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OPTIMIZING ENERGY USE AND SAVINGS FOR RESIDENTIAL PROSUMERS WITH AN ENERGY MANAGEMENT SYSTEM AS-A-SERVICE

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RESUMEN DE LA TESIS PARA OPTAR AL GRADO DE MAGÍSTER
EN CIENCIAS DE LA INGENIERÍA, MENCIÓN ELÉCTRICA y
MEMORIA PARA OPTAR AL TÍTULO DE INGENIERO CIVIL ELÉCTRICO
POR: MARTÍN ANDRÉS DE JESÚS VICENCIO ULLOA
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OPTIMIZANDO USO DE ENERGÍA Y AHORROS PARA PROSUMIDORES RESIDENCIALES CON UN SISTEMA DE GESTIÓN DE ENERGÍA COMO SERVICIO.

La creciente adopción de generación distribuida impulsa el interés en los Sistemas de Gestión de Energía (EMS) para optimizar el consumo energético. Esta investigación evalúa la viabilidad de EMS basados en la nube para reducir costos en hogares con generación solar. Utilizando diversas fuentes de datos, se desarrolló una simulación integral para medir los ahorros económicos de un EMS y se implementó un prototipo experimental.

La simulación aborda escenarios variados: tipos de hogares, tarifas, estacionalidades y niveles de satisfacción. Los resultados indican que hogares con consumos energéticos flexibles, como calentadores de agua y vehículos eléctricos, podrían lograr ahorros anuales de 118 USD en promedio con la tarifa BT1. Con una tarifa multi-parte, el ahorro anual promedio aumenta a 195 USD para estos hogares.

Se implementó un prototipo de EMS como Servicio (EMaaS) en un piloto de tres semanas, utilizando plataformas y estándares abiertos. Este enfoque demostró ventajas, en términos de desarrollo, en comparación con enfoques anteriores. A pesar de no haber alcanzado ahorros económicos, los desafíos prácticos encontrados contribuyen conocimientos valiosos para perfeccionar las herramientas desarrolladas.

En resumen, los resultados resaltan el potencial de los EMaaS para la gestión de energía y la sostenibilidad en hogares con generación distribuida.

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The growing adoption of distributed generation is driving interest in Energy Management Systems (EMS) as a means to optimize energy consumption. This research evaluates the viability of cloud-based EMS to reduce costs in homes with solar generation. Using various data sources, a comprehensive simulation was developed to assess the economic savings achievable with an EMS and an experimental prototype was implemented.

The simulation addresses a variety of scenarios: household types, tariffs, seasonality, and satisfaction levels. The results indicate that homes with flexible energy consumption, such as water heaters and electric vehicles, could achieve average annual savings of USD 118 with the BT1 tariff. With a multi-part tariff, the average annual saving increases to USD 195 for these homes.

An EMS as-a-Service (EMaaS) prototype was implemented in a three-week pilot, using open platforms and standards. This approach demonstrated advantages, in terms of development, compared to previous approaches. Despite not having achieved economic savings, the practical challenges encountered contribute valuable knowledge to refine the developed tools.

In summary, the results highlight the potential of EMaaS for energy management and sustainability in homes with distributed generation.

A mis padres, Cristina y Claudio.

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Hago público mi agradecimiento a todas las personas que me acompañaron durante estos años de vivencias universitarias. A mis amigos de plan común Sofía, Fabián y Luciano, así como a mis compañeros de especialidad, también conocidos como *Sumaria2*. Agradezco especialmente a los amigos de toda la vida: María José, Sofía, Valentina, Juan Ignacio, María Ignacia, Felipe, Ramiro, Vicente y Daniel, por haber alegrado mis días en los momentos difíciles. Agradezco también a mi profesor guía, Patricio Mendoza, no solo por sus enseñanzas, sino también por su calidad humana y por haberme dado la oportunidad de trabajar con él. Finalmente, agradezco enormemente a mi familia por su amor y apoyo incondicional.

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1. Introduction

1.1. Research Motivation

There are mainly two reasons for the realization of this research. In the first place, the importance of promoting practical research on demand response (DR) issues. Secondly, the benefits that energy management systems (EMS) may provide for small consumers with generation capacity (prosumers), who represent a growing market in Chile.

Regarding the first reason, DR refers to changes in the energy consumption of end-users at different time scales in response to certain incentive signals. DR is expected to play a key role in the transition to low-carbon energy systems because it can provide flexibility, among other benefits, to energy systems with a high penetration of renewable generation [1–4].

When reviewing barriers for DR some authors have criticized the lack of DR understanding and the simplicity of models used to predict demand behavior [5]. Others have called for more empirical evidence to improve DR modeling [6] and have highlighted the value of pilot programs to improve DR effectiveness [7]. Nolan S. and O'Malley M. stated in 2015 [8] there was a "Chicken and Egg" situation in which the limited understanding of the DR value compromised the investment in DR deployment. As a result, there was limited experience and data about DR. Then, the lack of evidence led to limited understanding of the DR value. Nowadays, that situation may have changed in markets where pilot programs and practical experiences led to better understanding of demand behavior and DR value assessment [9–13]. However, the "Chicken and Egg" situation still applies in developing countries like Chile where, to the best of my knowledge, DR has not been widely developed. Nevertheless, policy-makers are giving due consideration to DR. According to Chile's long-term energy planning, the demand capacity of DR loads (electric vehicles, heating, ventilation, air conditioning and H2 production) is expected to grow between 20.6 and 24 GW by the year 2060 [14].

If we want to consider active participation of the demand side in a future low-carbon grid, then we need to understand the behavior of users under DR schemes. Since users in different locations would behave differently, we should not rely solely on findings about DR in places where it has been developed. In this sense, practical research is needed to better understand the behavior of local consumers and assess the value of DR in Chile.

Regarding the second reason, distributed generation (DG) is rapidly growing in Chile. The added capacity of DG has grown from 4,8 MW to 157 MW between 2016 and 2022 [15], according to the capacity declared under the Chilean regulation known as *Net billing*. Where small prosumers can sell their generation surplus (what is not consumed instantly) at the energy component of their distribution tariff [16]. Since the selling price is typically lower, small consumers that invest on generation means would maximize the return on their investment by maximizing their self-consumption.

To maximize their self-consumption, prosumers could implement an EMS that predicts weather conditions, monitors their generation and consumption, and schedules their energy usage accordingly. However, for small prosumers it may be more convenient getting the capabilities of an EMS by subscribing to a service, rather than implementing a custom system. In this sense, some authors have explored the concept of cloud-based solutions for an EMS [17–22], sometimes referred to as: Energy Management as-a-Service (EMaaS). This type of solution could bring the known benefits of cloud computing; such as scalability, flexibility and interoperability, to small-scale energy management. The EMaaS could also allow the aggregation of small prosumers for more DR purposes, like ancillary services. Therefore, it is worth to explore EMaaS solutions that could improve DG profitability for prosumers and enable DR applications.

In this research, I explore the value of an EMS for prosumers in Chile and propose a stack of technologies to provide them EMaaS. Because the proposed stack consists mainly of open-source technologies, anyone could do a similar implementation for their use case.

1.1.1. Enerdis

The work done in this thesis arises from an entrepreneurship that is developed jointly with other master students at the University of Chile. This initiative, called Enerdis, seeks to empower small consumers and make them active agents in modern electrical grids. We firmly believe that the energy transition to low-carbon will require the engagement of every agent involved in the energy chain.

1.2. Hypotheses

There are two hypotheses to be tested in this research.

H_1: Consumers with solar production (prosumers) can achieve greater savings by adopting an EMS. Particularly those who rely on electricity as their main energy source.

H_2: Moving the main functions of an EMS to the cloud can ease its implementation in residential settings.

1.3. Research Objectives

To test the stated hypotheses, the general objective of the research is as follows.

GO: To evaluate the potential of a cloud-based EMS for reducing the energy costs of prosumers in Chile's metropolitan region (RM).

For its completion, the following specific objectives are defined.

SO_1: To characterize the typical energy consumption and generation of households in the RM.

SO_2: To simulate the benefits of an EMS for various types of prosumers subjected to different tariff structures.

SO_3: To design and develop a scalable and user-friendly cloud-based EMS prototype.

SO_4: To deploy the prototype in a real household to evaluate its effectiveness in reducing energy costs and improving energy management.

SO_5: To analyze the results of both experiments (simulation and prototype) and identify practical challenges and opportunities for further improvement of the EMS.

1.4. Research Scope

This study aims to evaluate the potential of a cloud-based EMS to reduce energy costs for prosumers in Chile's metropolitan region (RM). To achieve this, I will simulate the benefits of an EMS for various types of prosumers under different tariff structures, with a specific focus on reducing operational costs. The economic analysis will not consider capital costs for any asset (including the EMS itself) involved in the prosumer optimization problem, nor will it evaluate medium-to-long-term horizons. This is because such evaluations require forecasting many variables into the future and are outside the scope of the research. Instead, the study seeks to answer a specific question: How much can prosumers who have already invested in some set of technologies reduce their energy costs with an EMS?

Regarding the prototype, I will design and build a scalable and user-friendly cloud-based solution with only the core functionalities required to provide EMaaS. The prototype's main purpose is to act as a proof of concept and help us identify practical challenges and opportunities for this type of solution. The practical experience gained from its implementation will allow us to compare the theoretical formulation of the prosumer problem with a real-world case, which will help us improve future iterations of this or other prototypes.

With this research I want to provide insights into the feasibility of using a cloud-based EMS to reduce energy costs for prosumers in the RM, while keeping in mind the practical considerations.

1.5. Document Structure

The rest of the document is structured as follows. In the second chapter, Background, I review various concepts and technologies closely related to the topic of this study. The third and fourth chapters describe the primary activities of the thesis, namely the Simulation and the EMS prototype. Each of these chapters is divided into two sections, one for methodology and one for results. In the fifth chapter, Discussion, I analyze and discuss the results from the previous chapters. Finally, the conclusions chapter summarizes the research objectives and provides suggestions for future work in this field.

2. Background

In this chapter, I review four topics that are closely related to the subject of this research and present the tools used in this thesis. The first topic is “Modern Distribution Grids,” which refers to new ways of providing energy to customers, different from the traditional concept of electrical grid. The second topic is “Smart Homes in the Smart Grid,” which explores how technology can help manage energy consumption in homes. The third topic is “Energy Management as-a-Service,” which describes the key differences between this work and previous ones on the issue of cloud-based EMS. Then, the section “Demand Response Signaling” looks at the standards available for communicating signals that aim to modify energy usage on the demand side. Lastly, I introduce three tools that were used to achieve the research objectives. This chapter gives an overview of the essential concepts and tools used throughout the research.

2.1. Modern Distribution Grids

The grid term is used for an electrical system that supports all or some of the following four operations: electricity generation, electricity transmission, electricity distribution, and electricity control. Traditionally, the grid used to operate in a unidirectional fashion, carrying power from a few generators to many customers through the transmission and distribution networks. On the other hand, the modern grid or *Smart grid* (SG) considers bidirectional flows of electricity and information to create an advanced energy delivery network. Table 2.1 from [23] gives a brief comparison between the traditional grid and the SG.

Some of the main attributes of the SG are the ability to accommodate variable/intermittent generation, to offer products designed for each type of user, to create opportunities for new markets, to improve the quality of the electricity supply, to improve the resilience of the system, and to promote generation based on clean energy [25].

Back in 2007, the National Institute of Standards and Technology of the United States (NIST) was assigned the “primary responsibility to coordinate development of a framework that includes protocols and model standards for information management to achieve interoperability of Smart Grid devices and systems”. In 2010 the institute published their first version of the framework for smart grid interoperability [24], which presented a conceptual reference model of SG. The “Smart Grid Conceptual Reference Model” identifies seven domains. The actors of each domain are described in table 2.2 and their interactions are simplified in figure 2.1.

Table 2.1: Brief comparison between SG and traditional grid [23].

Traditional Grid	**Smart Grid**
Electromechanical	Digital
One-way communication	Two-way communication
Centralized generation	Distributed generation
Few sensors	Sensors throughout
Manual monitoring	Self-monitoring
Manual restoration	Self-healing
Failures and blackouts	Adaptive and islanding
Limited control	Pervasive control
Few customer choices	Many customer choices

Table 2.2: Domains and Actors in the Smart Grid Conceptual Model [24].

Domain	**Actors in the Domain**
Customers	The end users of electricity. May also generate, store, and manage the use of energy. Traditionally, three customer types are discussed, each with its own domain: residential, commercial, and industrial.
Markets	The operators and participants in electricity markets.
Service Providers	The organizations providing services to electrical customers and utilities.
Operations	The managers of the movement of electricity.
Bulk Generation	The generators of electricity in bulk quantities. May also store energy for later distribution.
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity.
Distribution	The distributors of electricity to and from customers. May also store and generate electricity.

This master's thesis considers the application of an EMS for the residential-customer domain provided through communication technologies by a third party from the service provider domain.

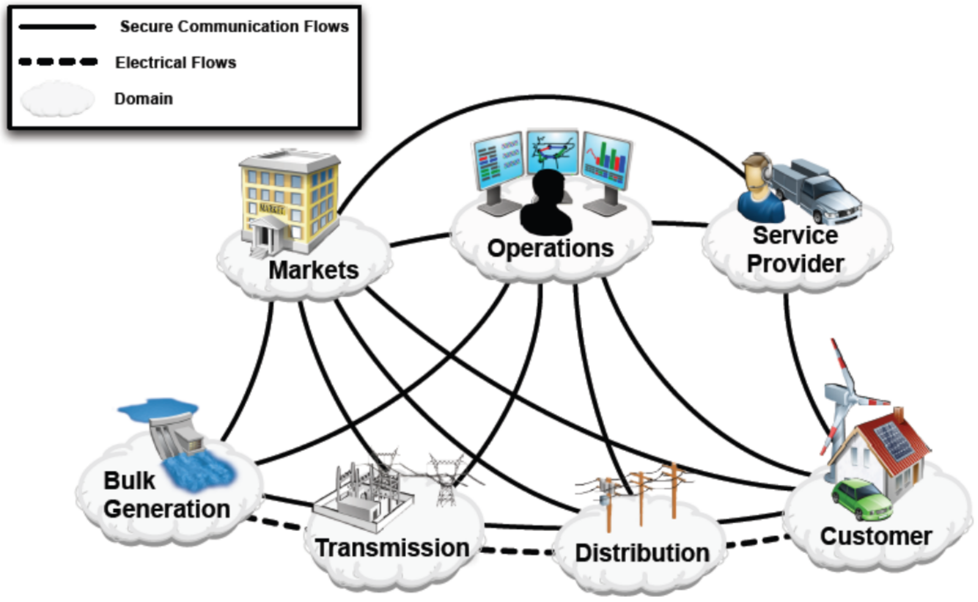

Figure 2.1: Interaction of actors in different Smart Grid Domains through Secure Communication Flows and Electrical Flows [24].

2.1.1. Demand response and BT1

In simple terms, DR refers to changes in the electricity consumption of an end-user from its normal demand in response to various signals (direct or indirect), such as varying electricity prices [26]. In the beginning, demand response was conceived as a countermeasure for critical peak-load events. Nowadays, the concept includes a variety of services such as demand curve flattening and frequency regulation, among others [27].

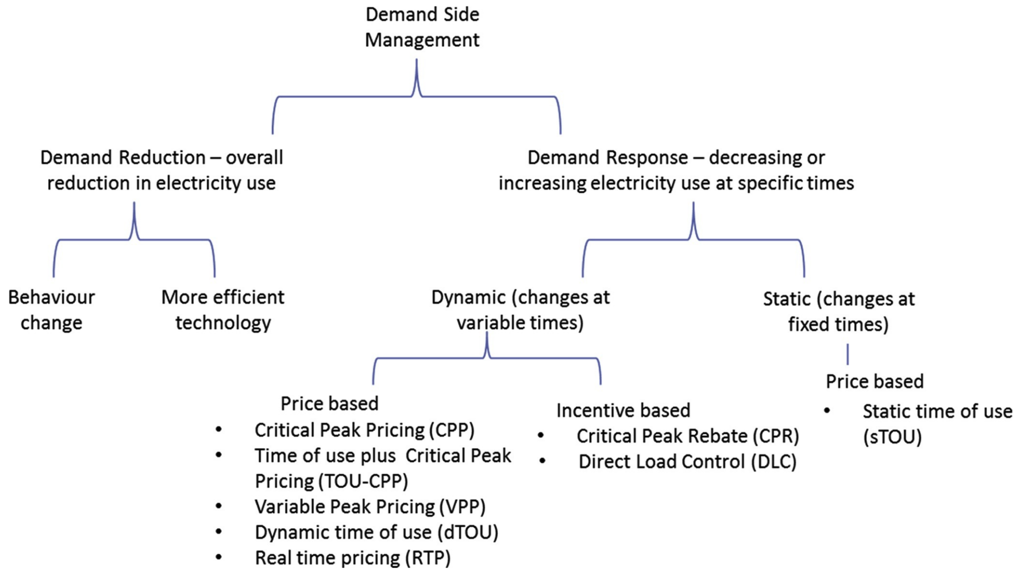

Figure 2.2: Classifications of demand reduction and demand response [6].

Customers in the SG can provide energy services by enrolling in demand response programs (DRP). The main classification of DRP is derived from the work in [26, 28], which indicates that there are two types of DRP where end-users can enroll voluntarily: incentive-based and price-based. For the first category, the end-user receives compensation for their consumption variation. In the second, the user accesses prices that vary over time to buy energy. Parrish *et al.* [6] provide a classification that follows the same principles and distinguishes between static and dynamic interventions. Table 2.3 and figure 2.2 present their classification.

Table 2.3: Types of pricing and other economic incentives in residential DR [6].

Price based schemes	**Description**
Static time of use	Prices vary by time of day between fixed price levels and over fixed periods. These may vary by season.
Critical peak pricing	Prices increase by a known amount during specified system operating or market conditions. This applies during a narrowly defined period and is usually applied only during a limited number of days in the year.
Time of use plus critical peak pricing	Critical peak pricing overlaid onto time of use pricing. TOU-CPP therefore has two pricing components – daily time of use pricing, and occasional critical peak pricing applied during critical system events (figure 2.2 refers to these as TOU-CPP-D and TOU-CPP-CE respectively)
Variable peak pricing	Similar to time of use, but the peak period price varies daily based on system and/or market conditions rather than being fixed.
Dynamic time of use	Prices vary between fixed price levels, but the timing of different prices is not fixed.
Real time pricing	Price can differ on a daily basis and change each hour of the day (or more frequently) based on system or market conditions.
Incentive based schemes	**Description**
Critical peak rebate	Similar to CPP, but customers are provided with an incentive for reducing usage during critical hours below a baseline level of consumption.
Direct load control	Customers are provided with an incentive for allowing an external party to directly change the electricity consumption of certain appliances. Customers can usually override control, although they may lose some incentive. DLC may also be combined with time varying pricing.

