi-Hourly (Daily)	1,12 €	0,81 €	0,30 €
After	Bi-Hourly (Weekly)	1,21 €	1,00 €	0,21 €

Moving the dishwasher has decreased the daily costs of bi-hourly rates as expected. However, it was not enough to be more beneficial than a single rate.

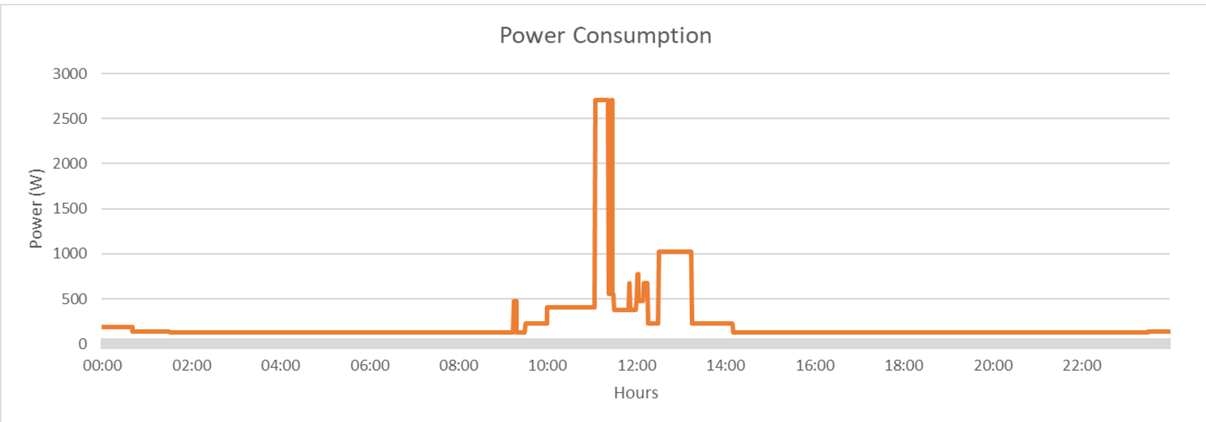


Figure 31 – Scenario 2 – Daily power consumption on Saturday before HEMS

Since most housekeeping tasks are done at weekends, the weekly cycle tariff is expected to have significantly lower costs than the single tariff.

Saturday is the only day that the weekly cycle does not have a simplified approach when it comes to define the time of use periods.
To that extent, when verifying what shiftable devices can be moved, it checks if they are entirely within an off-peak period already before proceeding to any shifting suggestion.

Figure 32 – Peak and Off-Peak Periods during Winter time on Saturdays for a weekly cycle

As per Figure 32, HEMS will try to shift any device consumption from the periods between 09:30 a.m. – 01:00 p.m. and 6:30 p.m. – 10:00 p.m.

Once in this scenario the algorithm is defined to leverage the weekly cycle, any load that may be scheduled during 01:00 p.m. and 06:30 p.m. will not be proposed to be moved by HEMS.

For Saturday, the couple is expected to run two devices that can be moved:

1. Washing machine between 11:00 a.m. and 12:19 p.m.
2. Tumble dryer between 12:30 a.m. and 01:14 p.m.

That is an excellent example for which HEMS cannot be fully automated.

In scenario 1, we can assume the user could leave the clothes already prepared before bedtime to run it during an off-peak period automatically.

In scenario 2, regardless of the time each device is expected to run, the user will always need some physical intervention to move the clothes from the washing machine to the tumble dryer because this is not a washer-dryer combo machine.
Therefore, these devices cannot be rescheduled next to each other automatically.

As the household members expect to leave the house around 01:00 p.m., they cannot leverage the afternoon off-peak time to run both the washer and dryer.

Considering HEMS starts to run for this day, before starting running the washing machine at 11:00 a.m., the user is alerted at 11:00 a.m. to shift it, once it is within a period when the electricity is more expensive.

In this case, HEMS suggests moving the load to 01:00 p.m. since it is the start of the next off-peak period.

Since on this day the couple will leave at lunch time and does not arrive home before 11:00 p.m., then the tumble dryer cannot start running in the next hours after the washing machine finishes its programmed at the proposed time.

The couple prefers not to leave any wet clothes on the machine for many hours, so they manually reschedule it to 10:00 p.m., which is an off-peak time for both bi-hourly tariffs.

Given that the washing machine finishes running at 11:20 p.m., it does allow the couple to arrive home, move any clothes to the dryer, and manually start it or reschedule it to some hours later. The couple decided to start it at midnight.

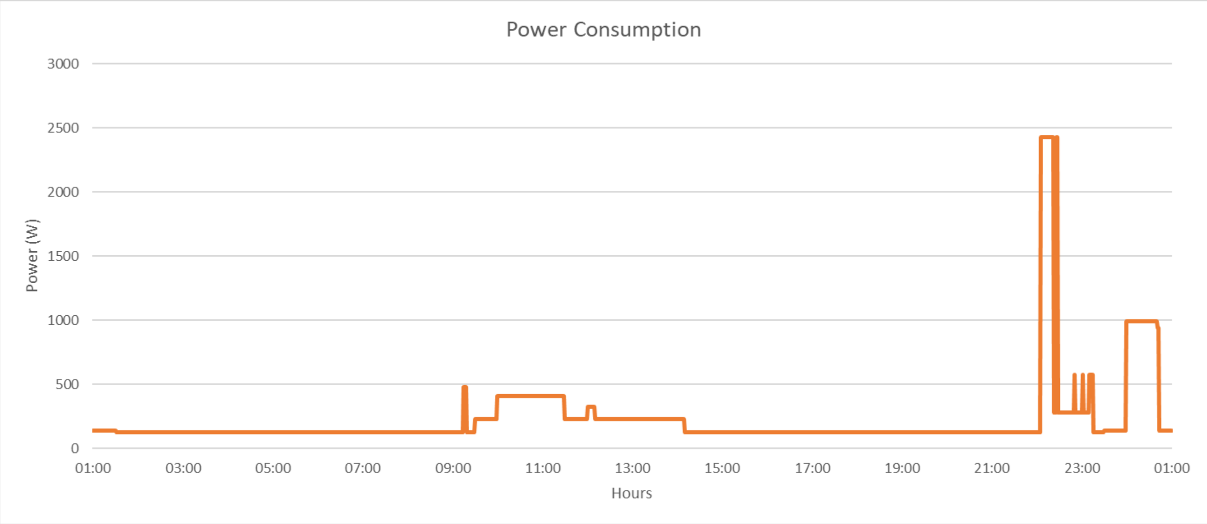


Figure 33 – Scenario 2 – Daily power consumption on Saturday after HEMS

With the decisions above, the consumption spread over the day, as observed in Figure 33.