In Chile, residential customers are subject to standardized tariffs, some of which include time-of-use characteristics. However, the most common tariff is BT1, which stands for *Baja tensión 1* (low voltage 1). This is the default tariff for practically every household in Chile and is basically a flat and volumetric tariff. Meaning that it charges for the amount of energy imported form the grid in a month, regardless of the time of the day in which it was consumed. The monthly cost of energy for a customer that contracts BT1 is described in equation 2.1, where $TC_{h,m}$ is the total cost for household h in month m, given its energy imports $E_{h,m}$ in that month.

$$TC_{h,m} = D_{admin} + E_{h,m} \cdot (T + G_{energy} + G_{capacity} + PS + D_{capacity}) \tag{2.1}$$

For simplicity this equation omits winter charges, which apply to customers who deviate largely from their typical monthly consumption during winter months, i.e., from April to September. It also omits cross-subsidies, which are charged to customers who consume more than 200 kWh in some regions of Chile [29]. With BT1, the energy bill has a fixed charge per user (D_{admin}), for administrative costs of the distribution company, and a volumetric charge composed of different components. First, a transmission component (T) that goes to pay the network tariff. Then, two generation components to pay the generators for both the energy (G_{energy}) and capacity ($G_{capacity}$) they provide to the grid. Then, a small part of the volumetric charge that goes to fund the independent operator of the grid and other public services (PS). Lastly, the distribution component to pay for capacity in the distribution network ($D_{capacity}$).

2.1.2. Net billing in Chile

Net billing and *net metering*, are regulatory policies that allow customers who generate their own electricity, typically through solar panels or other renewable sources, to offset part of their energy consumption with the excess electricity they inject to the grid [30]. They differ from each other, in how the offset is recognized. While in net metering schemes each kWh exported to the grid offsets an imported kWh (like running back the meter), in net billing the energy exported to grid is measured separately from the imports, and it discounts an amount from the energy bill (like selling it back to the grid at a certain price)[30].

In Chile, the net billing regulation was introduced in 2012, with its rules applying from 2014, as part of the country's efforts to promote the development of renewable energy and reduce reliance on fossil fuels. To be eligible for net billing in Chile, customers must have renewable energy systems with a capacity of up to 300 kW, and the price at which the exports are valued matches the energy component of their distribution tariff. For BT1 customers the energy component (G_{energy} in 2.1) comprises between 40% and 60% of their volumetric charges [31].

Net billing regulation has promoted the adoption of solar photovoltaic (PV) systems in Chile, with generation capacity growing from 4.8 MW to 157 MW between 2016 and 2022 [15], particularly in the metropolitan region (RM), where most of the installations were made. However, DG is still less than 1% of the added generation capacity in the country [31]. According to PV developers, some of the main barriers for solar rooftop adoption are the following [31]:

- High investment and recovery period for the customer
- Lack of policy incentives to develop projects in the sector
- Rigid regulations regarding project size
- Long administrative process and grid connection costs

Excepting the regulation on project size, all of these barriers affect residential customers in Chile. Currently, the investment cost for 1 kilowatt-peak (kWp) of solar PV rounds US$2,600, while 68% of households earn less than the national monthly average, which is US$1,750 [31]. However, there's a positive development. The *Casa solar* (Solar house) program has successfully cut costs for some households, achieving savings of up to 37% of the market price [32]. This initiative is leading the way into making residential DG more affordable in Chile.

2.1.3. Death spiral and fair tariffs

Even if the barriers for DG were tackled, a massive adoption of PV systems and other distributed energy resources (DER) could bring major technical and regulatory challenges for the distribution sector. One of these challenges is the so-called *death spiral*. This phenomenon occurs when the increasing use of DER reduces the revenue of distribution companies, leading to an increase in their rates, which causes more customers to adopt DER, and so on. This creates a cycle of declining revenue for distribution companies and increasing costs for customers [33, 34].

Volumetric tariffs, which charge customers based on their energy usage, can cause death spirals when many people adopt DER, because energy distribution companies still need to cover their network costs when fewer units of energy are being sold. This can make volumetric tariffs, like Chile's BT1, unfair for households with fewer financial resources that would not be able to invest in DER. As a result, low-income families may end up paying more for their energy bills than high-income families that would have reduced their grid dependency through DER investment.

If there is a correlation between income and energy consumption, this scenario would also render obsolete cross-subsidy measures that aim to make the customers that consume more energy contribute in reducing the cost of others, like Chile's tariff equity regulation [29]. As those who consume more would be the ones who can adopt DER sooner and reduce their energy imports, it results in high-income households no longer contributing to the subsidy.

To address the issues of volumetric tariffs and death spirals, some authors propose implementing more cost-reflective tariff designs, such as multipart tariffs. Multipart tariffs decouple the energy and capacity components, improving economic efficiency [33–35].

2.2. Smart Homes in the Smart Grid

In recent times, there has been a growing interest in solar generation, electric vehicles (EV), and smart homes, as depicted in figure 2.3. These trends are relevant for the SG in two ways. Firstly, increased adoption of solar PV and EV by consumers would lead to significant changes in their electricity consumption patterns, which would pose technical challenges for distribution networks. Secondly, smart homes offer users more control over their electrical appliances, therefore their energy usage. This control capability combined with Information and Communication Technologies (ICT) of the SG, can facilitate the implementation of demand-side applications that benefit both the consumer and the grid.

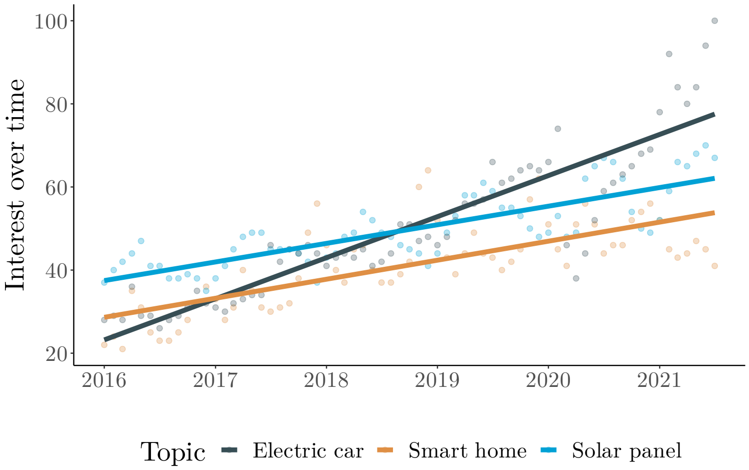

Figure 2.3: Worldwide smart home topics search trends^a.

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[a] source: https://trends.google.com

2.2.1. Home energy management system

The home energy management system (HEMS), sometimes with a *smart-* prefix in it (SHEMS), is the cluster of home devices having communication capability that creates an environment for energy management. HEMS can be deployed in homes to help manage power supply by controlling devices, monitoring energy usage, and receiving signals to reduce power consumption when prices rise [36].

The overall structure for a smart home with HEMS is shown in figure 2.4, where appliances and energy resources communicate within the HAN and are coordinated by a central controller (also called server or HEMS-center) connected to the internet. The smart home is communicated with an upper-level network through the Advanced metering infrastructure (AMI), which can be the neighbor area network (NAN), field area network (FAN), or wide area network (WAN).

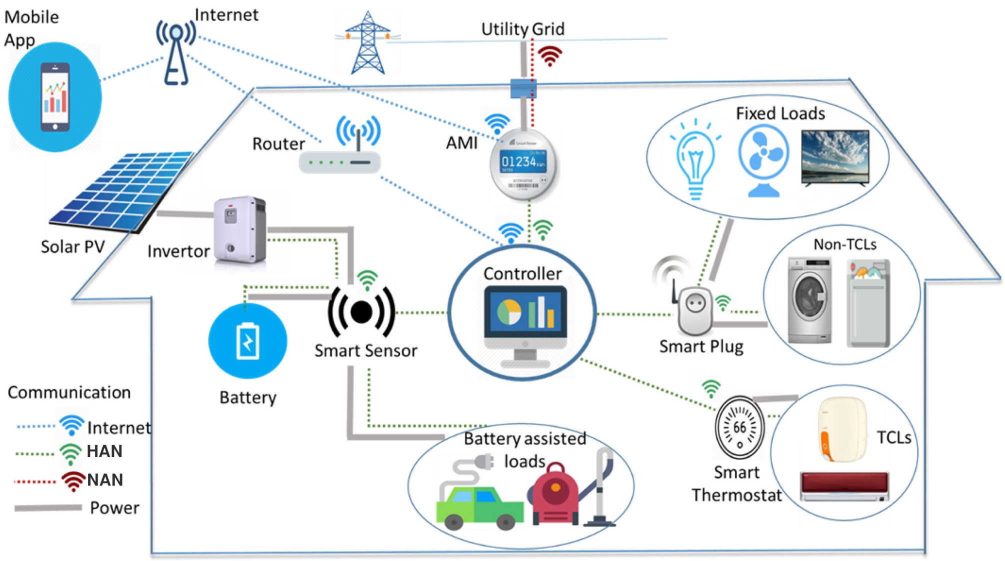


Figure 2.4: Typical HEMS architecture. Modified from [37].

2.2.2. Enabling technologies

Different technologies enable the energy management in the smart home. These are briefly described as follows:

2.2.2.1. Advanced metering infrastructure (AMI)

AMI is an important tool empowering the customer to play an active role in the electricity consumer market as it enables the bi-directional communication between the smart meter installed at consumer premises and the utility grid [37].

2.2.2.2. Smart appliances

Smart appliances are integrated with the internet of things (IoT) to interact with user interfaces such as speakers, smartphones, or tablets and to allow remote access to the homeowner. These appliances may communicate with the HEMS controller and participate in reducing energy consumption automatically. Privacy, control, and interoperability among smart appliances, majorly affect the consumer purchase decision [37].

2.2.2.3. Smart plug

A smart plug is an electric device that provides conventional home appliances with smart features such as automation, remote access, and scheduling. Some smart plugs identify the type of attached home appliance based on their load profile and measure the energy consumption over time [37].

2.2.2.4. Smart thermostat

A smart thermostat is a device with embedded sensing, automation and network communication features, used in thermostatically controlled loads. This device could also provide remote access, communicate with AMI, and guide the users based on their energy usage patterns for efficient management [37].

2.2.2.5. Communication technologies

Information and Communication Technologies (ICT) are essential in the development of strategies for home energy management. One important factor in creating a successful HEMS is the ability for different components to communicate and work together seamlessly. For this reason, researchers have studied various communication and networking technologies for home area networks (HAN).

Reviews of HEMS communication technologies [36–38] suggest that Zigbee and Wi-Fi are currently the most popular choices for HEMS infrastructure. While these technologies are commonly used in smart home devices, other standards like Z-Wave, Bluetooth Low Energy, X10, Insteon, and Thread are also available in the market.

The choice of communication technology for a HEMS will depend on factors such as cost, reliability, and compatibility with existing devices. Regardless of the technology chosen, ICT plays a critical role in enabling effective home energy management by facilitating communication and control between different components of the HEMS.

2.2.3. Load classification

HEMS can reduce and shift energy consumption by scheduling home appliances use without compromising user comfort. Commonly, load scheduling minimizes power demand during peak load and reduces cost according to a dynamic tariff [36, 39]. To achieve optimal appliance-energy-cost, authors have used various scheduling and control approaches [7, 36]. These are categorized into 3 groups [36]:

- Rule-based.
- Artificial intelligence (fuzzy control, neuronal networks, etc.).
- Optimization techniques (genetic algorithm, mixed-integer nonlinear programming, etc.)

Given that home appliances have different characteristics, power requirements, and operating modes, grouping residential loads based on consumer needs and behavior is crucial for any scheduling strategy. As pointed in [37], different authors have categorized home appliances based on their behavior and operating characteristics. However, the same type of appliances has been categorized differently depending upon each research objective, and there is no agreed taxonomy for load groups.

Based on the load groups described in [37, 40–44], a generic load classification is provided in figure 2.5.

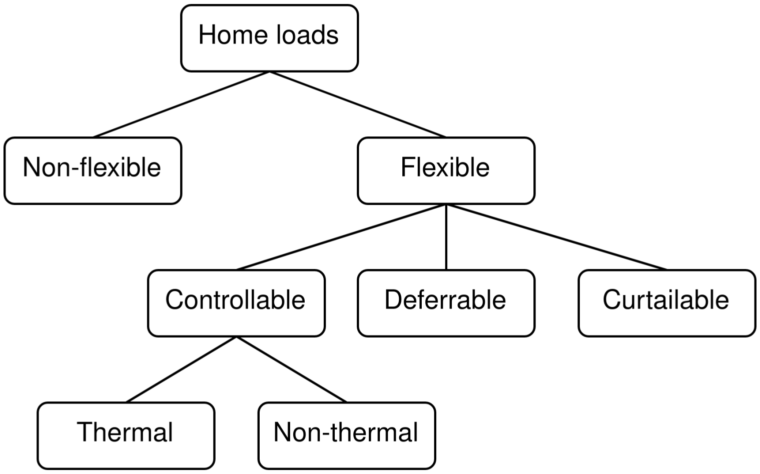


Figure 2.5: Generic residential load classification.

2.2.3.1. Flexible and Non-flexible loads

Flexible loads correspond to energy consumption that can be modified without affecting their utility beyond user tolerance. On the other hand, non-flexible or fixed loads correspond to energy demand that cannot be modified, as their interruption or delay would directly affect their utility. Typical cases of non-flexible loads include lighting, cooking, and entertainment appliances.

2.2.3.2. Curtailable loads

Curtailable loads, or non-critical loads, refer to electrical loads that can be limited under certain conditions, such as when energy costs reach a specified threshold or when the aggregated demand of the household exceeds a defined security limit. Decorative lighting is an example of curtailable load.

2.2.3.3. Deferrable loads

These are appliances whose energy consumption is tied to a defined task that can be delayed up to a specified time, as long as they fulfill their role. Typical cases of deferrable loads are dishwashers and washing machines.

2.2.3.4. Controllable loads

Loads for which their demand profile can be regulated over a period of time, either by interrupting or modulating their power draw.

2.2.3.5. Thermal controllable loads

Thermal controllable load (TCL) refers to an appliance that can be controlled based on the thermal requirements of a home. Examples of such loads may include heating, ventilation and air conditioning (HVAC) systems, as well as water heaters, among others. Some of these loads can leverage their thermal inertia as storage to buffer energy consumption during convenient periods, or to delay it into the future. Others can be regulated to fulfill their thermal requirement over a longer period of time to reduce peak power.

2.2.3.6. Non-thermal controllable loads

To manage the demand profile of non-thermal controllable loads, their power draw can be **adjusted**, or their operation can be **interrupted** while still maintaining functionality. Examples of non-thermal controllable loads include EV chargers, which offer multiple modes of operation, such as normal and fast charging. Other non-thermal controllable loads are pool pumps and phone chargers, which need to operate within a specific time period but can be interrupted multiple times without impacting their intended function. For instance, pool pumps are required to complete a set number of hours for pool cleaning, and phone chargers need to operate long enough to charge the battery.

2.2.4. Prosumer optimization problem

As mentioned earlier, HEMS have a key role in managing the usage of appliances to optimize energy costs while ensuring user comfort. To accomplish this goal, HEMS can implement a range of methods, including fuzzy control, neural networks, genetic algorithms, among others. An interesting approach to this problem can be found in [45], which proposes a mixed-integer linear programming model (MILP) that assigns a dissatisfaction function to each appliance and calculates the total cost as a weighted sum of energy cost and dissatisfaction. In this section, we will delve into the restrictions presented in that formulation of the prosumer problem. These constraints aim to address specific challenges and limitations related to the optimization of energy usage and user comfort of different appliance types.

2.2.4.1. Objective function

The objective function in equation 2.2 is the weighted sum of the energy cost (equation 2.4) and total dissatisfaction (equation 2.5). With this formulation, two arbitrary parameters, ω_1 and ω_2, indicate the importance of cost and comfort for the user.

Regarding the energy cost, in equation 2.4 the values of λ correspond to the purchase and sale prices of energy. As for the dissatisfaction equation 2.5, ζ_i is the user discomfort caused by the appliance i. This variable will be explained with more detail for each appliance in the following restrictions.

$$min\ \omega_1 \cdot J_1 + \omega_2 \cdot J_2 \tag{2.2}$$

$$\omega_1 + \omega_2 = 1, \quad \omega_1, \omega_2 \in [0, 1] \tag{2.3}$$

$$J_1 = \sum_{t \in \mathcal{T}} \left[\lambda_{buy}(t) \cdot P_{buy}(t) \cdot \Delta t - \lambda_{sell}(t) \cdot P^{PV}_{sell}(t) \cdot \Delta t \right] \tag{2.4}$$

$$J_2 = \sum_{i \in \mathcal{A}} \zeta_i \tag{2.5}$$

2.2.4.2. Deferrable appliances

$$P_i^{APP}(t) = 0 \quad u_i^{APP}(t) = 0 \quad \forall t \notin [L_i, U_i] \quad \forall i \in \mathcal{A}_{non} \tag{2.6}$$

Constraint 2.6 ensures that appliances are turned off outside their operation window. In this restriction $P_i^{APP}(t)$ and $u_i^{APP}(t)$ (binary) indicate the power and on/off state of the device respectively. L_i and U_i are the time limits in which the user requires to fulfill the appliance role, for instance the time period in which the user needs clothes to be washed in the case of a washing machine. $\mathcal{A}_{non}$ correspond to the set of non-interruptible appliances.

$$P_i^{APP}(t) = u_i^{APP}(t) \cdot P_{R,i}^{APP}(t) \quad \forall t \in \mathcal{T} \quad \forall i \in \mathcal{A}_{non} \tag{2.7}$$

Constraint 2.7 ensures power consumption when the appliance is turned on. In this equation $P_{R,i}$ is the rated power of the appliance i.

$$\sum_{t=j}^{j+T_{L,i}-1} u_i^{APP}(t) \geq T_{L,i} \cdot \left(u_i^{APP}(j) - u_i^{APP}(j-1) \right) \quad \forall j \in (L_i, U_i - T_{L,i} + 1] \quad \forall i \in \mathcal{A}_{non} \tag{2.8}$$

$$\sum_{t=L_i}^{U_i} u_i^{APP}(t) = T_{L,i} \quad \forall i \in \mathcal{A}_{non} \tag{2.9}$$

Constraints 2.8 and 2.9 ensure the operation of deferrable appliances is not interrupted. Where $T_{L,i}$ is the required power-on duration of the appliance i.

$$\zeta_i = \sum_{t=L_i}^{U_i} (1 + \epsilon_i \cdot t) \cdot u_i^{APP}(t) \quad \forall i \in \mathcal{A}_{non} \tag{2.10}$$

To reflect the user dissatisfaction generated by appliance i, the model proposes equation 2.10. Which assume users prefer to get appliances tasks to be completed as soon as possible . In this constraint, ϵ_i is a coefficient that indicates the importance a user gives to the appliance i finishing its task in a timely manner.

2.2.4.3. Interruptible appliances

$$P_i^{APP}(t) = 0 \quad \forall t \notin [L_i, U_i] \quad \forall i \in \mathcal{A}_{in} \tag{2.11}$$

Constraint 2.11 is analogue to 2.6, and ensures that the appliance only draw power within its intended time window.

$$\sum_{t=L_i}^{U_i} P_i^{APP}(t) \cdot \Delta t \geq E_i^{APP} \quad \forall t \in \mathcal{T} \quad \forall i \in \mathcal{A}_{in} \tag{2.12}$$

Although this type of appliance may divide its consumption into different time slots, constraint 2.12 ensures it consumes the amount of energy required to fulfill its role within the time frame in which the user expects it to be completed.

$$0 \leq P_i^{APP}(t) \leq P_{R,i}^{APP}(t) \quad \forall t \in \mathcal{T} \quad \forall i \in \mathcal{A}_{in} \tag{2.13}$$

Constraint 2.13 ensures that the power ranges in which the appliance operate do not exceed its rated power, in addition to being consistent with the hours in which the variable $u_i(t)$ indicates whether it is on or off.

$$\zeta_i = \sum_{t=L_i}^{U_i} (1 + \epsilon_i \cdot t) \cdot u_i^{APP}(t) \quad \forall i \in \mathcal{A}_{in} \tag{2.14}$$

User satisfaction (equation 2.14) for this type of appliance is analogous to the case of deferrable appliances, described in equation 2.10.

2.2.4.4. Thermal controllable appliances

For this type of load, two types of appliances are considered: Air Conditioning (AC) and Water Heater (WH). Since the behavior of both is different, some of the constraints describe ahead would apply specifically to each one.

$$\{AC, WH\} \in \mathcal{A}_{ther} \tag{2.15}$$

$$0 \leq P_i^{APP}(t) \leq P_{R,i}^{APP}(t) \quad \forall t \in \mathcal{T} \quad \forall i \in \mathcal{A}_{ther} \tag{2.16}$$

$$T_{c,i}(t) - \theta_i^{dn} \leq T_{u,i}(t) \leq T_{c,i}(t) + \theta_i^{up} \quad \forall t \in \mathcal{T} \quad \forall i \in \mathcal{A}_{ther} \tag{2.17}$$

Constraint 2.16 ensures that the power range in which thermal appliances operate do not exceed their rated power, and constraint 2.17 ensures that their temperatures remain within acceptable ranges.

$$\begin{gathered} T_{u,i}(t) = T_{u,i}(t-1) + \eta \cdot (W_{out}(t) - T_{u,i}(t-1)) + \gamma \cdot P_i^{APP}(t) \cdot \Delta t \\ \forall t \geq 1 \quad \forall t \in \mathcal{T} \quad \forall i \in AC \end{gathered} \tag{2.18}$$

For AC appliances, equation 2.18 describe the temperature dynamic over time ($T_{u,i}$), in the rooms conditioned by the AC i. In this equation, W_{out} is the exterior ambient temperature and η is a parameter that reflect the heat exchange between the interior and exterior in one time step. Additionally, the parameter γ indicates how much can the AC i reduce the room temperature per unit of energy.

$$\sum_{k=1}^{t} P_i^{APP}(k) \cdot \Delta t \geq \sum_{k=1}^{t} \rho_{wh}(t) \quad \forall t \in \mathcal{T} \quad \forall i \in WH \tag{2.19}$$

$$\rho_{wh}(t) = m(t) \cdot c_w \cdot (T_{u,i}(t) - T_{cold}) \quad \forall t \in \mathcal{T} \quad \forall i \in WH \tag{2.20}$$

$$\sum_{k=1}^{t} P_i^{APP}(k) \cdot \Delta t \leq M \cdot c_w \cdot (T_{c,i}(t) + \theta_i^{up} - T_0) + \sum_{k=1}^{t} \rho_{wh}(t) \quad \forall t \in \mathcal{T} \quad \forall i \in WH \tag{2.21}$$

For WH appliances, equation 2.20 describe the energy requirement to heat the mass of hot water demanded (m) over time. Where c_w is the specific heat capacity of water, T_{cold} is the temperature of water at the WH inlet and $T_{u,i}$ is the temperature of water at the outlet. Accordingly, constraint 2.19 ensures that the appliance gets enough energy to keep up with hot water demand at any moment. While constraint 2.21 ensures that the water tank, with capacity M, do not exceed the maximum temperature θ_i^{up} at any time step.

$$w_{1,i}(t) \leq z_{1,i}(t), \quad w_{2,i}(t) \leq z_{1,i}(t) + z_{2,i}(t), \quad w_{3,i}(t) \leq z_{2,i}(t) \quad \forall t \in \mathcal{T} \tag{2.22}$$

$$w_{1,i}(t) + w_{2,i}(t) + w_{3,i}(t) = 1 \quad w_{k,i}(t) \geq 0 \quad \forall k = 1,2,3 \quad \forall t \in \mathcal{T} \tag{2.23}$$

$$z_{1,i}(t) + z_{2,i}(t) = 1 \quad z_{k,i}(t) = 0 \; or \; 1 \quad \forall k = 1,2 \quad \forall t \in \mathcal{T} \tag{2.24}$$

$$\begin{gathered} T_{u,i}(t) = (T_{c,i}(t) - \theta_i^{dn}) \cdot w_{1,i}(t) + T_{c,i}(t) \cdot w_{2,i}(t) + (T_{c,i}(t) + \theta_i^{up}) \cdot w_{3,i}(t) \\ \forall t \in \mathcal{T} \quad \forall i \in \mathcal{A}_{ther} \end{gathered} \tag{2.25}$$

$$\zeta_i = \epsilon_i \cdot \sum_{t \in \mathcal{T}} w_{1,i}(t) + w_{3,i}(t) \quad \forall i \in \mathcal{A}_{ther} \tag{2.26}$$

Constraints from 2.22 to 2.26 describe the dissatisfaction ζ_i generated by thermal appliances (AC and WH) by failing to meet their desired temperature $T_{c,i}$ over time. Analogue to previous appliances, ϵ_i indicates the importance that a user give to the appliance i meeting its desired temperature at any moment. Auxiliary variables $w_{1,i}$, $w_{2,i}$ and $w_{3,i}$ indicate how close the appliance i is from the minimum, desired and maximum temperatures, according to equation 2.25. While auxiliary variables $z_{1,i}$ and $z_{2,i}$, ensures that only one of $w_{1,i}$ and $w_{3,i}$ is active at any moment. This ensures that in equation 2.25, the user perceived temperature $T_{u,i}$ is a linear combination of the desired set-point $T_{c,i}$ and only one of its limits, $(T_{c,i}(t) - \theta_i^{dn})$ and $(T_{c,i}(t) + \theta_i^{up})$, at each time step.

2.2.4.5. Power flow

$$P_{use}^{PV}(t) + P_{sell}^{PV}(t) = P^{PV}(t) \quad \forall t \in \mathcal{T} \tag{2.27}$$

$$P_{buy}(t) + +P_{use}^{PV}(t) = P_{non-flexible}(t) + \sum_{i \in \mathcal{A}} P_i^{APP}(t) \quad \forall t \in \mathcal{T} \tag{2.28}$$

$$P_{buy}(t) \leq N_1 \cdot \mu_{grid}(t) \quad \forall t \in \mathcal{T} \tag{2.29}$$

$$P_{sell}^{PV}(t) \leq N_2 \cdot (1 - \mu_{grid}(t)) \quad \forall t \in \mathcal{T} \tag{2.30}$$

Constraint 2.27 ensures that the energy sold and consumed from the solar panels do not exceed their energy production P^{PV} at any time step. Then, constraint 2.28 ensures that the energy imported from the grid P_{buy} in addition to the energy used from the solar panels P_{use}^{PV} meets the demand of all flexible and non-flexible loads at any moment. Finally, constraints 2.29 and 2.30 indicates that the household cannot export and import energy to, and from, the grid simultaneously. As the variable μ_{grid} is binary, while N_1 and N_2 are positive reals.

2.3. Energy Management as-a-Service

Authors in [17] proposed a cloud-based framework for providing EMaaS to various green communities, demonstrating that the proposed model can lead to global cost optimization and improve the integration of renewable generation. However, the experimental results are simulated from real data and lack practical prototypes.

Works in [18–22] showcase different prototypes and highlight that interoperability and heterogeneity of devices and their communication technologies pose significant challenges for implementing an EMaaS system. These works address the issue in various ways, typically developing solutions to unify different devices and communication technologies under a single system that abstracts away heterogeneity. They also develop basic user interfaces for operating the energy management systems.

In my opinion, for the residential sector, developing prototypes of EMaaS systems with the best potential to become a real service should focus on building on top of available solutions, instead of developing it all from the ground. Major companies' Internet of Things platforms like Google, Amazon, and Apple, which allow operating devices from multiple manufacturers with different communication technologies, are likely the most suitable platforms for developing a commercial energy management service. Building on top of these platform would also reduce the effort of designing complete user interfaces.

Because the scope of this research does not extend to a marketable service, I opted to use a different platform: Home Assistant. This open-source platform enables the abstraction and integration of a wide range of devices and protocols in the Internet of Things field.

Furthermore, each reviewed work employs its own method for transmitting energy consumption and control signals. However, I believe it is crucial to use defined standards for exchanging messages between distributed energy resources and the service provider. In this thesis, I chose to incorporate an open standard designed for the transmission of demand response signals.

2.4. Demand Response Signaling

Table 2.4: Standards related to Demand Response Signals [46]

Standard	**Description**
ANSI/CEA 709 and CEA 852.1 LON Protocol Suite	This is a general purpose local area networking protocol in use for various applications including electric meters, street lighting, home automation, and building automation.
Open Automated Demand 2.0 Response (OpenADR)	The specification defines messages exchanged between the Demand Response (DR) Service Providers (e.g., utilities, independent system operators (ISOs) and customers for price-responsive and reliability-based DR.
Organization for the Advancement of Structured Information Standard (OASIS) Energy Interoperation (EI)	Energy interoperation describes an information model and a communication model to enable demand response and energy transactions. XML vocabularies provide for the interoperable and standard exchange of: DR and price signals, bids, transactions and options, and customer feedback on load predictability and generation information.
Zigbeee alliance Smart Energy Profile (SEP)	SEP 1.0 provide pricing support and consumption for multiple commodities (electric, gas, water), text messaging, direct load control, and demand response capability. SEP 2.0 is IP based; as such it easily integrates with existing IP-based systems and protocols and operate over alternative MAC/PHY layers to provide more system flexibility.

According to the *Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0* [46], there are four standards relevant for DR signals, which are described in table 2.4.

Regarding these standards, OpenADR 2.0 is a subset of OASIS EI, and standardizes information exchange between utilities and energy management control systems. On the other hand, SEP 2.0 standardizes device communications in response to market signals once they have been received by a gateway. The OpenADR alliance provides a brief comparison between these two standards, which is available in table 2.5.

Considering we aim to provide EMaaS with a cloud-based solution in this research, the OpenADR 2.0 Specification fits well the study, as it standardizes only the information exchange between customer and service provider, and not the actual device control. In contrast, SEP 2.0 and LON Protocol Suite, standardize device communication within the local network once the signal has been received.

Table 2.5: Key difference between OpenADR and SEP 2.0 [47].

OpenADR 2.0	**SEP 2.0**
• Service provider (server) to customer energy system interface (client) • Enables automated AutoDR to commercial, industrial and residential customers • Communicates over the Internet using web services • Transmits larger data packets	• Enables residential and light commercial DR • Communicates over Automated Metering Infrastructure (AMI) or via a broadband gateway • Transmits small data packets • Ideally suited for use within a home or building

2.4.1. Open automated demand response

The open automated demand response communication specification arises from the large-scale electricity crisis of California in 2002. By 2013, more than 250 MW of load capacity was registered by the OpenADR 1.0 specification and participated in the commercial and industrial automatic demand response project of California [48].

OpenADR 2.0 covers the signal and data model of price and reliability in wholesale and retail markets. It provides two specifications, OpenADR 2.0a and OpenADR 2.0b, that differ on the set of functions each specification supports. The first one is meant to be used in simple devices and programs, while the latter is suited for more robust applications. The benefits of OpenADR 2.0 are shown in table 2.6 [49].

The main concepts in OpenADR are inherited from its parent standard, OASIS EI, and are the virtual top node (VTN) and virtual end node (VEN). For any interaction between participants, one is acting as VTN and the others as VEN. There is no peer-to-peer communication in OpenADR. That is to say, a VTN does not communicate directly with other VTN, nor does a VEN with other VEN [48].

An OpenADR system is composed of VTN-VEN interaction pairs, connecting different hierarchies through a node that acts as both VTN and VEN simultaneously. This arrangement forms the complete automatic DR architecture. By doing so, the system refines large-scale problems into smaller ones. This DR system is divided into three layers, as shown in figure 2.6, where large loads directly participate in automatic DR. Conversely, small users participate in automatic DR through aggregators using OpenADR signaling [48].

Table 2.6: OpenADR benefits [49].

Open Specification	Provides a standardized DR communications and signaling infrastructure using open, non-proprietary, industry-approved data models that can be implemented for both dynamic prices and DR emergency or reliability events.
Flexibility	Provides open communications interfaces and protocols that are flexible, platform-independent, interoperable, and transparent to end-to-end technologies and software systems.
Innovation and Interoperability	Encourages open innovation and interoperability, and allows controls and communications within a facility or enterprise to build on existing strategies to reduce technology operation and maintenance costs, stranded assets, and obsolesce in technology.
Ease of Integration	Facilitates integration of common Energy Management and Control Systems (EMCS), centralized lighting, and other end-use devices that can receive Internet signals (such as XML).
Supports Wide Range of Information Complexity	Can express the information in the DR signals in a variety of ways to allows for systems ranging from simple end devices (e.g., thermostats) to sophisticated intermediaries (e.g., aggregators) to receive the DR information that is best suited for its operations.
Remote Access	Facilitates opt-out or override functions for participants to manage standardized DR-related operation modes to DR strategies and control systems.

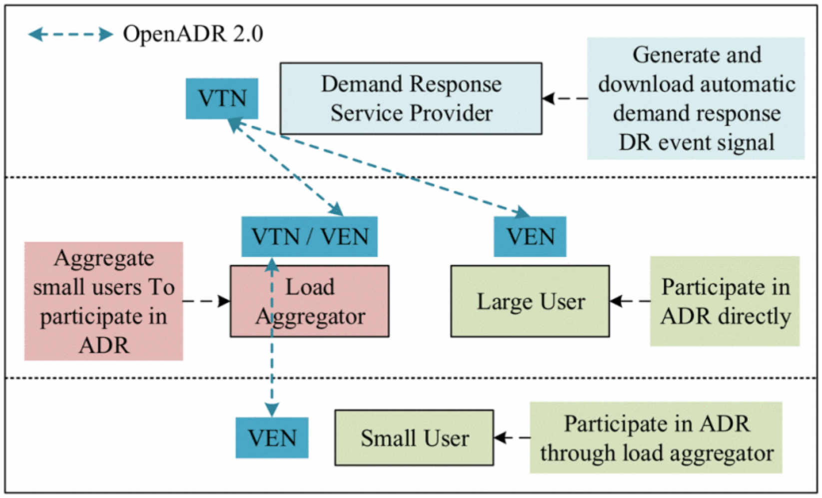


Figure 2.6: Layered architecture diagram of automatic demand response system [48].

This three-layer architecture, with load aggregator, is mainly applied to the multi area large-scale automatic demand response system. Small-scale pilot projects can remove the middle layer of load aggregator and have the end-user directly participating in automatic demand response. The simplified layered architecture is shown in figure 2.7.

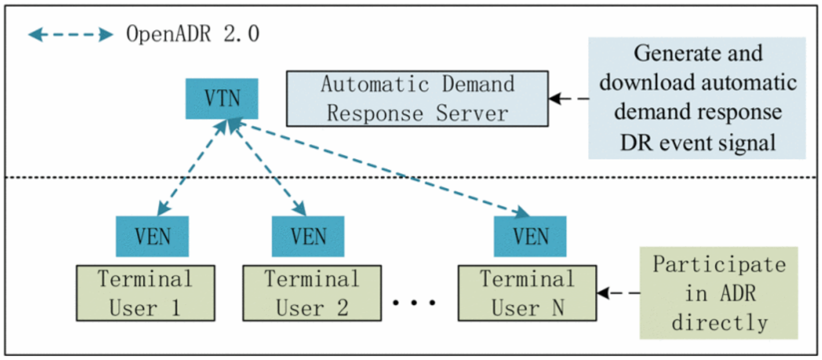


Figure 2.7: Simplified layered architecture diagram for small-scale automatic demand response system [48].

2.5. Summary of Tools

This section presents three important software tools used in this research. The first one was crucial for simulations, helping generate high-resolution residential load profiles for different types of families. The latter two made it much easier to put some concepts of this research into practice in the real world

2.5.1. Artificial load profile generator

The Artificial Load Profile Generator (ALPG) is an open-source tool, written in the programming language Python, designed to generate synthetic electricity consumption profiles for use in research on demand-side management and smart grid applications [50]. This tool is introduced in [51].

The ALPG uses statistical algorithms to model electricity consumption behavior at the household level. It takes into account various factors that affect electricity consumption, such as weather, time of day, day of the week, and seasonal variations. The tool is designed to be flexible and allows researchers to adjust parameters in order to generate custom load profiles according to their specific needs.

This tool has been used in a variety of research projects related to smart grids and demand-side management, including studies on the impact of electric vehicles on the electricity grid, the effectiveness of demand response programs, and the integration of renewable energy sources into the grid [52–54]. It is a valuable tool for researchers interested in understanding and modeling electricity consumption behavior at the household level. Its flexibility and adaptability make it useful for this research.

2.5.2. Home assistant

Home Assistant [55] is an open-source home automation platform, written in Python, that allows users to control and automate various devices and services in their home. It supports a wide range of devices and services, including lights, switches, thermostats, media players, and more, through a system of *integrations* and offers a central dashboard for controlling and monitoring them.

Home Assistant supports various protocols and technologies, such as MQTT, Z-Wave, Zigbee, and more, and can run on various platforms, including Raspberry Pi, Linux, macOS, Windows, and Docker. It also offers a mobile app for remote access and control.

With Home Assistant, users can create automations and scripts to perform various tasks, such as turning on lights when motion is detected, adjusting the thermostat based on the weather forecast, and more. The integrations architecture of Home Assistant also allows for anyone to easily integrate their own service or device into the platform, making it highly customizable and adaptable to individual needs.

2.5.3. Open LEADR

OpenLEADR [56], which stands for Open Linux Energy Automatic Demand Response, is an open-source Python library for developing applications that implement the OpenADR 2.0a and 2.0b specifications. The OpenLEADR library makes it easy to implement OpenADR in Python-based energy management systems. It provides a set of functions and tools that developers can use to build custom OpenADR clients and servers. The library is built on top of the asyncio framework, which allows it to handle multiple concurrent connections and events efficiently, providing scalability to servers implemented with OpenLEADR.