Table 15 – Summarised amounts per tariff for Saturday, before and after HEMS, considering a contracted power of 6,9 kVA and a period between from 01:00 a.m. (Saturday) until 01:00 a.m. (Sunday)

Before/After HEMS	Tariff	Daily Costs (Consumed Power)	Peak Period Costs	Off-Peak Period Costs
-	Single	0,78 €	-	-
Before	Bi-Hourly (Daily)	0,87 €	0,75 €	0,12 €
Before	Bi-Hourly (Weekly)	0,76 €	0,53 €	0,24 €
After	Bi-Hourly (Daily)	0,73 €	0,47 €	0,27 €
After	Bi-Hourly (Weekly)	0,64 €	0,28 €	0,36 €

The weekly rate was already the cheapest before any load shifting, but it was reduced even more by 14,5% after HEMS logic.

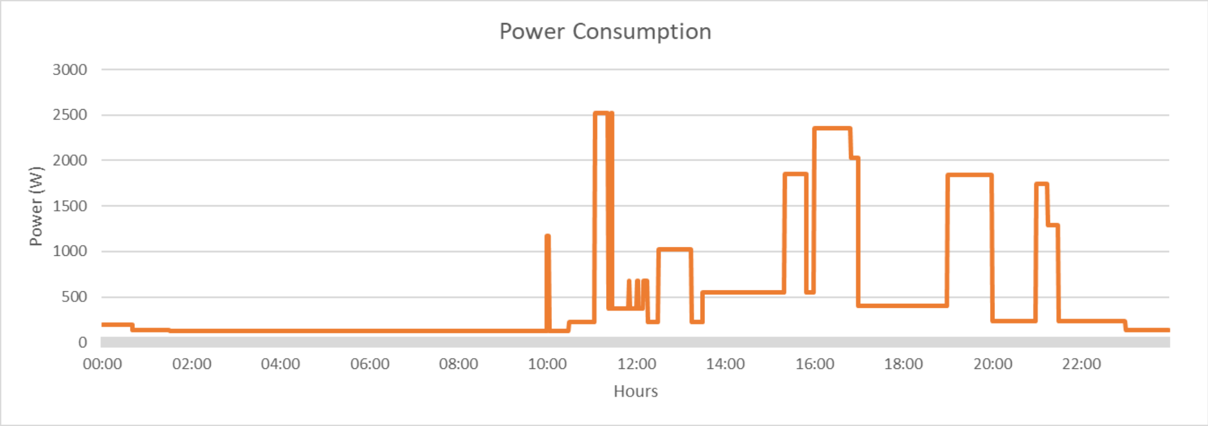


Figure 34 – Scenario 2 – Daily power consumption on Sunday

There is no need to shift any loads from a financial perspective for a weekly cycle since the whole day falls under the off-peak rate.
As observed in Figure 34, there is no relevant peak consumption for HEMS to possibly move other loads or turn off any devices.

HEMS will have no intervention on Sunday for a weekly cycle and neither for a single rate tariff.

However, for the daily cycle option of bi-hourly tariff, almost all daily consumption falls under the most expensive period (08:00 a.m. – 10:00 p.m.).

Considering the user has indicated the following times for the two shiftable devices to run:

1. Washing machine: 11:00 a.m. – 12:19 p.m.;
2. Tumble dryer: 12:30 p.m. – 01:59 p.m.

HEMS would initially propose the following period for the washing machine since this is the first shiftable device to run:

1. Washing machine: 05:40 a.m. – 06:54 a.m.

Once again, this proposed time would not fit the purpose because the tumble dryer would be only possible to run after and the couple's goal would be to use the iron only once per week and on Sundays.

We can see that the daily cycle is not the best option for this family's routine, however and even with this tariff in mind, a good alternative would be to:

- Schedule the washing machine at 10:00 p.m. and tumble dryer at 12:00 a.m.;
- Use the iron in the next day (Monday) after 10:00 p.m.

Unless the couple accepts the change in habit, for this type of tariff, they would need to change their usual habits.

Although an additional preference to define dependencies between loads can be added, that would not solve the problem presented on this day.

Below there is a table with the daily costs of Sunday, assuming the couple accepted changing their habits and postpone their activities.

Table 16 – Daily costs per tariff for Sunday after HEMS, considering a contracted power of 6,9 kVA

Tariff	Daily Costs (Consumed Power)	Peak Costs	Off-Peak Costs
Single	1,75 €	-	-
Bi-Hourly (Daily)	1,79 €	1,35 €	0,44 €
Bi-Hourly (Weekly)	1,12 €	0,00 €	1,12 €

We can observe that the weekly cycle tariff is made for those who majorly spends the day at home on Sunday and focus their housekeeping activities on the weekend.

To conclude the analysis of this scenario, the costs of November have been calculated and summarised in Table 17.

Table 17 – Monthly costs predicted during November 2021 for scenario 2

Contracted Power (kVA)	Tariff	Consumed Power Amount	Contracted Power Amount	Taxes + VAT	Total Bill Amount
6,90	Single	29,66 €	12,94 €	11,71 €	54,31 €
	Bi-Hourly (Daily) - Before HEMS	33,02 €	13,34 €	12,55 €	58,91 €
	Bi-Hourly (Weekly) – Before HEMS	30,45 €	13,34 €	11,96 €	55,75 €
	Bi-Hourly (Daily) - After HEMS	29,55 €	13,34 €	11,75 €	54,65 €
	Bi-Hourly (Weekly) - After HEMS	28,27 €	13,34 €	11,46 €	53,08 €
5,75	Single	29,83 €	11,26 €	11,36 €	52,44 €
	Bi-Hourly (Daily)	29,52 €	11,54 €	11,33 €	52,40 €
	Bi-Hourly (Weekly)	28,25 €	11,54 €	11,04 €	50,84 €
4,60	Single	29,58 €	9,43 €	10,89 €	49,91 €
	Bi-Hourly (Daily)	29,50 €	9,75 €	10,92 €	50,18 €
	Bi-Hourly (Weekly)	28,23 €	9,75 €	10,63 €	48,61 €
3,45	Single	28,51 €	7,42 €	8,56 €	44,50 €
	Bi-Hourly (Daily)	29,41 €	7,93 €	8,69 €	46,03 €
	Bi-Hourly (Weekly)	28,14 €	7,93 €	8,40 €	44,47 €

Although the costs in Table 14 and Table 15 have been based on a contracted power of 6,90 kVA, we can observe that even before HEMS, 5,75 kVA or even probably 4,60 kVA could be enough.

After HEMS logic, it is perfectly doable for the couple to have a 3,45 kVA contract instead.

Analysing the costs, due to the lower pricing for the contracted power amount in single rate tariffs, the single rate has almost the same cost as the bi-hourly (weekly).

Considering a conservative approach of the contracted power being 4,60 kVA before HEMS, we could aim to save from 49,91€ (Single) to 44,47€ (Bi-hourly – weekly), a total of 5,44€.

Along with a lower contracted power pricing, the single rate tariff has another advantage. The consumption tariff [€/kWh] decreases 3,61% for 3,45 kVA (Table 5) while in the bi-hourly rates (Table 6), the drop in price is barely noticeable.
Additionally, the VAT over the energy consumption is 13% only for contracted powers until 3,45 kVA.

So, for a single rate, we can observe that the three main components of the bill amount decrease significantly when reducing the contracted power to 3,45 kVA.

For a contracted power of 4,60 kVA, we can see that the weekly cycle tariff is the best fit for the couple.

To start realising the impact of the algorithm in terms of moving loads to an off-peak period, a summary comparison is presented in the table below:

Table 18 – Scenario 2 – Peak/Off-Peak periods comparison before and after HEMS, for a total consumption of 205,29 kWh

Tariff	Before/After HEMS	Peak Consumption	Off-Peak Consumption
Bi-Hourly (Daily)	Before	154,03 kWh	51,26 kWh
Bi-Hourly (Daily)	After	116,00 kWh	89,29 kWh
Bi-Hourly (Weekly)	Before	125,89 kWh	79,40 kWh
Bi-Hourly (Weekly)	After	102,02 kWh	103,26 kWh

We can observe that some significant part of the overall consumption has been shifted to the off-peak consumption, however for a reduced contracted power, it has not been enough to clearly justify signing a new contract for a bi-hourly tariff.

4.1.3 Scenario 3

The third scenario will be the characterisation of a couple with two children.
For this family, the following characteristics have been assumed:

- Lives in a detached house;
- Both parents work remotely from home;
- The scenario happens in May (Spring), for which the air conditioner starts to be more used;
- Contracted power of 6,90 kVA;
- Six solar panels of 340 W each;

- Single rate tariff.

The family bought a set of solar panels, with a total power of 2040 W, including installation for 3236,40€ [47] and want to also understand how much more they can save with HEMS.

The solar power generated each day is assumed to follow the values and pattern as in the Figure 11 for Spring. The solar panel characteristics and respective location are defined in the respective subsection 3.1.4.

The resulting generation power from all the solar panels can then be illustrated below:

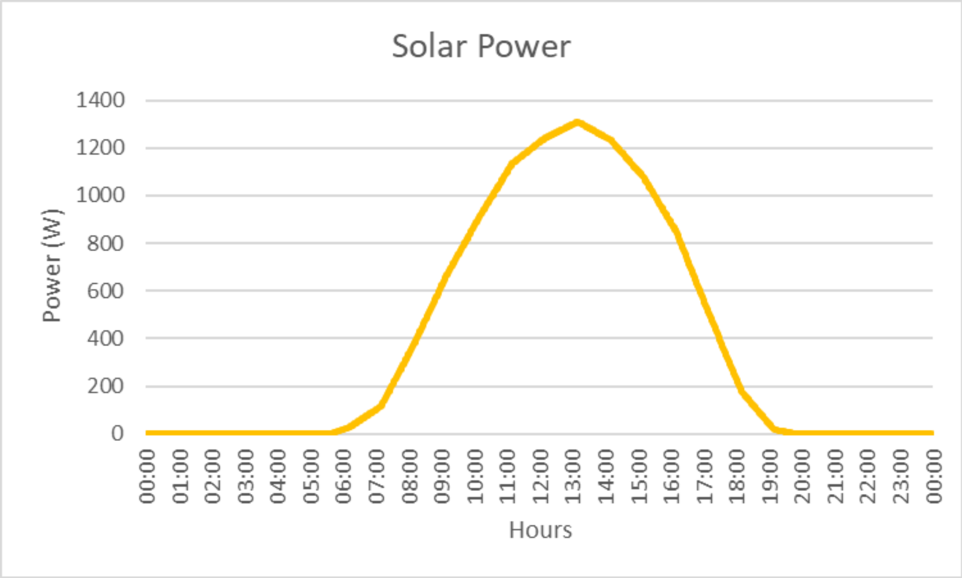


Figure 35 – Scenario 3 – Solar Power production from a 2,040-kW system in the Spring season

When it comes to the user preferences, the following parameters have been defined:

- **Bedtime** – 12:30 a.m.;
- **Wake-up Time**:
  - 07:30 a.m. (Weekdays);
  - 08:00 a.m. (Weekends).
- **Laundry Schedule –** Day**;**
- **Dishes Schedule** – Night;
- **Housekeeping Period** – 20 minutes;
- **Tariff**: Single;
- **Off-Peak Time Period** – Bi-hourly (weekly);
- **Predefined schedule** – Yes.

In the simulation of this scenario, the off-peak time is based on a daily cycle, meaning HEMS will primarily suggest moving the loads to the period between 12:00 a.m. and 7:00 a.m. for a single rate tariff simulation.

Regardless, the optimal scenario for each tariff will be included in the final results.

HEMS will always try to fetch a period during the day for which a shiftable device can be moved to maximise the power generated from the solar PV.