The library supports both the XML and JSON versions of the OpenADR message format, as well as a number of other features such as authentication, encryption, and error handling. OpenLEADR is designed to be flexible and extensible, allowing developers to easily add their own custom functionality. As an open-source library, OpenLEADR is free to use and can be modified to meet the specific needs of a particular project.

3. Estimating Potential Savings for Prosumers

3.1. Methodology

3.1.1. Overview

To estimate the benefits of an EMS for a prosumer in Chile's metropolitan region (RM), I conducted a simulation of the operation of 200 representative households under different scenarios. The simulation consisted of four weeks for each household, with one week per season, and the initial day of each week was randomly selected from its corresponding season. The simulation involved three steps, which are summarized in figure 3.1.

In the first step, I gathered various sources of information to characterize the consumption and solar generation of households in the RM, which is detailed in section 3.1.2. Using this information, I modified the ALPG to generate 200 household load profiles that reflect the characteristics of RM households. The outputs from ALPG that were used in this simulation are the following:

- Fixed load, solar generation and hot water demand profiles.
- Thermostat set-points.
- Washing machine start times, end times and load profile.
- Dishwasher start times, end times and load profile.
- Electric vehicle charging start times, end times and required energy.

Once the representative profiles were generated, I used them together with BT1 tariff data and energy marginal cost data to determine a 3-part time-of-use tariff, which was used in the following step.

In the second step, I defined the scenarios in which household operations would be simulated. Then, I solved the prosumer problem, presented in section 2.2.4, for each household profile in all scenarios using the CBC solver [57] and the Pulp Python library [58]. Each scenario is characterized by a household type, a satisfaction parameter and a tariff scheme. The household types are defined in terms of the flexible appliances a household has in a scenario, ranging from "conventional" to "fully flexible". The definition of each type will be detailed later. As for the satisfaction parameter, it indicates the value of ω_2 in the prosumer problem of that scenario. Lastly, the tariff scheme defines how the energy cost J_1 is calculated in the prosumer problem of that scenario.

Then, in the third step, I processed the solutions generated in the second step to calculate the yearly energy cost for each household in every scenario and determine savings achieved by the EMS. To calculate the yearly cost, I extrapolated the cost of each operation week into a quarter of the year and added them up. In addition to energy cost, I also compared the peak load of every household in each scenario and the curtailment of thermal appliances due to cost reduction.

Regarding the reference scenarios, one consists of the households without solar generation and without EMS (labeled "w\o DG"). The second reference scenario consists of the households with solar generation and without EMS (labeled "w\o EMS").

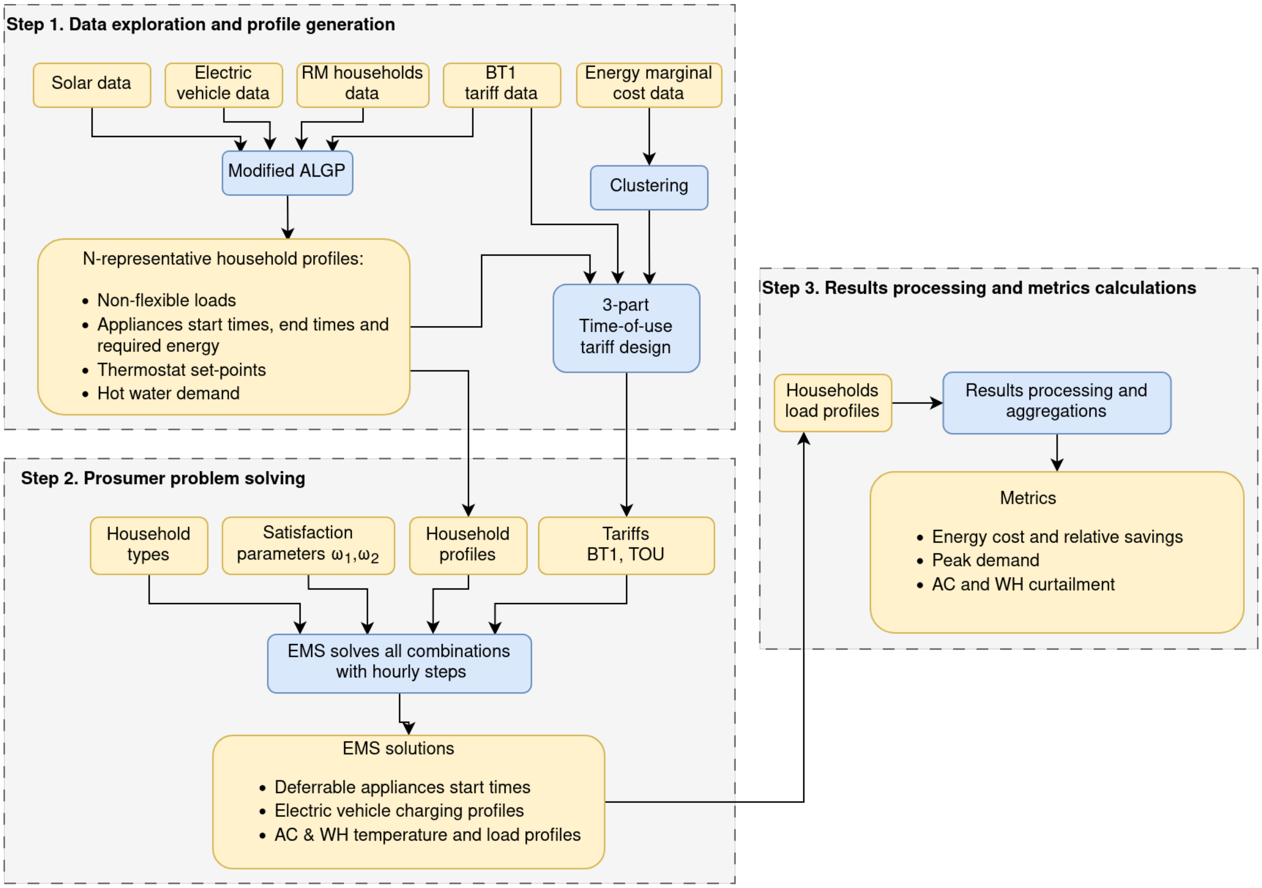


Figure 3.1: Simulation methodology overview.

3.1.2. Household characterization

3.1.2.1. Solar parameters

To generate solar production profiles for each household using ALPG, the researcher must configure input parameters to describe the direction the solar panels will face. To determine the optimal angle and azimuth, I used the solar explorer [59] tool provided by the Ministry of Energy in Chile. I obtained the necessary data using the Beauchef campus of the University of Chile, which is located in the center of Santiago, as reference location in the solar explorer. The remaining parameters were kept at their default values. Table 3.1 displays these parameters.

Table 3.1: ALPG solar parameters.

Parameter	**Value**
PVAngleMean	26°
PVAngleSigma	10°
PVAzimuthMean	-6°
PVAzimuthSigma	90°
PVEfficiencyMin	15%
PVEfficiencyMax	20%

Furthermore, the ALPG requires an input file containing the global horizontal irradiation (GHI) for a full year to calculate the energy produced by the solar systems on any given day of the year. This data is available in the solar explorer as typical year data, which includes an hourly GHI for a year, as well as ambient temperature.

3.1.2.2. Electric vehicle parameters

To determine the energy needed for an electric vehicle each day, the ALPG uses the commute distance of workers and the battery capacity of their cars as input. In the simulation, the ALPG prioritizes households with longer commutes to receive an EV before a PHEV.

The commute distance parameter used in the simulation is based on the annual driving distance of lightweight vehicles in the RM [60]. This is calculated by dividing 18,000 km by 365 days. The deviation parameter for the commute distance remains the same as in the default configuration. To determine the battery capacity and maximum charging power, I used the most sold EV and PHEV models in Chile as a reference [61]. The *DS 3 Crossback* [62] and *Volvo XC60* [63] were used for EV and PHEV, respectively. For PHEV, the households would use AC charging at 220 V, while EV owners would use a wall charger [64]. Table 3.2 displays the parameters used for EV and PHEV.

Table 3.2: ALPG electric vehicle parameters.

Parameter	Value
commuteDistanceMean	24.65 km
commuteDistanceSigma	10 km
capacityEV	50 kWh
powerEV	7 kW
capacityPHEV	18 kWh
powerPHEV	3.5 kW

3.1.2.3. Typical seasonal consumption

In order to determine the average energy consumption of households in the RM for each season, I analyzed data from the *Comisión Nacional de Energía* (CNE) which is publicly available on the web portal *Energía Abierta* [65]. Specifically, I used the monthly consumption data of BT1 billed clients in 2021 as a reference to calculate the average consumption for each season. These values are presented in table 3.3.

Table 3.3: 2021 average monthly consumption in RM.

Season	Energy
Autumn	229.7 kWh
Spring	215 kWh
Summer	224 kWh
Winter	269.8 kWh

3.1.2.4. Family representation parameters

The ALPG provides different family types to simulate load profiles based on household size and working habits. These family types are listed in table 3.4, omitting configurations for part-time workers. Generating 150 representative households for the RM, requires determining the representation of each family type in the sample. This was done using data from the 2017 Chilean census [66].

To map the information available in the 2017 national census to ALGP family types, I did a process of re-labeling based on census household types and job information. The 2017 census identifies 7 types of families, which are described in table 3.5, and contains individual's job data in responses to question P17: "Did you work during last week?" This question had eight possible answers, which are shown in table 3.6. I considered adults who gave answer 1 or 3 as being workers, and answer 7 as retired.

For some households, including Single-person, Single-parent nuclear, Two-parent nuclear, and Two-parent nuclear without children, the census-type could be directly mapped to ALPG types. For households that could not be directly mapped, I used additional information available in the census on each household member, such as age, occupation, and relationship with the head of household, to complete the re-labeling process. This resulted in a representation of households that is shown in table 3.7.

Table 3.4: Family types built in ALPG.

Family type	**Description**
FamilyDualParent	Two working adults with kids
FamilyDualParent(jobless = True)	Two adults with kids, only one working
FamilySingleParent	One working adult with kids
FamilySingleParent(jobless = True)	One adult without job and with kids
SingleWorker	Single working adult
SingleRetired	Single retired adult
SingleJobless	Single adult without job
Couple	Two working adults
Couple(jobless = True)	Two adults, only one working
DualRetired	Two retired adults

Table 3.5: Family types defined in 2017 Chilean census.

Family type	**Description**
Single-person household	Households consisting of a single person who is the head of household.
Single-parent nuclear household	Households consisting only of the head of household and their children (or children of the spouse or partner).
Two-parent nuclear household without children	Households consisting only of the head of household and a spouse, cohabitant or civil union partner. There are no children in the household.
Two-parent nuclear household with children	Households consisting of the head of household, a spouse, cohabitant or civil union partner, and their children - whether from both, only from the head or only from the spouse, cohabitant or partner.
Composite household	Households that have a nucleus (nuclear family) and also include non-relatives of the head of household. Other relatives of the head of household may or may not be included.
Extended household	Households that have a nucleus (nuclear family) and also include other relatives of the head of household.
Non-nuclear household	Households that do not have a nucleus (nuclear family) but include other relatives or non-relatives of the head of household.

Table 3.6: Answers to question P17: “Did you work during last week?”

n°	**Possible Answers**
1	For a payment in cash or goods
2	Without payment for a family member
3	Had a job but was on vacation, on leave, on sick leave, etc.
4	Was looking for a job
5	Was studying
6	Did household chores
7	Is retired, on a pension, or receives rental income
8	Other situation

Table 3.7: Family types representation in simulation.

ALPG type	**Representation**
Couple	6.6 %
Couple(jobless = True)	5.7 %
DualRetired	3.8 %
FamilyDualParent	42.1 %
FamilyDualParent(jobless = True)	19.0 %
FamilySingleParent	7.4 %
FamilySingleParent(jobless = True)	3.5 %
SingleJobless	1.6 %
SingleRetired	3.4 %
SingleWorker	7.0 %

3.1.2.5. Other ALPG adjustments

I kept most of the configuration parameters of ALGP (cooking appliances rated power, fridge energy consumption, kettle rated power, among others) as in the default configuration. In addition to the modified parameters that were explained in previous sections, two more were adjusted to fit the simulation, namely the *consumptionFactor* and *PVProductionPerYear*.

The *consumptionFactor* determines how the non-flexible loads of each household are scaled in the output profiles. I calculated this value to ensure that when adding the consumption of non-flexible and flexible loads, the average of that sum would match the average monthly consumption of households in the RM during each season (see table 3.3). This calculation was based on the “conventional” household type as the base scenario.

As for *PVProductionPerYear*, ALPG inner logic tries to assign PV systems that produce in a year the same energy that the households’ non-flexible loads consume, when *consumptionFactor* is equal to 1. It does so, by using the parameter *PVProductionPerYear* that indicates beforehand the yearly energy production of a square meter of solar panels. Given that the simulation in this study varies consumption between seasons, I calculated a value for this parameter that would result in households, in average, producing the same solar energy that the sum of flexible and non-flexible appliances in the “conventional” household type scenario. The values used for *consumptionFactor* and *PVProductionPerYear* are shown in table 3.8

Table 3.8: ALPG consumption and solar generation factors.

Parameter	**Season**	**Value**
consumptionFactor	Autumn	0.854
consumptionFactor	Spring	0.789
consumptionFactor	Summer	0.830
consumptionFactor	Winter	1.024
PVProductionPerYear	All	655 $\frac{kWh}{m^2}$

Lastly, I modified the inner logic of ALPG to adjust the number of children in family households to fit the data from the 2017 census. Originally, ALPG uses a normal distribution with mean 1.7 and standard deviation 0.4, I used a normal distribution with mean 1.93 and standard deviation 1.2, based on census data.

3.1.3. Household types

3.1.3.1. Conventional

This is the base case for the simulation. In this scenario each household can have two flexible appliances, a washing machine and a dishwasher. The washing machine is present in all simulated households, while the dishwasher is randomly assigned following the probabilities shown in table 3.9. These probabilities are defined in the inner logic of ALPG.

Table 3.9: ALPG dishwasher probabilities.

ALPG type	**Dishwasher probability**
Couple	40 %
DualRetired	40 %
FamilyDualParent	60 %
FamilySingleParent	60 %
SingleJobless	20 %
SingleRetired	40 %
SingleWorker	20 %

It is worth to note that houses without dishwasher use more hot water than those of the same size that have a dishwasher.

3.1.3.2. Air-conditioned

In this scenario, every household gets an air conditioner unit besides the flexible appliances from the previous scenario. The properties of these air conditioner units depend on the number of persons in the household. These properties are displayed in table 3.10.

Table 3.10: Air conditioner properties.

Persons	**Rated power**	γ
1	1.4 kW	-6.786 $\frac{°C}{kWh}$
2	1.8 kW	-5.278 $\frac{°C}{kWh}$
3-5	2.1 kW	-4.524 $\frac{°C}{kWh}$
6	2.5 kW	-3.8 $\frac{°C}{kWh}$
7 or more	3.5 kW	-2.714 $\frac{°C}{kWh}$

3.1.3.3. Thermal-electric

For this scenario each household gets a water heater on top of their air conditioner unit and flexible appliances. The properties of these water heaters depend on the number of persons in the household. These properties are shown in table 3.11.

Table 3.11: Water heaters properties.

Persons	**Rated power**	**Capacity**
1	2 kW	60 kg
2	2 kW	100 kg
3	2 kW	150 kg
4	2 kW	200 kg
5	3 kW	250 kg
6	3 kW	300 kg
7 or more	3 kW	350 kg

3.1.3.4. Fully flexible

In this scenario each hosuhold gets an EV or PHEV on top of their water heater, air conditioner and flexible appliances. The inner logic of the ALPG assigns the EV first to the households with longer commute distances. The proportion of EV and PHEV used in the simulation is 80 % EV and 20 % PHEV.

3.1.4. Multi-part tariff design

This section describes the steps taken to determine a three-part tariff that decouples capacity and energy charges, reflecting the changes in energy prices throughout the day, while keeping it comparable to the tariff currently in place.

Firstly, I clustered the hours of a day into three blocks based on energy marginal price. I decided to use three daily blocks to mimic the time-of-use tariff of the Santiago de Chile metro network, as this could enhance the assimilation of a new electricity tariff type among the population.

Then, I defined a monthly billed tariff that would consist of a fixed charge, a capacity charge, and an energy charge. In this scheme, the capacity charge would be based on the maximum hourly-average power demand for each household within a month, and the energy charge would apply to the amount of energy imported from the grid in each daily block. Then I calculated the tariff prices that ensure no changes in revenue when customers do not install solar systems, nor do they use an EMS when compared to the current BT1 tariff.

3.1.4.1. Energy price clustering

To cluster energy prices into three blocks, I used the 2021 data for the *Quillota* node of the electrical national system (SEN) [67], known as the reference for marginal prices for Chile's central regions. Applying the k-means algorithm with Euclidean distance, I obtained the clusters shown in figure 3.2. The average marginal price of each cluster was divided by the average price of block A, to get a normalized price of energy.

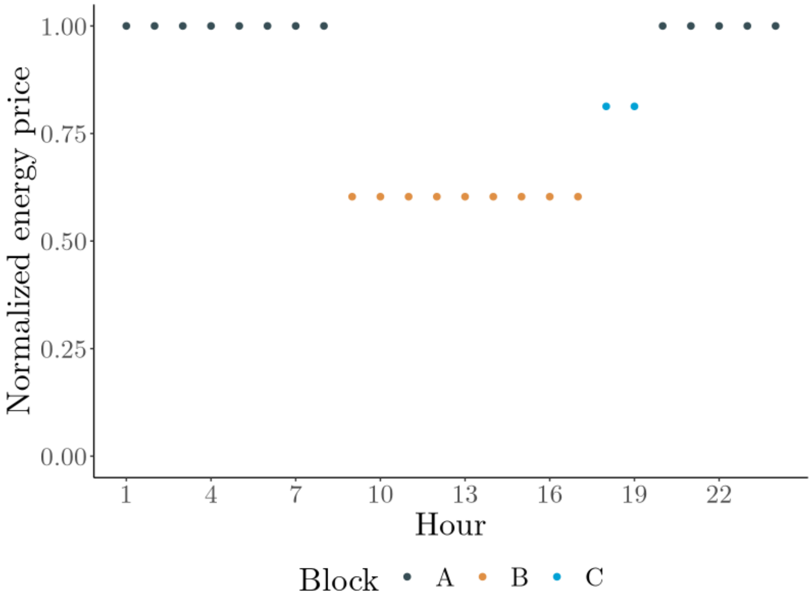


Figure 3.2: 2021 *Quillota's* marginal price clusters.

3.1.4.2. Revenue-neutral TOU tariff

In the previous chapter, we discussed that the BT1 tariff consists of two parts: a fixed charge that applies per customer, and a volumetric part that charges based on the amount of energy consumed in a month (see equation 2.1). Table 3.12 presents the values used in the simulation for each component of BT1. These values were calculated using the ratios available in [68] for typical BT1 billing in the RM, in addition to the 2021 tariff data from Enel [69], which is the main distributor in RM. The values are presented in cents of US dollars, using the annual exchange rate of 2021, reported by Chile's central bank [70].