A pre-defined set of devices with a scheduled time was defined in the following table to simulate the consumption pattern of the consumer throughout the day:

Table 19 – Devices usage pattern across the week in May 2021

ID	Load Type	Tuesday/Thursday		Other Weekdays		Saturday		Sunday	
		Start	End	Start	End	Start	End	Start	End
1	Air Conditioner (Living Room)	12:00	16:29	12:00	16:29	12:00	14:29	-	-
2	Air Conditioner (Bedroom)	-	-	-	-	-	-	-	-
3	Blender	07:50	07:52	-	-	09:15	09:18	-	-
4	Coffee Machine	08:00	08:01	08:00	08:01	08:30	08:31	08:30	08:31
5	Cooker Hood	19:30	19:59	19:30	19:59	-	-	19:30	19:59
6	Desktop (Computer)	21:00	22:39	21:00	22:39	13:30	16:49	-	-
7	Dishwasher (*)	21:00	21:54	21:00	21:54	-	-	21:00	21:54
8	Hair Dryer	08:10	08:14	08:10	08:14	-	-	-	-
9	Laptop 1	09:00	17:59	09:00	17:59	-	-	-	-
10	Laptop 2	09:00	18:29	09:00	18:29	-	-	-	-
11	Light Bulb	00:00	00:30	00:00	00:30	22:30	23:59	20:30	23:59
12	Light Bulb	20:00	23:59	20:00	23:59	22:30	23:59	20:30	23:59
13	Microwave	08:20	08:23	08:20	08:23	08:20	08:23	08:20	08:23
14	Monitor	21:00	22:39	-	-	13:30	16:49	-	-
15	Oven	12:00	12:39	12:00	12:39	12:00	12:39	-	-
16	Phone (Fast Charging)	00:00	00:40	00:00	00:40	00:00	00:40	00:00	00:40
17	Phone (Regular Charging) 1	00:00	01:30	00:00	01:30	00:00	01:30	00:00	01:30
18	Phone (Regular Charging) 2	00:00	01:30	00:00	01:30	00:00	01:30	00:00	01:30
19	Phone (Regular Charging) 3	00:00	01:30	00:00	01:30	00:00	01:30	00:00	01:30
20	Playstation 5	21:00	22:29	21:00	22:29	-	-	18:30	21:29
21	Refrigerator	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59
22	Stove Burner	19:30	19:59	19:30	19:59	-	-	19:30	19:59
23	Toaster	-	-	07:50	07:56	07:50	07:56	07:50	07:56
24	Tumble dryer	14:00	14:44			14:00	14:44	-	-
25	TV 1	19:00	23:49	19:00	23:39	09:30	16:59	19:00	22:59
26	TV 2	21:00	23:49	19:00	23:39	14:00	16:59	19:00	22:59
27	TV Box	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59
28	Vacuum Cleaner	-	-	-	-	14:00	14:59	-	-
29	Washing Machine (*)	12:00	13:19	-	-	12:00	13:19	-	-
30	Wi-Fi Router	00:00	23:59	00:00	23:59	00:00	23:59	00:00	23:59

The devices marked with an asterisk were defined as shiftable.
This family uses the dishwasher almost every day since both meals are consumed at home while having all the remaining housekeeping activities spread across the whole week.

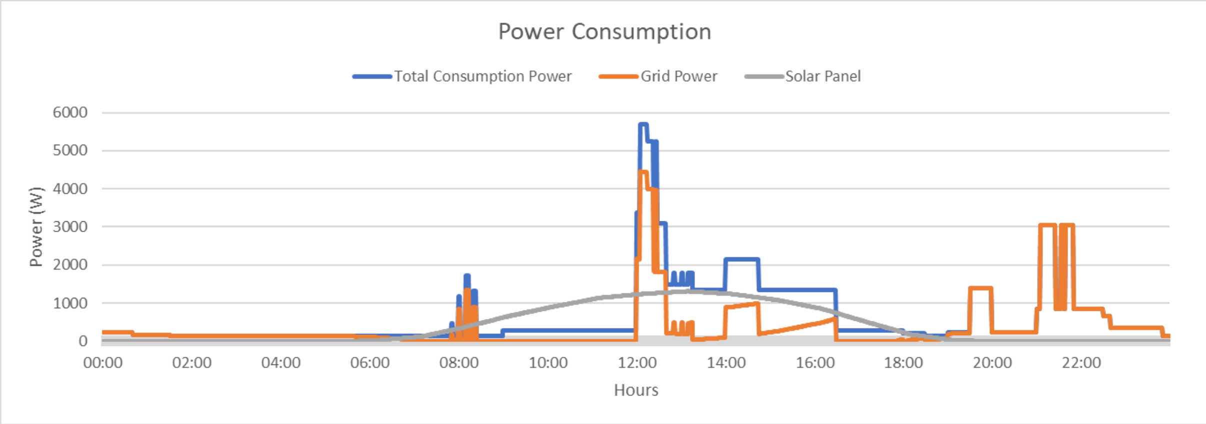


Figure 36 – Scenario 3 – Daily power consumption on Tuesday/Thursday before any logic applied

Starting with the pattern for Tuesday and Thursday, we can observe that the consumption is higher during lunchtime.

We can also see that between 10:00 a.m. and 12:00 p.m., there is no need to ask for more power to the grid, and we even see some power generated from the solar PVs that is not used.

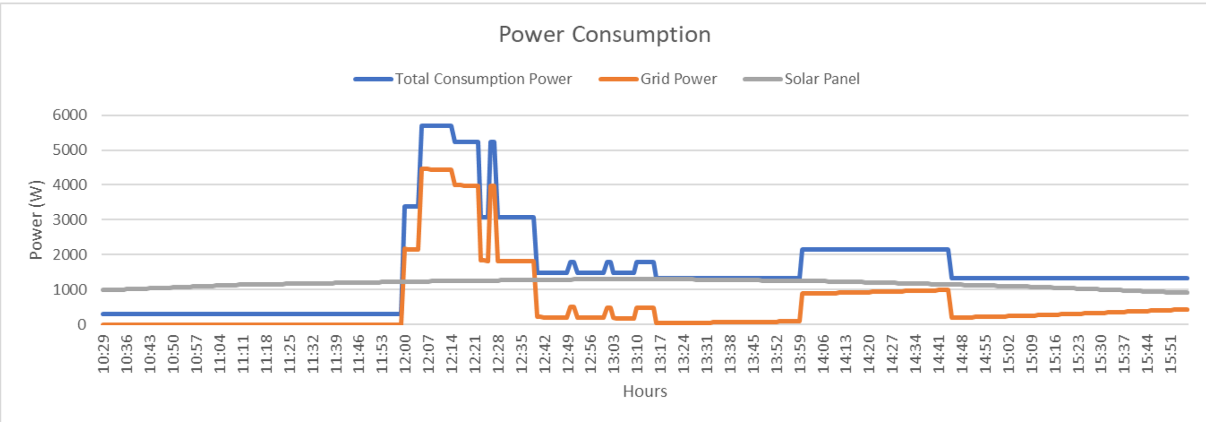


Figure 37 – Scenario 3 – Daily power consumption on Tuesday/Thursday before any logic applied, zoomed in the lunch period

The system initially detects the washing machine device is the first to be moved and tries to find the best period of 80 minutes (runtime of the washing machine) for which the unused energy generated by solar PVs is the greatest.

HEMS returns 10:39 a.m. – 11:58 a.m. as the optimal period with an energy of 1,136 kWh available.

So we have the following information available:

- Energy available on HEMS proposed interval: 1,136 kWh;
- Energy consumed by the machine programme: 0,944 kWh.

Suppose that the user moves the load to that period, then the daily consumption would look like Figure 38. We observe that although we have reduced a peak at the initially scheduled time, the shift is not ideal due to the non-regular pattern of the washing machine programme.

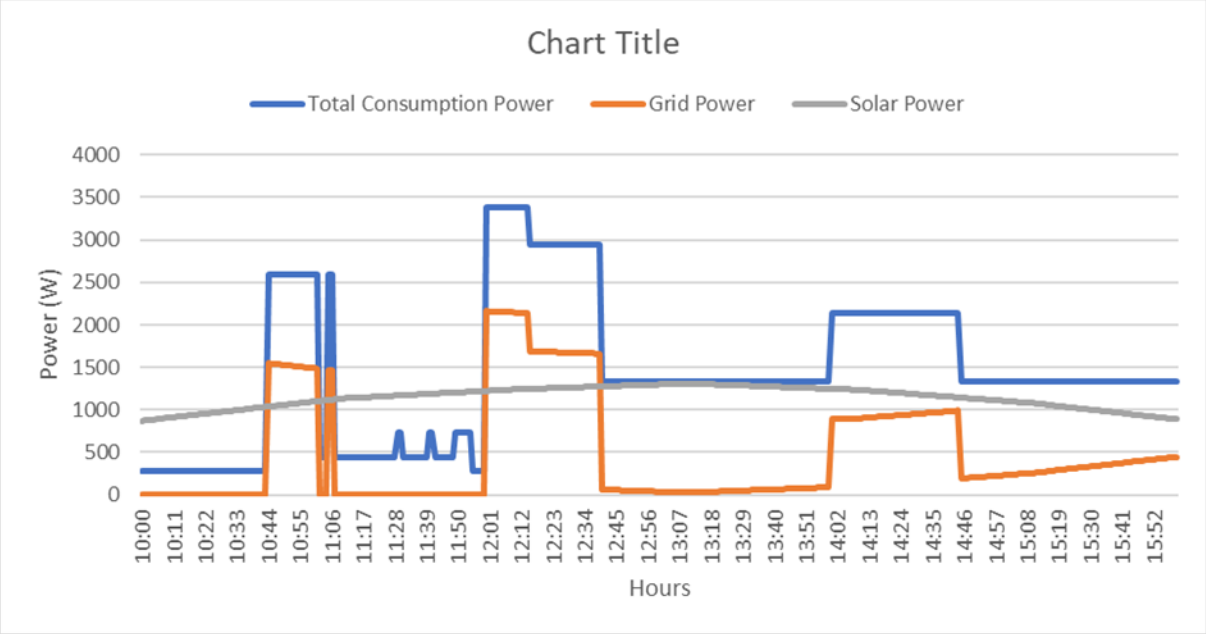


Figure 38 – Scenario 3 – Daily power consumption on Tuesday/Thursday after possibly shifting the washing machine to 10:39 a.m.

The energy required from the grid during the whole day would decrease from 8,94 kWh to 8,50 kWh.

There would be a total saving of 0,4403 kWh required from the grid. The house still requires an additional 0,5037 kWh. For a single rate tariff, this is the proposed time by the system, since there is no advantage moving the load to another time.

However, in a bi-hourly rate tariff, before proposing a time to the user, the system compares running the washing machine at a peak time and using energy from the solar PV, with shifting it completely to an off-peak period:

1. Moving the load to 10:39 a.m.:
    a. 0,5037 kWh x 0,1836 €/kWh = 0,0925 €
2. Moving to an off-peak time (e.g., 05:00 a.m.):
    a. 0,9440 kWh x 0,0924 €/kWh = 0,0872 €

Although rounded up there is no visible difference for a single day, if we multiply it by the number of times this happens in a month, moving this load to an off-peak time in the long term is better.

On top of that, if the user can sell the energy surplus from the solar PV to a supplier (e.g., 0,035 €/kWh), the second approach becomes even better.

At the end, the system proposes to move the load to 05:40 a.m. because we have set a predefined schedule, i.e., since the family had indicated prior to this day the scheduling, then the system could anticipate running this load to a prior time.

Nevertheless, we have reduced two major factors that contribute to reduce the electricity costs:

- The biggest peak power of the day has been reduced;
- Less energy from the grid is required.

Continuing HEMS logic, the next shiftable device to run is the tumble dryer. Once again, the system tries to find the optimal period to run it in order to leverage the energy from the solar PVs:

- Proposed period: 11:14 a.m. – 11:58 a.m.;

There is an energy of 0,671 kWh available on that period.
Considering the simple consumption pattern and a total of 0,6 kWh, the system proposes moving the tumble dryer to start working at 11:14 a.m. and no grid energy is needed to run the tumble dryer in the new period.