Table 3.12: BT1 tariff components.

Component	**Value**	**Value with VAT**
D_{admin}	$75.783\ \frac{¢}{\text{client}}$	$90.182\ \frac{¢}{\text{client}}$
T	$1.458\ \frac{¢}{kWh}$	$1.735\ \frac{¢}{kWh}$
G_{energy}	$8.706\ \frac{¢}{kWh}$	$10.36\ \frac{¢}{kWh}$
$G_{capacity}$	$1.72\ \frac{¢}{kWh}$	$2.047\ \frac{¢}{kWh}$
$D_{capacity}$	$2.203\ \frac{¢}{kWh}$	$2.622\ \frac{¢}{kWh}$
PS	$0.072\ \frac{¢}{kWh}$	VAT-exempt

To define prices of the three-part and time-of-use tariff (hereafter referred to as TOU3) that ensure the same revenue for utilities than the current BT1 tariff, I followed the steps described below.

Firstly, I assumed that BT1 is efficient and covers all transmission, distribution, and generation costs, similar to the approach taken in [34]. Accordingly, I calculated the yearly BT1 revenue for each component in the base scenario, which consists of conventional households without solar generation. The BT1 revenue was calculated with equations 3.2, 3.3 and 3.4. Here, $P_{h,t}$ represents the average power demand of household h at time step t, H represents the set of all households, m represents the index of months, and Y represents the set of all time steps t in a year.

$$\text{(Aggregated energy)} \quad E_t = \sum_{h \in H} P_{h,t} \cdot \Delta t \quad \forall t \in Y \tag{3.1}$$

$$\text{(Fixed revenue)} \quad FR_{BT1} = \sum_{m=1}^{12} \sum_{h \in H} D_{admin} \tag{3.2}$$

$$\text{(Capacity revenue)} \quad CR_{BT1} = \sum_{t \in Y} E_t \cdot (T + G_{capacity} + D_{capacity} + PS) \tag{3.3}$$

$$\text{(Energy revenue)} \quad ER_{BT1} = \sum_{t \in Y} E_t \cdot G_{energy} \tag{3.4}$$

Next, I calculated the components of TOU3, ensuring that it generates the same revenue as BT1.

The revenue of TOU3 is defined by equations 3.5, 3.6 and 3.7. Here, $P_{h,m}^{max}$ represents the maximum value of $P_{h,t}$ for household h in the month m, NEP_t is the normalized price of energy in time step t (see clusters in figure 3.2), and EF is a factor that multiplies the normalized price of energy.

By calculating the energy component as $NEP_t \cdot EF$, the TOU3 tariff proportionally reflects the variation in marginal prices across the clusters defined for node *Quillota*.

In these equations, FC_{TOU3}, CC_{TOU3}, and $EC_{TOU3,t}$ represent the fixed, capacity, and energy components of TOU3, respectively.

$$\text{(Fixed revenue)} \quad FR_{TOU3} = \sum_{m=1}^{12} \sum_{h \in H} FC_{TOU3} \tag{3.5}$$

$$\text{(Capacity revenue)} \quad CR_{TOU3} = \sum_{m=1}^{12} \sum_{h \in H} CC_{TOU3} \cdot P_{h,m}^{max} \tag{3.6}$$

$$\begin{aligned} \text{(Energy component)} \quad & EC_{TOU3,t} = NEP_t \cdot EF \quad \forall t \in Y \\ \text{(Energy revenue)} \quad & ER_{TOU3} = \sum_{t \in Y} E_t \cdot EC_{TOU3,t} \end{aligned} \tag{3.7}$$

By imposing the revenue restrictions described in equation 3.8, I determined the values for FC_{TOU3}, CC_{TOU3}, and EF. Table 3.13 presents the values obtained.

$$FR_{TOU3} = FR_{BT1} \quad CR_{TOU3} = CR_{BT1} \quad ER_{TOU3} = ER_{BT1} \tag{3.8}$$

Table 3.13: TOU3 tariff components.

Component/factor	**Value**	**Value with VAT**
FC_{TOU3}	$75.783\ \frac{¢}{\text{client}}$	$90.182\ \frac{¢}{\text{client}}$
CC_{TOU3}	$7.55797\ \frac{\$}{kW}$	$8.99398\ \frac{\$}{kW}$
EF	$10.314\ \frac{¢}{kWh}$	$12.273\ \frac{¢}{kWh}$

3.1.5. HEMS problem

In the previous chapter, the prosumer problem from [45] was introduced. I used that model to simulate the optimal operation of each household on a daily basis over four weeks of operation, with one week per season. This problem was solved for each type of household (conventional, air-conditioned, thermal-electric, and fully flexible), for each type of tariff (BT1 and TOU3), and for different values of household satisfaction (ω_2).

Regarding the BT1 tariff, the daily energy cost function J_1 used in the prosumer problem is described in equations 3.9 and 3.10. Here, the fixed cost D_{admin} is divided by the average duration of a month, the price of imports is charged with VAT, and the price for exports is the generation component for energy of the BT1 tariff.

$$J_1 = \frac{D_{admin}}{30.5} \cdot (1 + VAT) + \sum_{t \in \mathcal{T}} \Big[\lambda_{buy}(t) \cdot P_{buy}(t) \cdot \Delta t - \lambda_{sell}(t) \cdot P^{PV}_{sell}(t) \cdot \Delta t \Big] \tag{3.9}$$

$$\begin{aligned} \lambda_{buy} &= (1 + VAT) \cdot (T + G_{capacity} + G_{energy} + D_{capacity}) + PS \\ \lambda_{sell} &= G_{energy} \end{aligned} \tag{3.10}$$

Regarding the TOU3 tariff, the daily cost J_1 is defined in equation 3.11. Here, both the capacity and fixed costs are divided by the average duration of a month to obtain a daily price. For this tariff, the prices of imports and exports are the same, although VAT charges apply when the user is importing energy from the grid. Additionally, the variable P^{max} is introduced to the problem, indicating the maximum power draw from the grid in a day. Accordingly, constraint 3.12 describes the relationship between P^{max} and the power imports.

$$\begin{aligned} J_1 = \Big(\frac{FC_{TOU3}}{30.5} + \frac{CC_{TOU3}}{30.5} \cdot P^{max} \Big) \cdot (1 + VAT) + \\ \sum_{t \in \mathcal{T}} \Big[EC_{TOU3,t} \cdot \Big((1 + VAT) \cdot P_{buy}(t) - P^{PV}_{sell}(t) \Big) \cdot \Delta t \Big] \end{aligned} \tag{3.11}$$

$$P^{max} \geq P_{buy}(t) \quad \forall t \in \mathcal{T} \tag{3.12}$$

The rest of parameters used to solve the prosumer problem are presented in table 3.14.

Table 3.14: Prosumer problem parameters.

Parameter	**Value**
Washing machine ϵ	0.05
Dishwasher ϵ	0.05
Electric vehicle ϵ	0.05
Water heater ϵ	0.1
Water specific heat capacity	$4182 \ \frac{J}{kg \cdot K}$
Water heater inlet temperature T_{cold}	$30°C$
Water heater desired temperature $T_{c,WH}(t)$	$50°C$
Water heater downward range θ^{dn}	$5°C$
Water heater upward range θ^{up}	$15°C$
Water heater initial temperature T_0	$50°C$
Air conditioner heat exchange factor η	0.9
Air conditioner ϵ	0.1
Air conditioner downward range θ^{dn}	$3°C$

Air conditioner upward range θ^{up}	$5°C$
VAT	19%
Satisfaction ω_2 (3 cases)	0, 0.25, 0.5
Time step	1 hour

3.2. Results

This section presents the simulation results for each household type, organized by metric. Within each subsection, the metrics are grouped by tariff scheme and satisfaction parameter, making it easy to compare results. Additionally, reference values are provided for each metric, calculated for the same households in (at least one of) two scenarios: one where they do not have solar generation or energy management (labeled “w/o DG”), and another where they have solar generation but no energy management (labeled “w/o EMS”). This allows for a clear comparison of the impact of solar generation and energy management on the various metrics.

Regarding the definition of each metric, “Peak load” corresponds to the maximum average power imported from the grid ($P_{buy}(t)$ in the prosumer problem) of each household in every week of simulation. “Energy savings” refer to savings in energy costs for each household in every scenario. These savings were calculated using the energy cost of the case “w/o EMS” as a reference to reflect the savings achieved by implementing the EMS. Equations in (3.13) describe how savings were calculated for each scenario. The values related to currency were rounded to improve readability.

$$\begin{aligned} \text{Savings}_{\text{scenario}}[\$] &= Cost_{\text{reference}} - Cost_{\text{scenario}} \\ \text{Savings}_{\text{scenario}}[\%] &= 100 \cdot \frac{\text{Savings}_{\text{scenario}}[\$]}{Cost_{\text{reference}}} \end{aligned} \tag{3.13}$$

As for the metric “thermal curtailment”, it refers to the reduction in energy demanded for a thermal appliance in a year due to cost savings. This value is calculated by comparing the energy demanded in each scenario with that demanded in the reference case “w/o EMS”, as described in equations 3.14.

$$\text{Curtailment}_{\text{scenario}}[kWh] = Energy_{\text{reference}} - Energy_{\text{scenario}} \tag{3.14}$$

Finally, each subsection includes figures that provide additional context for the results. In addition, the tables for each metric display the average value and standard deviation across households.

3.2.1. Conventional

This section presents the results obtained in the case of conventional households implementing the EMS to manage dishwasher and washing machine use.

3.2.1.1. Peak load

Figure 3.3 shows the average load curves of conventional households when ω_2 is equal to 0.5 (high value of satisfaction) alongside the average load curves of the reference cases. The figure illustrates that by only managing dishwashers and washing machines, there is limited potential for peak clipping or load shifting.

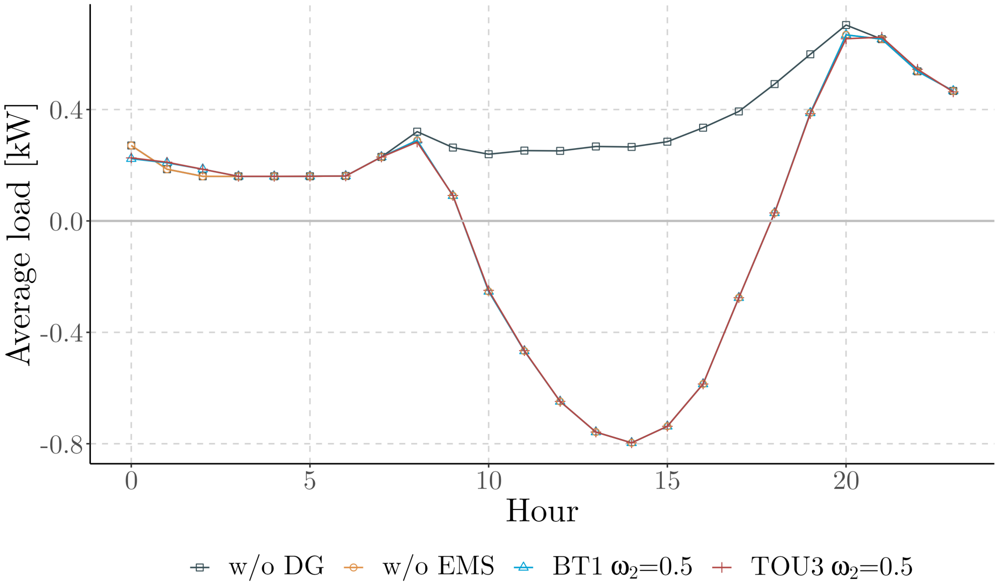


Figure 3.3: Average load across conventional households.

More detail on peak load reduction is found in table 3.15, which displays the average peak load of conventional households in each season of the year. This table indicates, for example, that for both tariffs the average peak load decreases by less than 0.1 kW across all seasons when the parameter ω_2 is set to 0.5.

Table 3.15: Average peak load for conventional households.

Scenario	Autumn [kW]	Spring [kW]	Summer [kW]	Winter [kW]
BT1 ω_2=0	1.54 ±0.43	1.36 ±0.36	1.38 ±0.42	1.79 ±0.52
BT1 ω_2=0.25	1.67 ±0.5	1.46 ±0.41	1.52 ±0.48	1.92 ±0.58
BT1 ω_2=0.5	1.67 ±0.5	1.46 ±0.41	1.52 ±0.48	1.92 ±0.58
TOU3 ω_2=0	1.44 ±0.39	1.25 ±0.32	1.26 ±0.34	1.69 ±0.49
TOU3 ω_2=0.25	1.47 ±0.38	1.29 ±0.31	1.28 ±0.32	1.72 ±0.48
TOU3 ω_2=0.5	1.58 ±0.42	1.42 ±0.37	1.46 ±0.42	1.83 ±0.5
w/o DG	1.71 ±0.48	1.56 ±0.42	1.65 ±0.46	1.94 ±0.57
w/o EMS	1.67 ±0.5	1.46 ±0.41	1.52 ±0.48	1.92 ±0.58

3.2.1.2. Energy cost

Regarding energy cost, figure 3.4 presents the dispersion of annual costs obtained across conventional households in each scenario. It is important to know that these results are not meant to be concentrated, given that the households were simulated to represent the different family realities of Chile's metropolitan region.

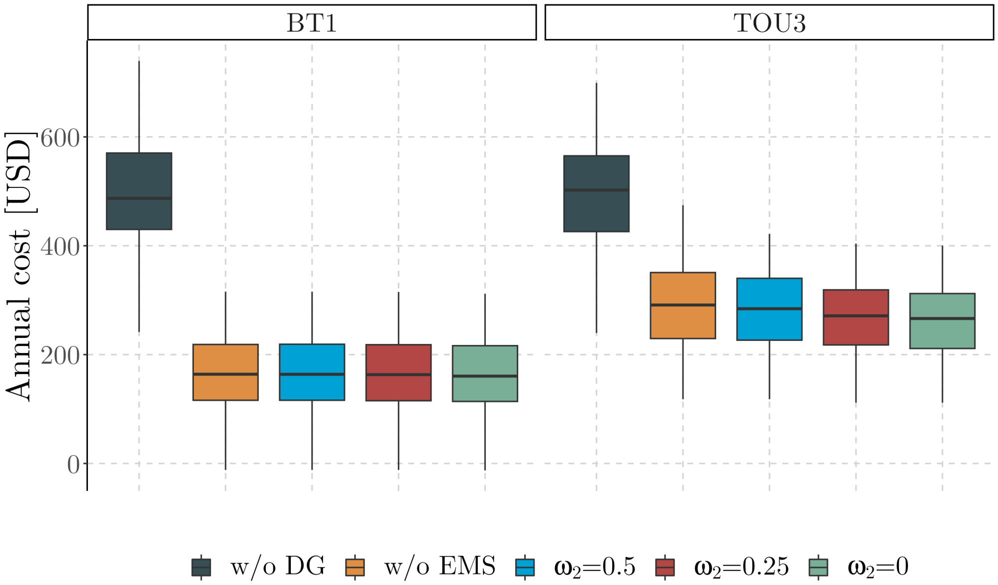


Figure 3.4: Annual energy costs for conventional households.

In the figure, each box visualizes five summary statistics (the median, two hinges, and two whiskers), and all outlying points individually. The lower and upper hinges correspond to the first and third quartiles. The upper whisker extends from the hinge to the largest value no further than 1.5 times the distance between the first and third quartiles, or interquartile range (IQR). The lower whisker extends from the lower hinge to the smallest value, at most 1.5 IQR of the hinge. Data beyond the end of the whiskers are outlying points and would have been plotted individually. In the case of conventional households, there are not any outlying points.

More details about the savings achieved by the implementation of the EMS are presented in table 3.16. In this case, for example, it is seen that conventional households with tariff TOU3, saved an average of \$8 per year when a ω_2 parameter of 0.5 is used, equivalent to 2.24% of their tariff when compared to the case of not having implemented an EMS. For better context, the table also shows the average annual costs of each scenario, and the cost per unit of energy in cents.

Table 3.16: Average annual cost and savings for conventional households.

Satisfaction	Tariff	Cost [\$]	Cost [¢/kWh]	Savings [\$]	Savings [%]
ω_2=0	BT1	164 ±66	6 ±2	4 ±4	2.42 ±4.88
ω_2=0.25	BT1	167 ±67	6 ±2	1 ±2	0.45 ±1.21
ω_2=0.5	BT1	168 ±67	6 ±2	0 ±1	-0.02 ±0.39
ω_2=0	TOU3	263 ±66	9 ±2	27 ±23	8.54 ±6.41
ω_2=0.25	TOU3	268 ±67	10 ±2	23 ±20	7.02 ±5.67
ω_2=0.5	TOU3	282 ±73	10 ±2	8 ±13	2.24 ±3.47

3.2.2. Air-conditioned

This section presents the results obtained in the case of air-conditioned households implementing the EMS to manage the temperature set-point of AC units, in addition to dishwasher and washing machine use.

3.2.2.1. Peak load

Figure 3.5 shows the average load curves of air-conditioned households when ω_2 is equal to 0.5 alongside the average load curves of the reference cases. For this type of household, peak-clipping occurs in the afternoon hours using both tariff schemes.

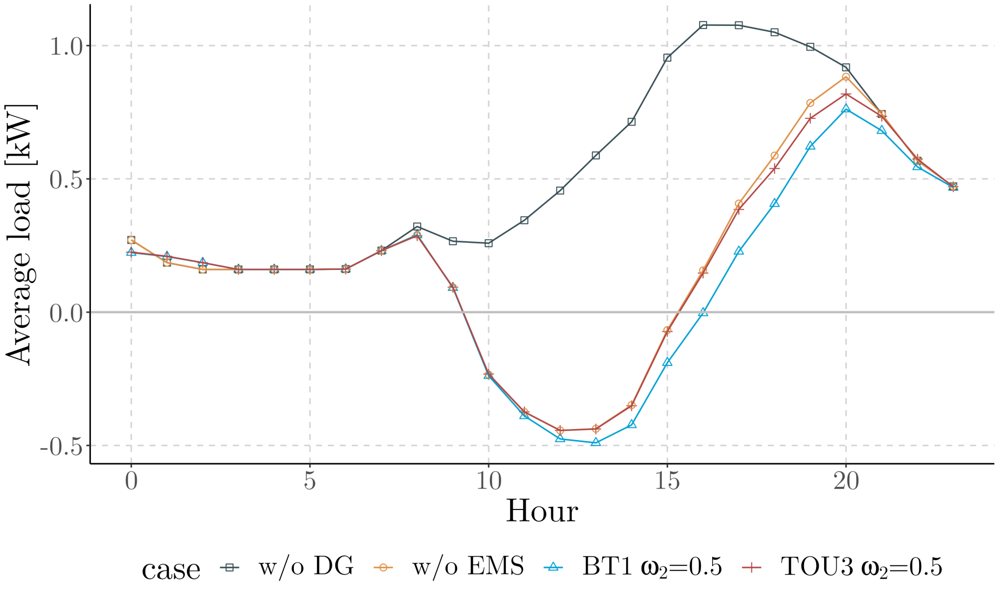


Figure 3.5: Average load across air-conditioned households.