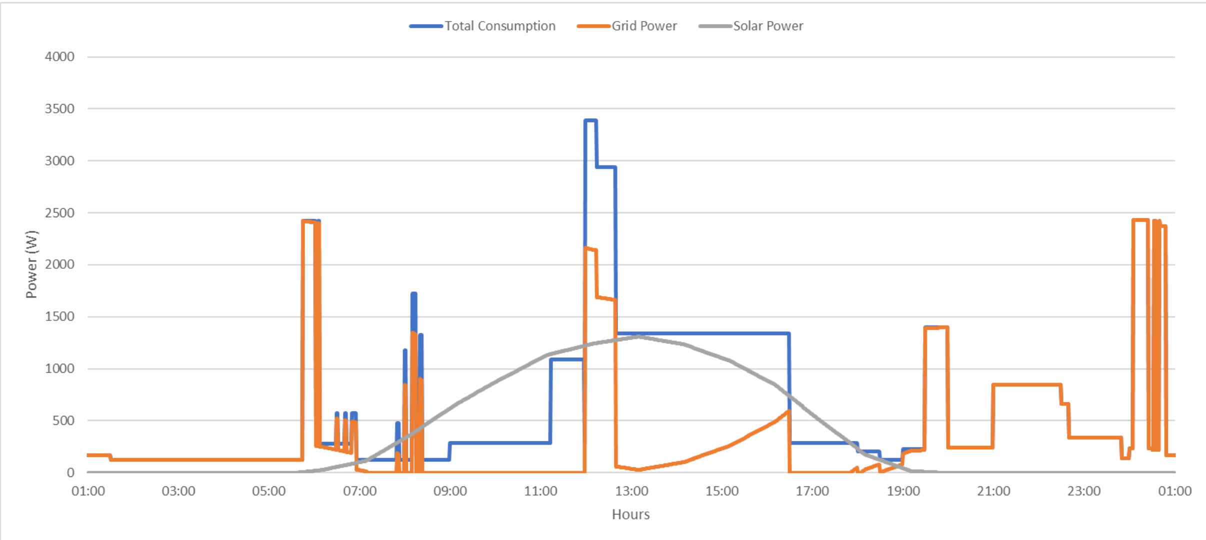


Figure 39 – Scenario 3 – Daily power consumption on Tuesday/Thursday after HEMS

The dishwasher is moved to 12:00 a.m. according to the user preferences

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Table 20 – Scenario 3 – Daily costs per tariff on Tuesday/Thursday, considering a contracted power of 6,9 kVA. The costs only consider the energy consumption tariff.

Tariff	Costs before HEMS	Costs after HEMS
Single	1,29 €	1,21 €
Bi-Hourly (Daily)	1,47 €	1,15 €
Bi-Hourly (Weekly)	1,56 €	1,24 €

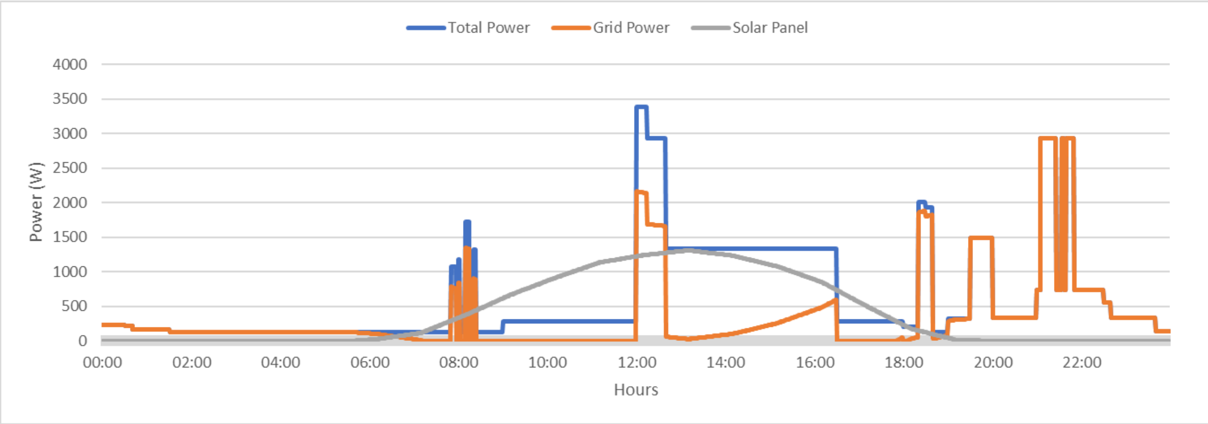

Figure 40 – Scenario 3 – Daily power consumption on the remaining weekdays before HEMS

After all the HEMS logic to the remaining weekdays:

- Dishwasher is moved to 12:00 a.m. since the energy available at lunch time was not enough to be cheaper than moving to an off-peak period.

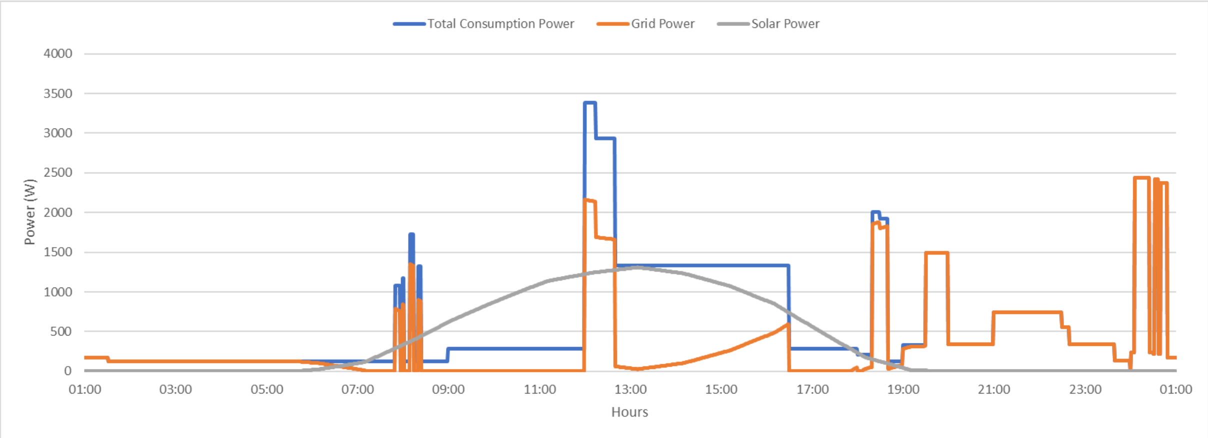

Figure 41 – Scenario 3 – Daily power consumption on the remaining weekdays after HEMS

The highest power peak at night was reduced, as observed in the figure above, but the total energy required from the grid is still the same.

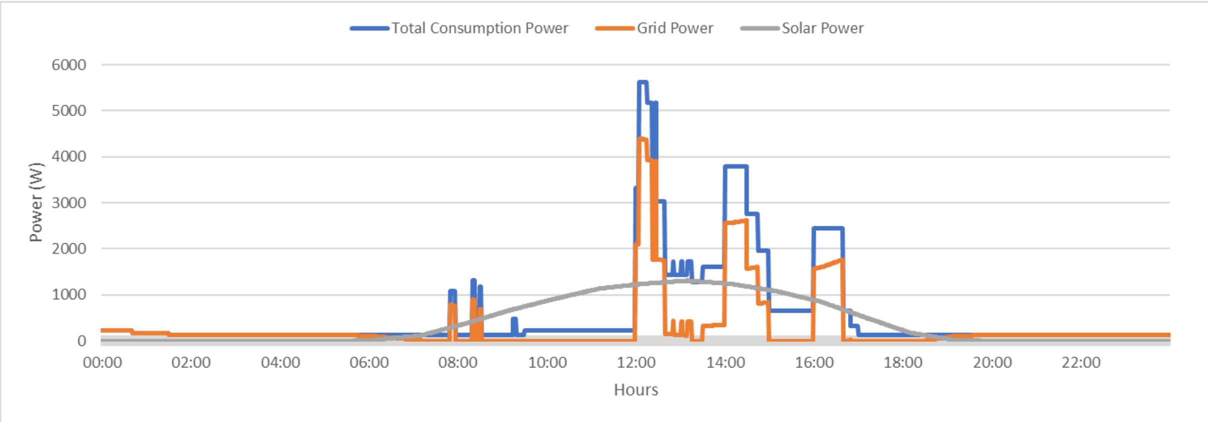

Figure 42 – Scenario 3 – Daily power consumption on Saturday before HEMS

If we observe the daily pattern of Saturday, we may have a gap before noon that we can use to move a load.

HEMS suggests the following for the day:

1. Moving the washing machine to 07:20 a.m. since it is not worth to move during a period for which the solar PV is generating energy;
2. Moving the tumble dryer to 11:10 am.

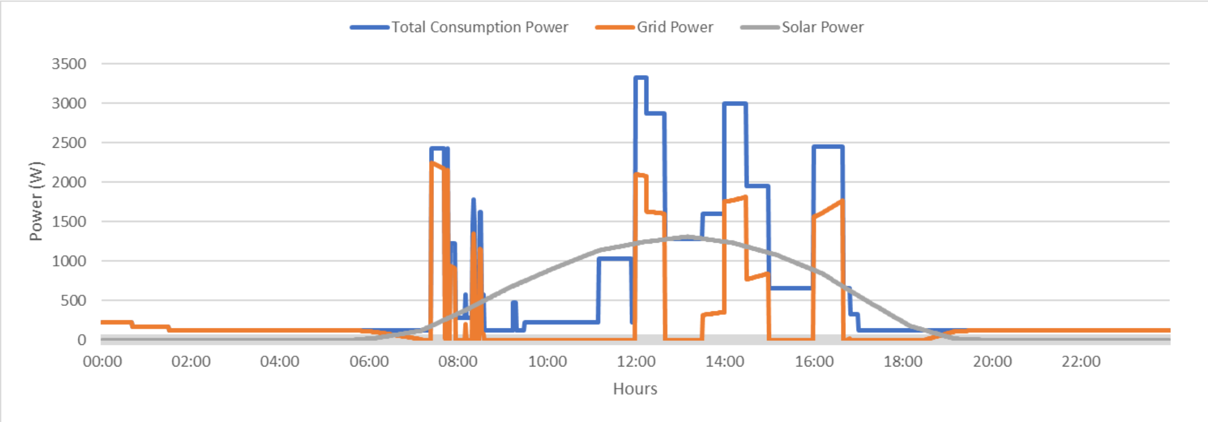

Figure 43 – Scenario 3 – Daily power consumption on Saturday after HEMS

After accepting the new proposals, we have a reduction on the energy required from the grid from 7,04 to 6,31 kWh.

The highest peak has been reduced as well, which so far means the family could easily live with a contracted power of 3,45 kVA.

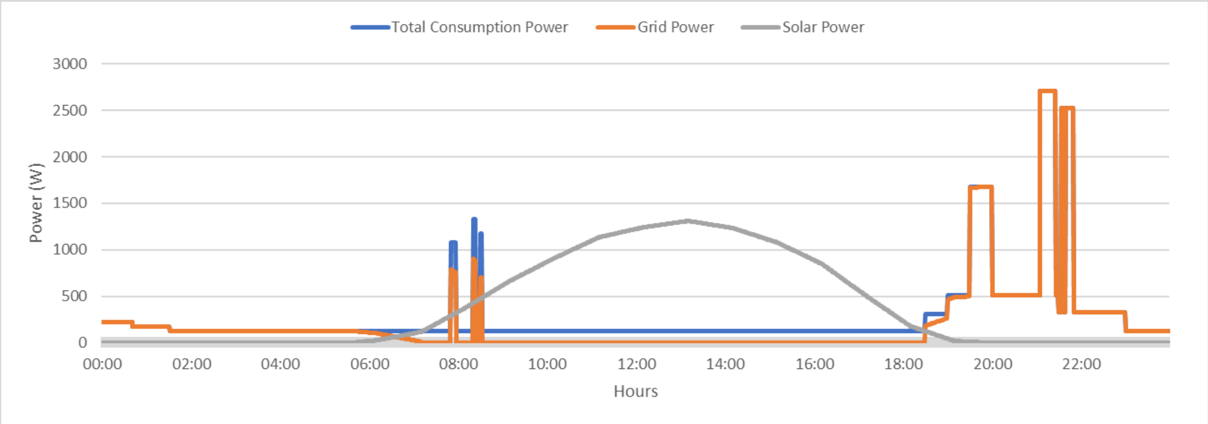

Figure 44 – Scenario 3 – Daily power consumption on Sunday before HEMS

On the last day of the week, there is no significant consumption most of the day.

For this scenario, there are three possible outcomes after the system suggests moving the dishwasher to a period between 12:10 p.m. and 01:04 p.m.:

1. The family accepts that proposed time and manually wash the dishes after dinner;
2. The family waits for the next day (Monday). In this case, it does not run at all;

3. The family does not leverage solar power and keeps it at 09:00 p.m. since it is an off-peak period from a weekly cycle perspective (defined at the user preferences).

Since the dishwasher needs to accommodate dishes from three main meals for the second outcome, the family decided to go with the third option that is more practical. Therefore, they have chosen to do nothing.

We can check if the family has decided correctly from a financial perspective if we consider the following set of data:

- Solar PV energy available: 1,166 kWh;
- Dishwasher energy consumption: 1,32 kWh;
- Energy still required from the grid due to a special pattern: 0,63 kWh;

It is an obvious choice for a single rate tariff since the energy always has the same price.

But in a bi-hourly tariff:

Tariff	Peak Period Costs	Off-Period Costs
Bi-Hourly	0,12 €	0.12 €

Rounded up, they cost the same, although we are not considering possible costs with water or revenue selling excess energy to the grid, which would always favour the outcome of keeping it in the original period.