The detail of how the EMS affects peak load in each season of the year is contained in table 3.17, which displays the average peak loads of air-conditioned households in each scenario with the reference cases' values at the bottom of the table.

Table 3.17: Average peak load for air-conditioned households.

Scenario	Autumn [kW]	Spring [kW]	Summer [kW]	Winter [kW]
BT1 ω_2=0	1.56 ±0.43	1.53 ±0.39	1.63 ±0.44	1.79 ±0.52
BT1 ω_2=0.25	1.67 ±0.5	1.63 ±0.41	1.75 ±0.49	1.92 ±0.58
BT1 ω_2=0.5	1.69 ±0.49	1.73 ±0.4	1.88 ±0.45	1.92 ±0.58
TOU3 ω_2=0	1.46 ±0.39	1.44 ±0.36	1.52 ±0.39	1.69 ±0.49
TOU3 ω_2=0.25	1.48 ±0.38	1.48 ±0.34	1.55 ±0.39	1.72 ±0.48
TOU3 ω_2=0.5	1.59 ±0.42	1.64 ±0.36	1.74 ±0.4	1.83 ±0.5
w/o DG	1.87 ±0.53	2.58 ±0.53	2.77 ±0.52	2.02 ±0.57
w/o EMS	1.73 ±0.51	2 ±0.49	2.2 ±0.55	1.93 ±0.58

3.2.2.2. Energy cost

Regarding energy cost for air-conditioned households, figure 3.6 presents the dispersion of annual cost, while table 3.18 details the average costs and savings achieved. These figure and table are analogous to those shown for conventional households.

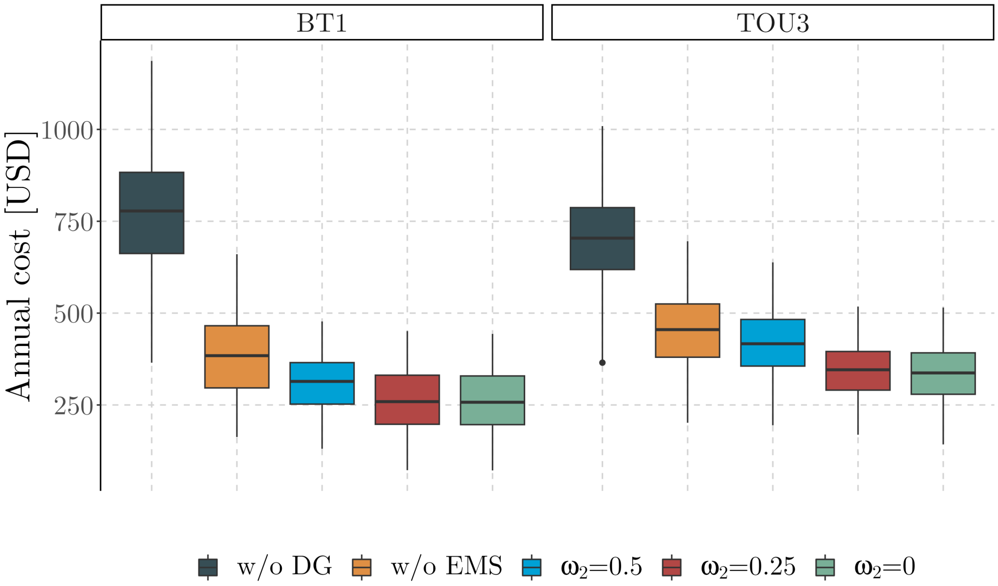


Figure 3.6: Annual energy costs for air-conditioned households.

Table 3.18: Average annual cost and savings for air-conditioned households.

Satisfaction	Tariff	Cost [$]	Cost [¢/kWh]	Savings [$]	Savings [%]
ω_2=0	BT1	262 ±84	6 ±2	120 ±36	32.01 ±7.28
ω_2=0.25	BT1	265 ±85	6 ±2	117 ±36	31.28 ±7.35
ω_2=0.5	BT1	309 ±70	7 ±2	74 ±57	17.01 ±12.63
ω_2=0	TOU3	337 ±77	8 ±2	115 ±36	25.41 ±5.24
ω_2=0.25	TOU3	347 ±74	8 ±2	106 ±40	22.83 ±6.07
ω_2=0.5	TOU3	416 ±90	9 ±2	36 ±19	7.78 ±3.15

3.2.2.3. Thermal curtailment

Regarding thermal curtailment, figure 3.7 displays the average temperatures in air-conditioned households during summer for each type of tariff scheme, illustrating how the EMS trades higher temperatures for economic savings. These temperatures are presented with different lines for each level of satisfaction parameter (ω_2) studied, alongside the curve for the reference case. In contrast to results related to peak load and energy cost, the reference case without DG is omitted, as the presence of solar generation has no effect on AC use. Thus, the curve for the case without DG would be the same as the curve for the case without EMS.

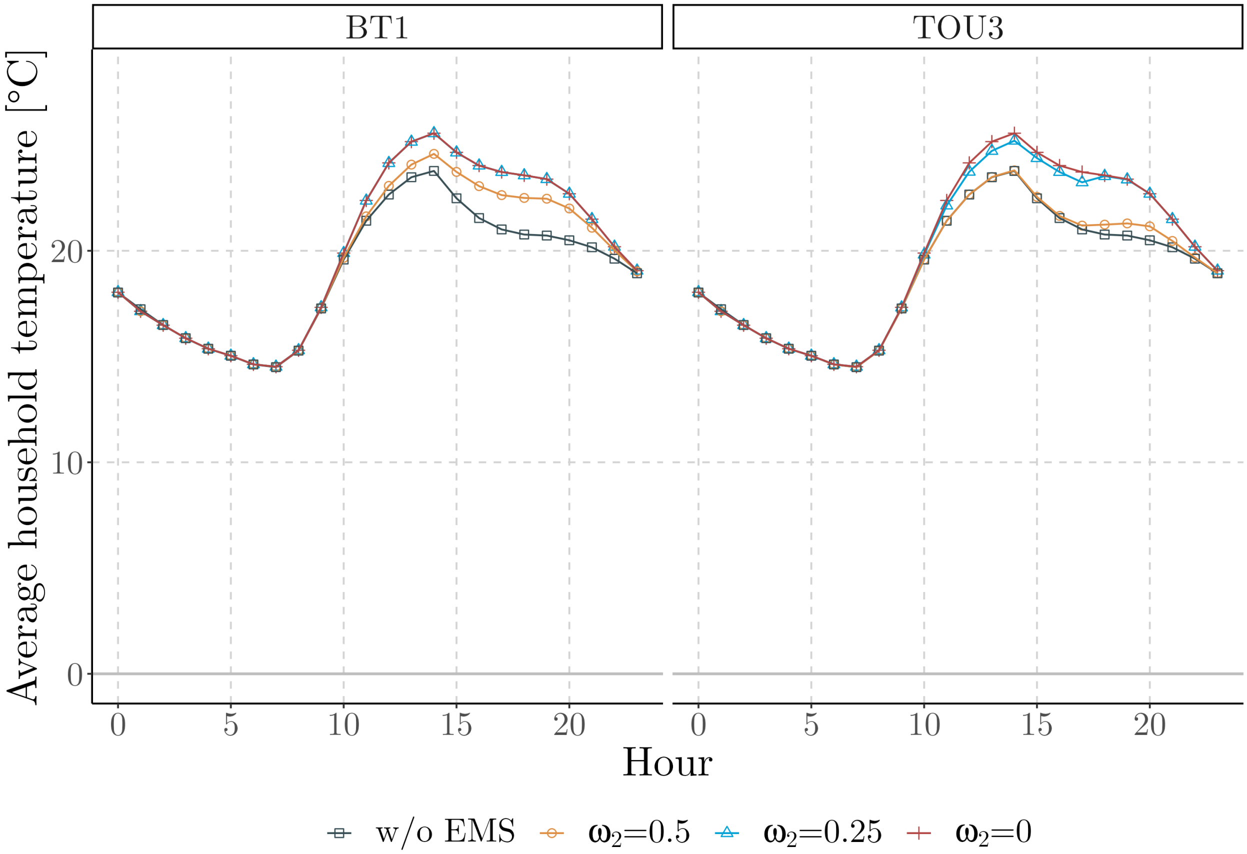


Figure 3.7: Summer room temperatures for air-conditioned households.

The details of how the EMS affects the curtailment of thermal energy throughout the year are presented in table 3.19. The second column of this table displays the average of annual energy consumption of AC units in air-conditioned households for each tariff and satisfaction parameter studied. The third column indicates the average curtailment experienced by air-conditioned households in each scenario studied. The last row presents the reference case values for better context.

Table 3.19: Average annual consumption and curtailment of AC for air-conditioned households.

Scenario	AC energy [kWh]	AC curtailment [kWh]
BT1 ω_2=0	836 ±322	805 ±241
BT1 ω_2=0.25	837 ±321	804 ±243
BT1 ω_2=0.5	1202 ±377	439 ±339
TOU3 ω_2=0	836 ±322	805 ±241
TOU3 ω_2=0.25	920 ±292	721 ±309
TOU3 ω_2=0.5	1563 ±512	78 ±44
w/o EMS	1641 ±544	0 ±0

3.2.3. Thermal-electric

This section presents the results obtained from simulating thermal-electric households implementing the EMS to manage the temperature set-point of electric water heaters, along with controlling the use of AC units, dishwashers, and washing machines.

3.2.3.1. Peak load

Figure 3.8 and table 3.20 depict the impact of the EMS on peak loads of thermal-electric households, similar to sections 3.2.2.1 and 3.2.1.1.

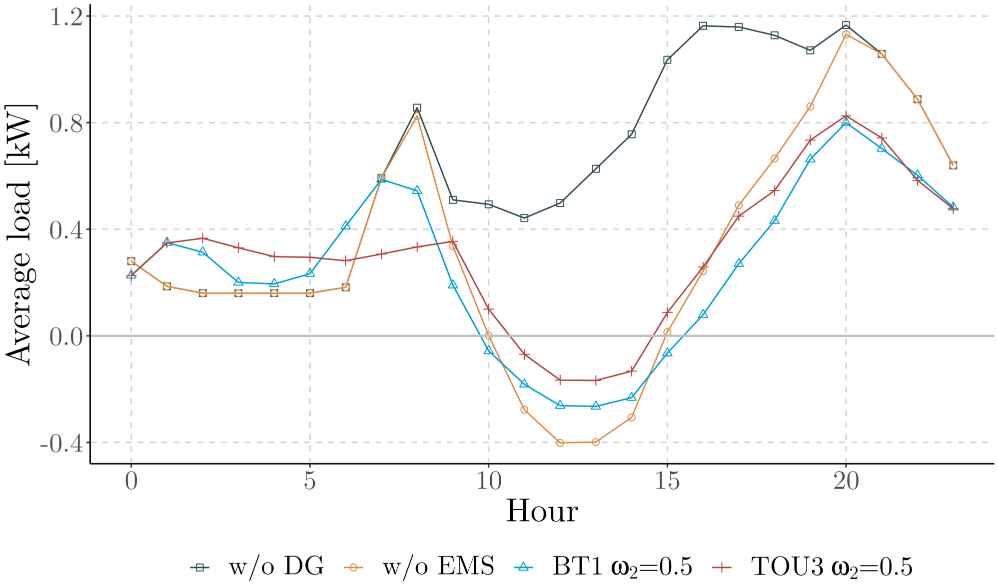


Figure 3.8: Average load across thermal-electric households.

Table 3.20: Average peak load for thermal-electric households.

Scenario	Autumn [kW]	Spring [kW]	Summer [kW]	Winter [kW]
BT1 ω_2=0	2.29 ±0.83	2.17 ±0.8	2.28 ±0.82	2.45 ±0.82
BT1 ω_2=0.25	2.23 ±0.79	2.1 ±0.72	2.27 ±0.76	2.48 ±0.8
BT1 ω_2=0.5	2.39 ±0.77	2.37 ±0.7	2.54 ±0.68	2.57 ±0.81
TOU3 ω_2=0	1.55 ±0.44	1.53 ±0.38	1.6 ±0.41	1.75 ±0.5
TOU3 ω_2=0.25	1.53 ±0.4	1.52 ±0.36	1.6 ±0.4	1.74 ±0.48
TOU3 ω_2=0.5	1.63 ±0.43	1.68 ±0.37	1.78 ±0.41	1.86 ±0.5
w/o DG	2.62 ±0.77	3 ±0.76	3.24 ±0.8	2.79 ±0.87
w/o EMS	2.57 ±0.78	2.68 ±0.78	2.9 ±0.81	2.75 ±0.87

3.2.3.2. Energy cost

Regarding energy cost for thermal-electric households, figure 3.9 presents the dispersion of annual cost, while table 3.21 details the average costs and savings achieved. These figure and table are analogous to those shown for conventional and air-conditioned households.

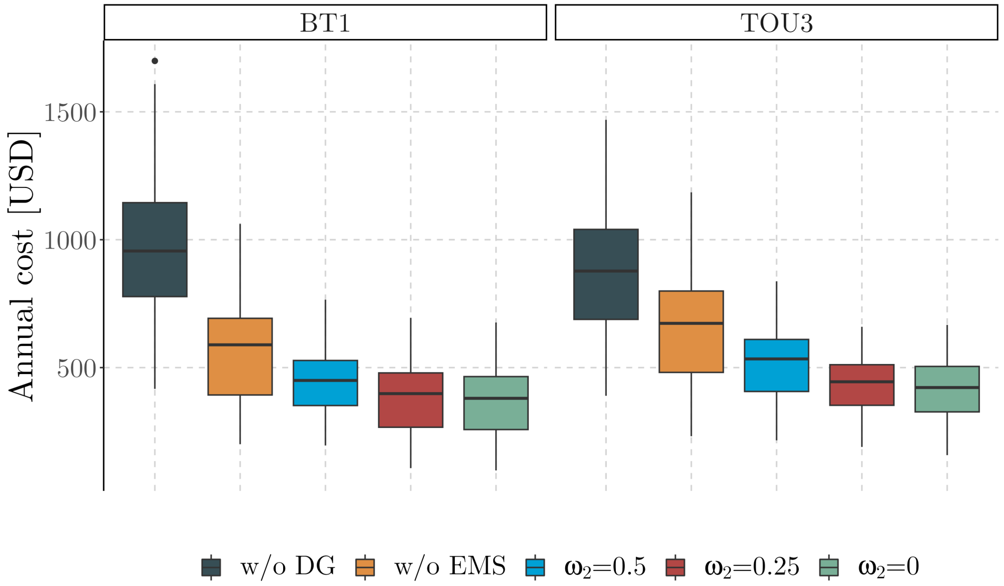


Figure 3.9: Annual energy costs for thermal-electric households.

Table 3.21: Average annual cost and savings for thermal-electric households.

Satisfaction	Tariff	Cost [$]	Cost [¢/kWh]	Savings [$]	Savings [%]
ω_2=0	BT1	373 ±130	7 ±1	192 ±70	34.09 ±5.89
ω_2=0.25	BT1	387 ±133	7 ±1	178 ±66	31.58 ±5.59
ω_2=0.5	BT1	450 ±122	8 ±1	116 ±80	17.87 ±10.52
ω_2=0	TOU3	417 ±112	8 ±1	236 ±103	35.11 ±7.89
ω_2=0.25	TOU3	435 ±107	8 ±2	219 ±106	31.93 ±8.53
ω_2=0.5	TOU3	516 ±135	9 ±1	138 ±77	19.9 ±7.07

3.2.3.3. Thermal curtailment

Regarding thermal curtailment, figure 3.10 displays the average temperatures in thermal-electric households during summer for each type of tariff scheme, while table 3.22 illustrates the annual curtailment of AC energy consumption. This is analogous to figure 3.7 and table 3.19, which address air-conditioned households in Section 3.2.2.3.

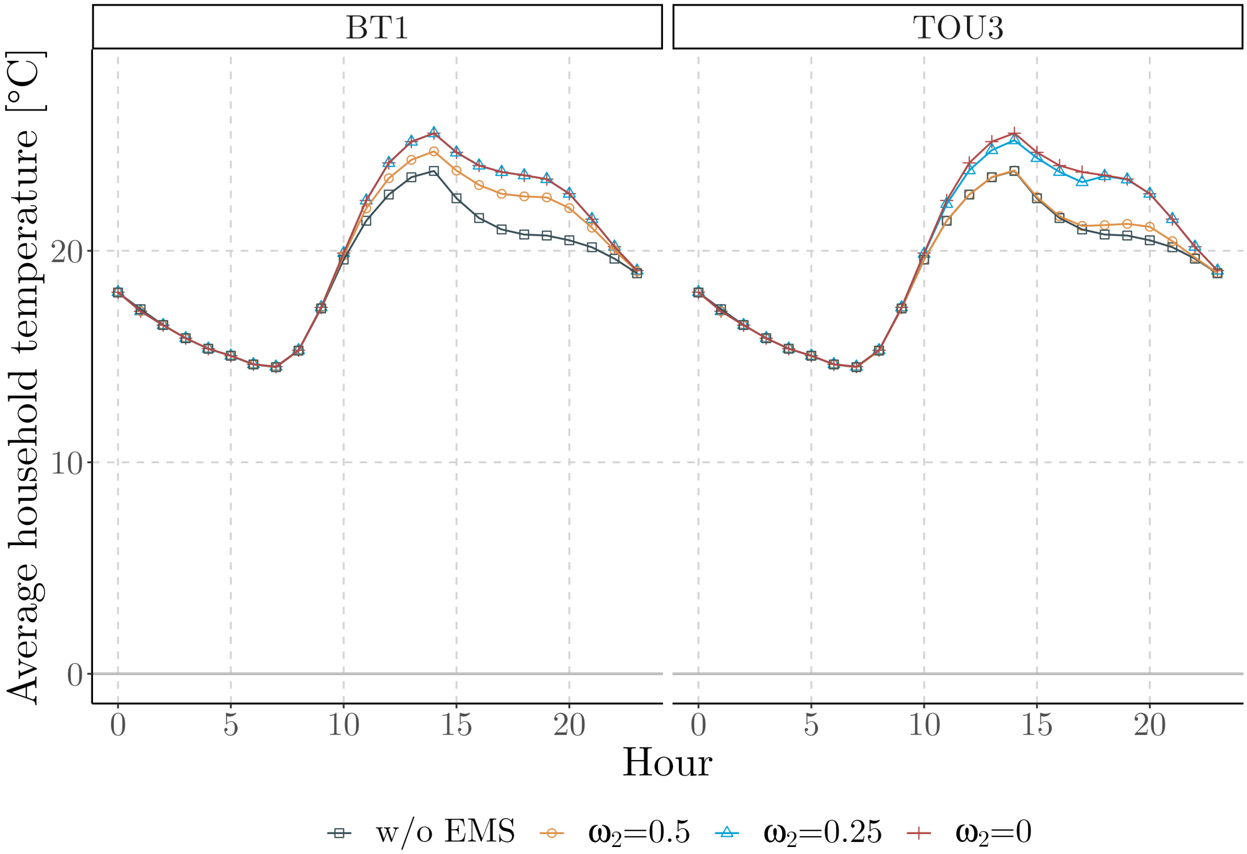


Figure 3.10: Summer room temperatures for thermal-electric households.