At the end of the day, no changes were performed to the existing loads. The system would move it to 10:00 p.m. in case the user preferences were assuming the daily off-peak period.

To conclude the analysis of this scenario, the costs of May have been calculated and summarised in the Table 21 to see the impact of HEMS on families that use solar PV.

Table 21 – Monthly costs predicted during May 2021 for scenario 3

Contracted Power (kVA)	Tariff	Consumed Power Amount	Contracted Power Amount	Taxes + VAT	Total Bill Amount
6,90	Single	33,60 €	12,94 €	12,65 €	59,19 €
	Bi-Hourly (Daily) - Before HEMS	37,91 €	13,34 €	13,71 €	64,97 €
	Bi-Hourly (Weekly) – Before HEMS	37,40 €	13,34 €	13,59 €	64,33 €
	Bi-Hourly (Daily) - After HEMS	33,55 €	13,34 €	12,71 €	59,60 €
	Bi-Hourly (Weekly) - After HEMS	33,19 €	13,34 €	12,62 €	59,16 €
5,75	Single	33,79 €	11,26 €	12,30 €	57,35 €
	Bi-Hourly (Daily)	33,52 €	11,54 €	12,29 €	57,35 €
	Bi-Hourly (Weekly)	33,16 €	11,54 €	12,21 €	56,91 €
4,60	Single	33,51 €	9,43 €	11,83 €	54,77 €
	Bi-Hourly (Daily)	33,50 €	9,75 €	11,87 €	55,12 €
	Bi-Hourly (Weekly)	33,14 €	9,75 €	11,79 €	54,68 €
3,45	Single	32,30 €	7,42 €	9,46 €	49,18 €
	Bi-Hourly (Daily)	33,39 €	7,93 €	9,64 €	50,95 €
	Bi-Hourly (Weekly)	33,03 €	7,93 €	9,56 €	50,52 €

As observed, there is no clear advantage for going with a bi-hourly tariff in case the contracted power gets reduced to 3,45 or 4,60 kVA.

These values are more than enough for this family that leverages the energy produced by solar PVs to avoid using energy coming from the grid during the day.

Although the solar panel is a major advantage when it comes to save in the invoice, overall HEMS didn't capitalise the surplus solar energy that was generated for the dishwasher and washing machine, since their peak power surpasses what was still available for consumption from the solar PV.

The family would need to have more solar panels to start moving the main appliances to a period in the middle of the day.

4.2 Comparison Summary and Discussion

Finally, the following table summarises the costs and best available tariff for each scenario, as well as the potential gains.

Table 22 – Costs of the three scenarios before and after HEMS, considering the best options for the user

Scenario ID	Initial Tariff & Contracted Power	Initial Costs	Final Tariff & Contracted Power	Final Costs	Monthly Savings (%)
Scenario 1	Single & 5,75 kVA	54,27 €	Single & 3,45 kVA	46,05 €	15,1 %
Scenario 2	Single & 4,60 kVA	49,91 €	Bi-Hourly (Weekly) & 3,45 kVA	44,47 €	10,9 %
Scenario 3	Single & 6,90 kVA	59,19 €	Single & 3,45 kVA	49,18 €	16,9%

To make a fair comparison, it has been assumed the contracted power immediately above the peak power of each scenario before HEMS was implemented as the initial contracted power.

More than leveraging the time of use tariff, HEMS allows the user to save costs by potentially reducing the contracted power.

The algorithm that verifies the risk of a power outage will be important to avoid people using two or three high consumption appliances simultaneously. The user needs to decide if he/she is willing to lose the ability to switch on some devices of this kind at the same time.

The focused weekend pattern on scenario 2 provided an advantage to the weekly cycle over the other tariffs since the consumers in the house heavily focused their energy consumption on weekends.

Generally speaking, a HEMS system of this kind helps more on the reduction of the contracted power than to leverage the off-peak periods of ToU tariffs, at least in terms of costs.

By way of conclusion, moving loads to an off-peak period potentially has a major impact in the overall grid since it can avoid a possible overload in case many homes follow this approach.

5 Conclusion and Future Work

5.1 Contributions

The results of all simulations show that HEMS has a potentially positive impact on reducing the monthly bill.

To take full advantage of HEMS, instead of changing the electricity contract to a bi-hourly tariff, the consumer should focus more on reducing contracted power.

The results show that, for a 3,45 kVA contracted power, the time of use tariffs lose their main advantage since the single rate tariff components become cheaper at this power capacity.

Given the tariffs offered by EDP in Portugal, their customers should generally not consider switching from a single rate tariff if they have a reduced contracted power.

When the available capacity power is 4,60 kVA or greater, the family needs to have a particular routine focused on the off-peak periods, for the bi-hourly tariff to be the right choice.

A daily cycle for a bi-hourly tariff was the least efficient for the tested scenarios since it should be focused on very specific users. It is probably the right choice for anyone who barely has any relevant energy consumption at home during the day.

The weekly cycle in a bi-hourly tariff should be more suited for secondary residences, only used on weekends, or for people who usually only spend the day at home on Sundays or during the specific off-peak periods on Saturdays.

As the power through day never reached a value near the standard contracted value (3,45), there was no need to ask the user to switch off some devices eventually. For example, with the washing machine, dishwasher, and tumble dryer running at off-peak times and not simultaneously with other devices, avoids having a possible power failure at home.

As observed in the second tested scenario, a system of this kind should not be fully automated. For some cases needs to ask the user's approval because there may be no ideal periods to shift a set of devices. Therefore, some compromises may be made.

Additionally, and even bringing the devices consumption history of the house owners into account, people do not stick to a unique routine every day, every year, leading to a more user-intervention focused system than an automated application.

5.2 Future Work

As future work, since the consumption pattern of some devices was simplified, a more realistic approach should be considered in future simulations.

When it comes to the algorithm that was used, HEMS should also account for dependencies between devices before proposing any time to move a shiftable load. Since only the dishwasher, washing machine and tumble dryer are classified as shiftable devices on this thesis, other types of possible shiftable devices should be explored to try to leverage the bi-hourly tariffs, but always without compromising the wellbeing of the consumers.

The logic to avoid a power outage can also be more explored for residences with lower contracted power since in this thesis, the peak instant power after using HEMS was usually lower than 3 kW.

As future work, the implementation should be extended to another platform such as NodeRed by IBM, in order to have a more dynamic simulation tool to easily test more scenarios.
Other countries' electricity tariffs should also be explored to understand the applicability of this algorithm in other markets.

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