Table 3.22: Average annual consumption and curtailment of AC for thermal-electric households.

Scenario	AC energy [kWh]	AC curtailment [kWh]
BT1 ω_2=0	836 ±322	805 ±241
BT1 ω_2=0.25	836 ±321	805 ±242
BT1 ω_2=0.5	1151 ±362	490 ±380
TOU3 ω_2=0	836 ±322	805 ±241
TOU3 ω_2=0.25	914 ±291	727 ±305
TOU3 ω_2=0.5	1567 ±515	74 ±42
w/o EMS	1641 ±544	0 ±0

Similarly, figure 3.11 displays the average temperatures of hot water for each studied tariff scheme, illustrating how the EMS trades lower hot water temperatures for economic savings. Meanwhile, table 3.23 provides details on the annual energy consumption and curtailment associated with water heating in each scenario.

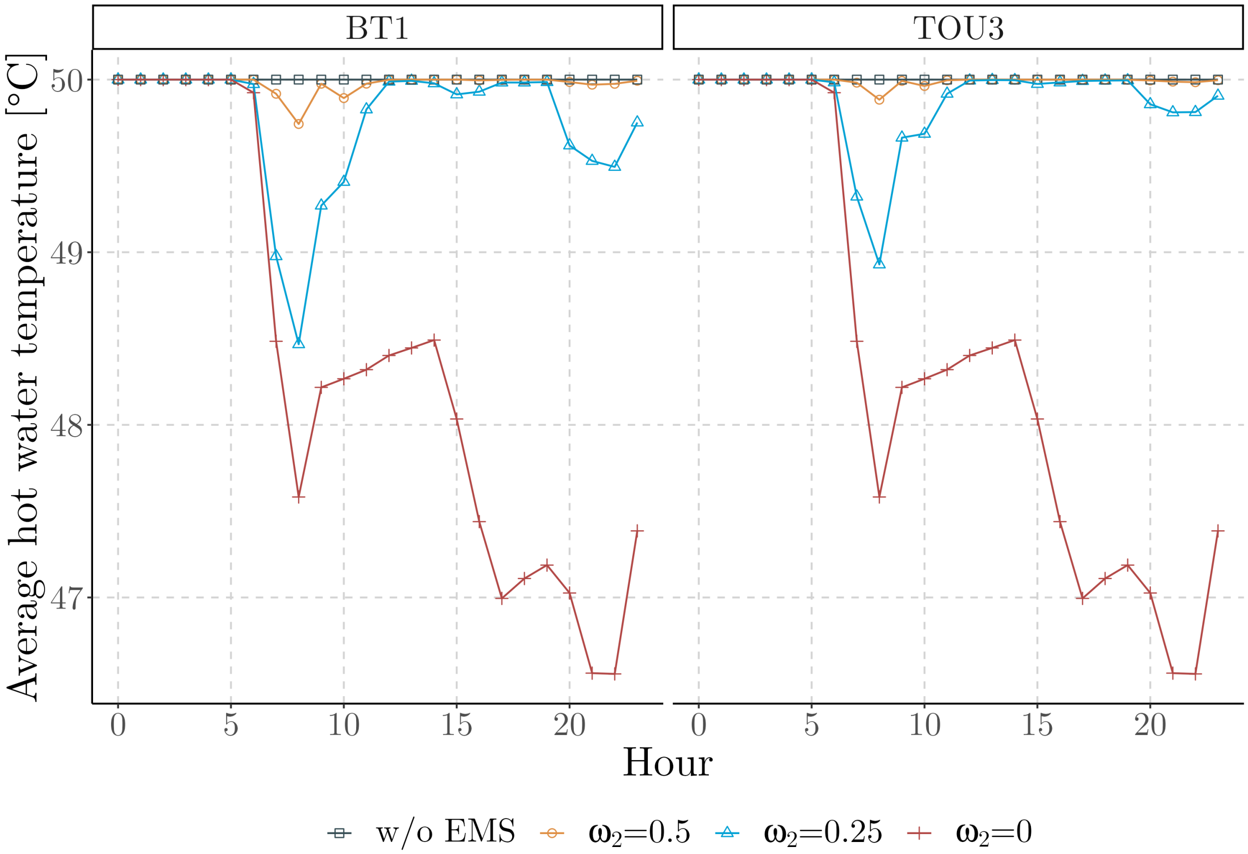


Figure 3.11: Hot water temperatures for thermal-electric households.

Table 3.23: Average annual consumption and curtailment of WH for thermal-electric households.

Scenario	WH energy [kWh]	WH curtailment [kWh]
BT1 ω_2=0	846 ±494	281 ±164
BT1 ω_2=0.25	950 ±526	176 ±138
BT1 ω_2=0.5	1094 ±618	33 ±58
TOU3 ω_2=0	846 ±494	281 ±164
TOU3 ω_2=0.25	1009 ±552	118 ±119
TOU3 ω_2=0.5	1113 ±640	14 ±34
w/o EMS	1127 ±658	0 ±0

3.2.4. Fully flexible

This section presents the results obtained from simulating fully-flexible households implementing the EMS to manage EV battery charging, alongside controlling the use of electric water heaters, AC units, dishwashers, and washing machines.

3.2.4.1. Peak load

Figure 3.12 and table 3.24 depict the impact of the EMS on peak loads of fully-flexible households, similar to how this impact is presented for all previous household types.

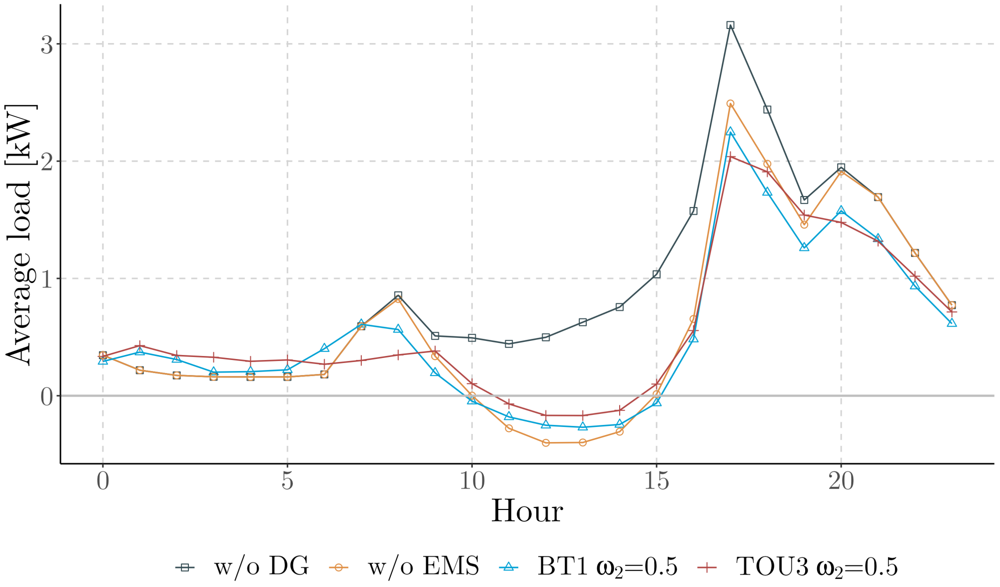


Figure 3.12: Average load across fully flexible households.

Table 3.24: Average peak load for fully flexible households.

Scenario	Autumn [kW]	Spring [kW]	Summer [kW]	Winter [kW]
BT1 ω_2=0	6.62 ±2.46	6.66 ±2.4	6.71 ±2.42	6.79 ±2.14
BT1 ω_2=0.25	6.49 ±2.32	6.59 ±2.21	6.8 ±2.23	6.74 ±2.05
BT1 ω_2=0.5	6.55 ±2.3	6.7 ±2.18	6.91 ±2.2	6.79 ±2.09
TOU3 ω_2=0	2.17 ±0.8	2.17 ±0.76	2.37 ±0.79	2.34 ±0.72
TOU3 ω_2=0.25	5.09 ±1.99	5.37 ±1.93	5.47 ±1.99	5.17 ±1.72
TOU3 ω_2=0.5	5.45 ±2.09	5.73 ±1.97	5.84 ±2.02	5.47 ±1.75
w/o DG	6.97 ±2.38	7.79 ±2.38	8.1 ±2.37	7.23 ±2.16
w/o EMS	6.8 ±2.34	7.24 ±2.3	7.49 ±2.3	7.05 ±2.13

3.2.4.2. Energy cost

Regarding energy cost for fully-electric households, figure 3.13 presents the dispersion of annual cost, while table 3.25 details the average costs and savings achieved. These figure and table are analogous to those shown for previous household types.

Table 3.25: Average annual cost and savings for fully flexible households.

Satisfaction	Tariff	Cost [$]	Cost [¢/kWh]	Savings [$]	Savings [%]
ω_2=0	BT1	759 ±270	9 ±2	195 ±74	21.26 ±6.84
ω_2=0.25	BT1	774 ±274	10 ±2	180 ±67	19.67 ±6.12
ω_2=0.5	BT1	836 ±264	11 ±2	118 ±81	11.38 ±7.38
ω_2=0	TOU3	754 ±238	10 ±2	601 ±196	43.95 ±6.48
ω_2=0.25	TOU3	1059 ±337	13 ±3	296 ±109	22.2 ±5.97
ω_2=0.5	TOU3	1159 ±354	15 ±3	195 ±81	14.58 ±4.47

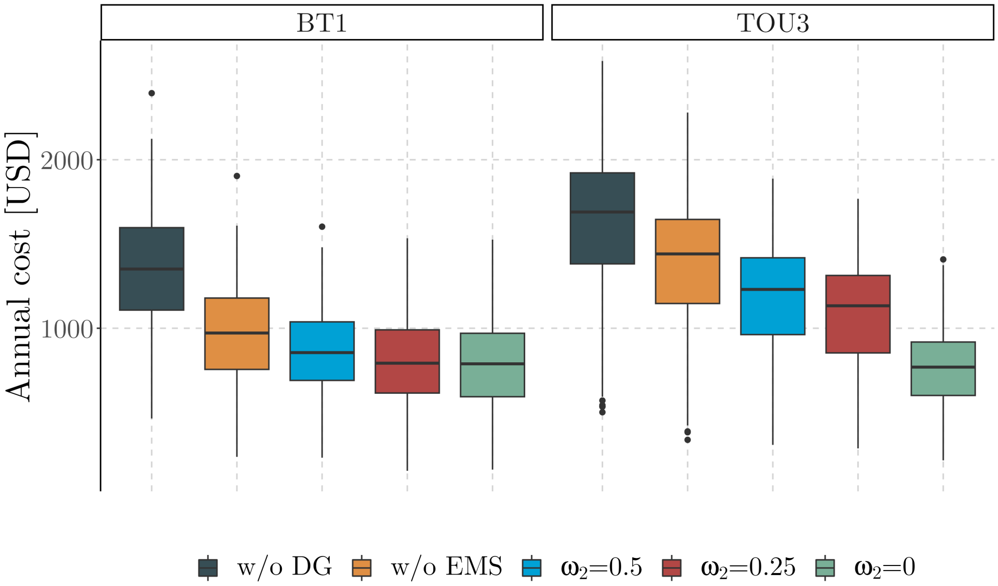


Figure 3.13: Annual energy costs for fully flexible households.

3.2.4.3. Thermal curtailment

Regarding thermal curtailment, and similar to how results are presented in section 3.2.3.3, figure 3.14 displays the average temperatures in fully-electric households during summer for each type of tariff scheme, while table 3.26 illustrates the annual curtailment of AC energy consumption.

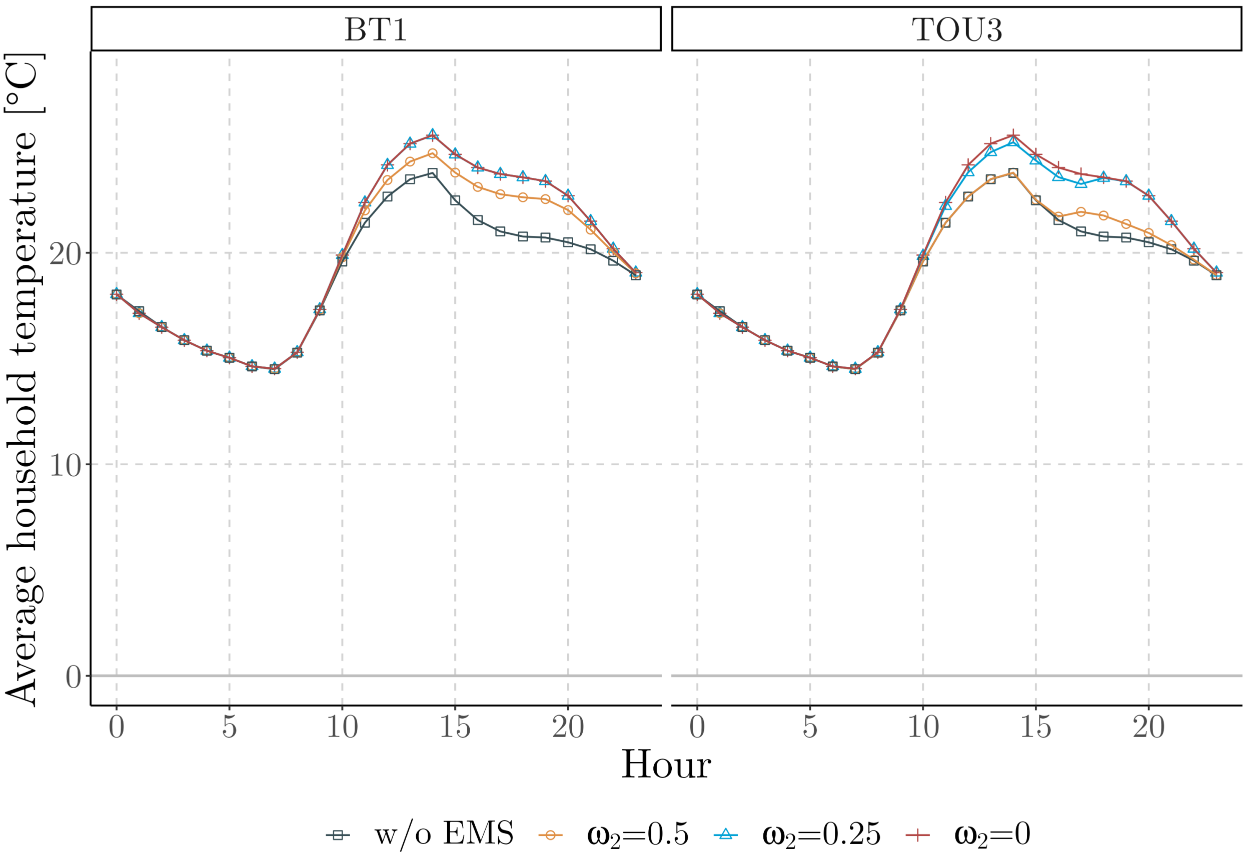


Figure 3.14: Summer room temperatures for fully flexible households.

Table 3.26: Average annual consumption and curtailment of AC for fully flexible households.

Scenario	AC energy [kWh]	AC curtailment [kWh]
BT1 ω_2=0	836 ±322	805 ±241
BT1 ω_2=0.25	836 ±321	805 ±242
BT1 ω_2=0.5	1139 ±362	502 ±385
TOU3 ω_2=0	836 ±322	805 ±241
TOU3 ω_2=0.25	919 ±292	722 ±301
TOU3 ω_2=0.5	1513 ±501	128 ±67
w/o EMS	1641 ±544	0 ±0

Lastly, figure 3.15 displays the average temperatures of hot water for each studied tariff scheme, illustrating how the EMS trades lower hot water temperatures for economic savings. Meanwhile, table 3.27 provides details on the annual energy consumption and curtailment associated with water heating in each scenario.

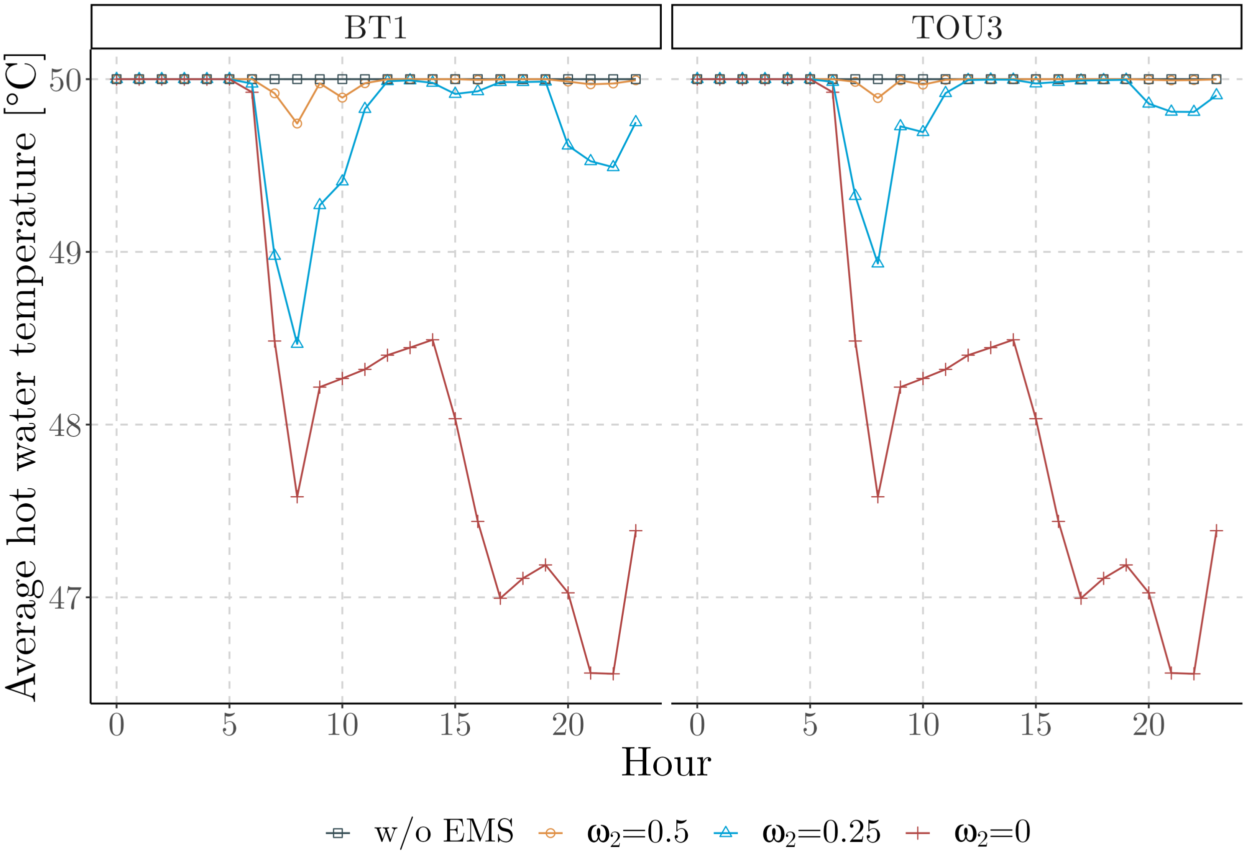


Figure 3.15: Hot water temperatures for fully flexible households.

Table 3.27: Average annual consumption and curtailment of WH for fully flexible households.

Scenario	WH energy [kWh]	WH curtailment [kWh]
BT1 ω_2=0	846 ±494	281 ±164
BT1 ω_2=0.25	950 ±526	177 ±138
BT1 ω_2=0.5	1094 ±618	33 ±58
TOU3 ω_2=0	846 ±494	281 ±164
TOU3 ω_2=0.25	1011 ±554	116 ±117
TOU3 ω_2=0.5	1114 ±641	12 ±32
w/o EMS	1127 ±658	0 ±0

4. Developing an EMaaS System

4.1. Methodology

4.1.1. Overview

To demonstrate the feasibility of an Energy Management as-a-Service (EMaaS), I developed a prototype and conducted a pilot program by deploying the system in a household located in Chile's Metropolitan Region (RM).

The prototype system was designed to be easily developed and implemented, with the server and client supporting only core functionalities for energy management, while being user-friendly. Then the pilot program was design to give insight upon automation effectiveness in demand side management, and cost reduction, taking into consideration the household specific characteristics beforehand.

After installing all the necessary hardware, the pilot program was initially planned to last only three weeks. However, due to practical challenges, an extra day was added, during which the system's operation was closely supervised. This is in contrast to the original three-week pilot period when the system operated without special supervision.

4.1.2. Design

The main concept behind EMaaS is that a third party, the *EMaaS Provider*, will handle the optimization problem for the prosumer and determine the best schedule for their appliances. This approach helps simplify the tasks at the client site and allows for more information to be utilized in the optimization process, as the EMaaS interacts with multiple clients simultaneously. As a result, not only is the complexity reduced for prosumers, but the EMaaS provider can also find solutions for its clients that, when combined, offer greater benefits for the grid and its users compared to solutions that would be generated individually by each client EMS.

For this design, shown in figure 4.1, the prosumer interacts with their flexible appliances through Home Assistant. This platform has a custom-developed integration that communicates with the provider's server using DR signaling over the Internet. By using Home Assistant, the prototype provides the user with a user-friendly interface, which can be accessed locally and remotely. It also allows control over both local and cloud-based appliances.

On the other hand, the EMaaS Provider infrastructure consists primarily of two components. The first is the Demand Response (DR) Server, which handles the data management and the communication of demand response signals between the EMaaS Provider and the client. The second component is the Home Energy Management System (HEMS) Optimizer, which solves the prosumers' optimization problem and generates the optimal scheduling of appliances.

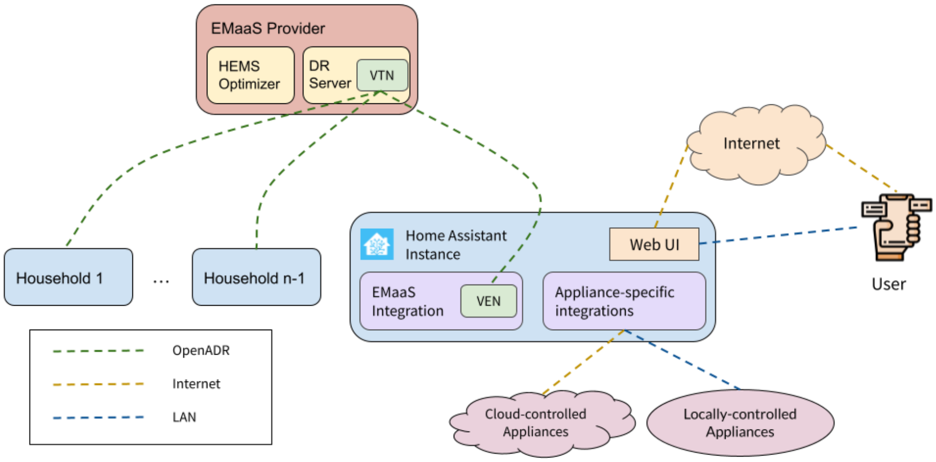


Figure 4.1: EMaaS prototype design.

4.1.3. EMaaS Provider implementation

The prototype implementation of the EMaaS Provider side consists of a laptop with an Intel i3-3110M processor and 4 GB RAM. The EMaaS Provider software runs on Ubuntu 20.04 Operating system and comprises two docker containers and three routines. These containers operate in tandem to provide the functions of the DR server, while the mentioned routines provide the functions of the HEMS optimizer.

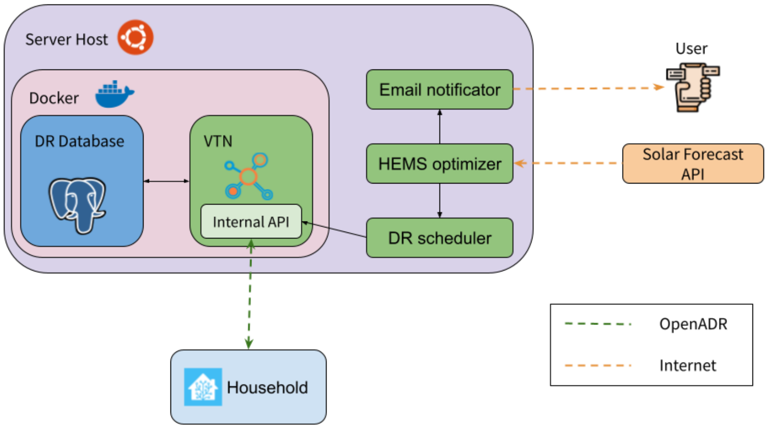


Figure 4.2: EMaaS server implementation diagram.

4.1.3.1. DR server

The DR server comprises two docker containers that operate together. The first container runs a PostgreSQL image database that stores data about the prosumer and all the DR signaling. Meanwhile, the second container runs a virtual top node (VTN) using the OpenLEADR library on a Python image that provides secure exchange of OpenADR signals with the client. To ensure secure exchange, self-signed certificates over HTTPS are used. The VTN's built-in web server was extended to expose an internal application programmable interface (API) that enables the EMaaS provider to interact with the database and use the core functionalities of the VTN. The database schema and routes exposed by the internal API of the VTN are described in tables 4.1 and 4.2.

Table 4.1: DR server database entities.

Entities	**Columns**	**Description**
customers	customer_id, customer_name, customer_phone, customer_email and customer_company.	Basic customer information.
vens	ven_id, ven_name, registration_id, fingerprint and customer_id.	Virtual end node (VEN) information. Relation n:1 with customers (One customer can have more than one VEN).
resources	resource_id, ven_id and program.	Represents individual distributed energy assets, which are managed by a single VEN. Relation n:1 with vens.
reports	ven_id, resource_id, measurement, unit, scale, value and timestamp.	Measurement data from a resource, reported periodically by the VEN. Relation n:1 with resources.
events	event_id, ven_id, canceled and timestamp.	Represents a demand response event sent from the VTN to a single VEN, and wether is was canceled. Relation n:1 with vens.
signal_intervals	event_id, signal_name, signal_type, interval_start, interval_duration and interval_signal_payload.	Intervals of demand response signals. Relation n:1 with events (one event can contain multiple intervals).

event_targets	event_id and resource_id.	Indicates which resources are targeted by a single event. Relation n:m with resources (the same event can target multiple resources).
opts	event_id, opt and timestamp.	Indicates the VEN's response to an event, wheter it opts-in or opts-out.

Table 4.2: DR server internal API endpoints.

Method	**Endpoint**	**Description**
POST	`/customers`	Adds a customer to the database.
GET	`/customers/{customer_id}`	Retrieves information of a single customer.
GET	`/customers`	Lists all customers in database.
PUT	`/customers/{customer_id}`	Updates information of a single customer.
POST	`/vens`	Adds a VEN to the database.
GET	`/vens/{ven_id}`	Retrieves information of a single VEN.
GET	`/vens`	Lists all VEN in database.
PUT	`/vens/{ven_id}`	Updates information of a single VEN.
POST	`/vens/{ven_id}/resources`	Adds a resource to the database.
GET	`/vens/{ven_id}/resources`	Retrieves information of all resources related to a single VEN.
PUT	`/vens/{ven_id}/resources/{res_id}`	Updates information of a single resource.
GET	`/vens/{ven_id}/reports`	Retrieves information of all reports related to a single VEN, within a search period.
POST	`/events`	Adds an event to the database and to the VTN.
GET	`/events`	Retrieves information of all events in database.
GET	`/events/{event_id}`	Retrieves information of a single event.

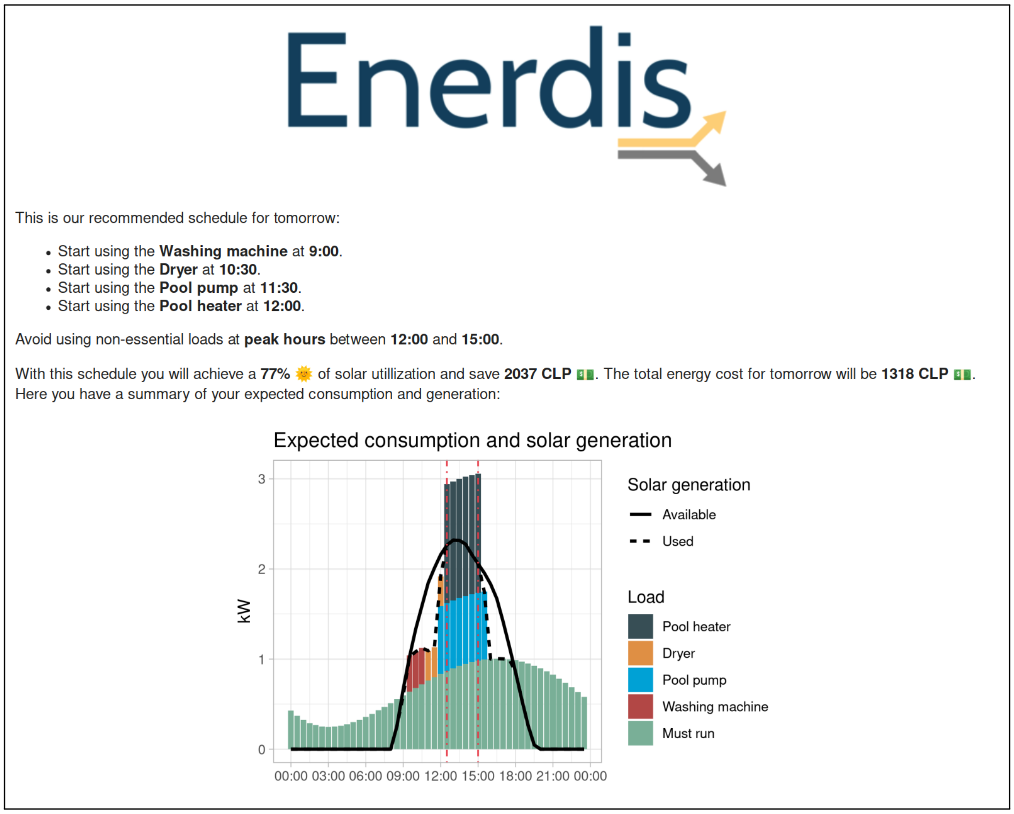
DELETE	`/events/{event_id}`	Marks an event as canceled in database and cancels the event in the VTN.

4.1.3.2. HEMS optimizer

The HEMS optimizer consists of three routines that are scheduled to run once a day. The most important routine is the HEMS optimizer itself, which comprises two Python scripts, one that fetches the solar radiation forecast for the prosumer's site and another that solves their optimization problem using the Pulp library. The forecast is obtained from an external service [71] that provides a daily solar radiation forecast one day in advance.

Following this, the solution of the optimization problem is passed to the remaining two routines. The Email notification routine is an R script that translates the output of the optimizer into a human-friendly message. This message is sent to the client's email address at 6 PM on the day before, and it indicates the optimal scheduling of appliances. Figure 4.3 shows an example of the email notification.

On the other hand, the DR scheduler routine is a Python script that transforms the output of the optimizer into OpenADR events. These events are added to the VTN by making calls to its internal API.



Enerdis

This is our recommended schedule for tomorrow:

- Start using the **Washing machine** at **9:00**.
- Start using the **Dryer** at **10:30**.
- Start using the **Pool pump** at **11:30**.
- Start using the **Pool heater** at **12:00**.

Avoid using non-essential loads at **peak hours** between **12:00** and **15:00**.

With this schedule you will achieve a **77%** 🌞 of solar utillization and save **2037 CLP** 💵. The total energy cost for tomorrow will be **1318 CLP** 💵.
Here you have a summary of your expected consumption and generation:

Figure 4.3: Email notification with appliance schedules.

4.1.3.3. Supported DR signaling

The OpenADR 2.0 Specification provides various demand response signals such as energy prices, load control, and customer bids [49]. However, this prototype only incorporates one signal, called "SIMPLE," to simplify development. The SIMPLE signal can take four possible levels, and the interpretation of each level and its corresponding actions must be predetermined between the EMaaS Provider and the prosumer.

4.1.4. EMaaS client implementation

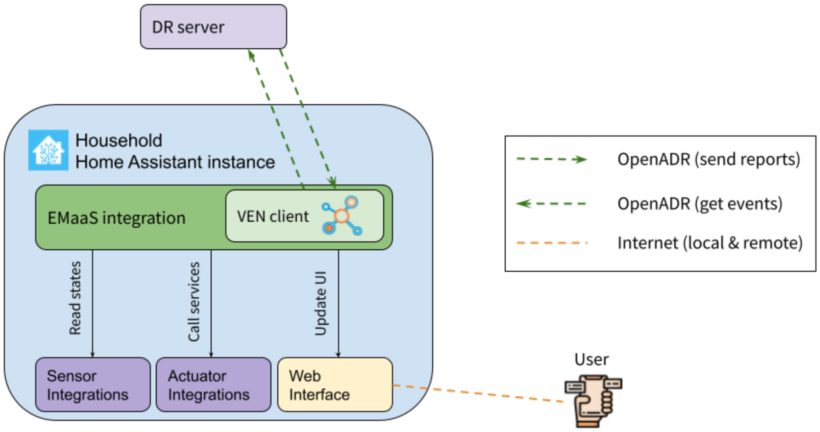


Figure 4.4: EMaaS client implementation diagram.

The client side of the prototype implementation features a custom-developed integration for Home Assistant platform. This integration employs the OpenLEADR library to initiate an OpenADR virtual end node (VEN) that establishes communication with the EMaaS Provider VTN to exchange DR signals.

The integration periodically retrieves OpenADR Event data by polling the DR server. Each event refers to a specific resource corresponding to a home appliance. It indicates the duration for which the resource should operate and provides instructions such as temperature set-points or toggling on and off. The integration can also periodically report values to the DR server via OpenADR reports. Similar to how it handles events, the integration associates OpenADR reports with specific resources like sensors or appliances within the house. These reports can convey energy data, such as the amount of kWh consumed in a specific timeframe, or state data like *on* or *off*.

In order to understand how data is gathered for reports, or how events are translated into physical actions, it is important to have an idea of how Home Assistant represents real devices and performs automations. Home Assistant uses integrations and entities to represent devices. Integrations are abstract and can provide methods to communicate with third-party services, like our custom integration, or represent categories of devices that share functionalities, regardless of the manufacturer, such as lights and switches. Entities, on the other hand, are simple representations of something with a state, such as devices, sensors, and automations.

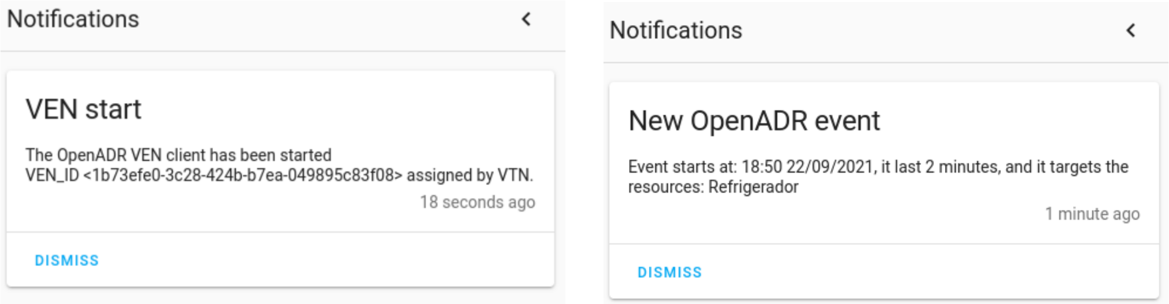
For instance, to control a smart light in your house using Home Assistant, you would use an integration that connects Home Assistant with the manufacturer's cloud services. This integration, in turn, would use the general *light* integration to expose the various methods that the platform can call to control the smart light. These methods are known as *services*, and in the case of a light, they could be `light.turn_on()`, `light.turn_off()`, `light.toggle()`, and others. Subsequently, the *light* integration would create an entity that represents the current state of the smart light.

Regarding the EMaaS Integration developed for the prototype. It gathers data from entities' state to make the OpenADR reports it sends to the VTN, and schedules service calls to translate the OpenADR events into real demand response from appliances. It does so by following a configuration file with the format presented in code block 4.1. In this example, the integration would report energy data of resource `pool_pump_energy` each 10 seconds by reading the state of entity `sensor.pool_pump_energy`. It would also schedule calls to the service `switch.turn_on` for entity `switch.sonoff_10012d8af9` when the DR events present an interval with payload: `level_1`.

The rest of the configuration defines where the self-signed certificates are located, in order to establish the exchange of DR signals securely over HTTPS, and the entity name that would be included in Home Assistant graphical interface. Figures 4.6 and 4.5 depict how the integration is shown to the user in different situations.

Code 4.1: Example of the EMaaS Integration configuration file.

```
openadr_ven:
name: Casa_G
vtn_url: https://23.239.29.103:8080/OpenADR2/Simple/2.0b
vtn_fingerprint: 43:B7:85:73:1B:F1:47:E6:69:61
ssl:
  ven_cert: /config/oadr_certs/vtn_ssl.crt
  ven_key: /config/oadr_certs/ven.key
reports_sampling_rate: 00:00:10
reports:
 - entity_id: sensor.pool_pump_energy
   measurement: ACTIVE_ENERGY
   report_specifier: Energy
   resource: pool_pump_energy
   scale: k
signal_responses:
 - resource:  pool_pump_energy
   entity_id:  switch.sonoff_10012d8af9
   level_1:
    service: switch.turn_on
   level_0:
    service: switch.turn_off
```



VEN start

The OpenADR VEN client has been started VEN_ID <1b73efe0-3c28-424b-b7ea-049895c83f08> assigned by VTN.

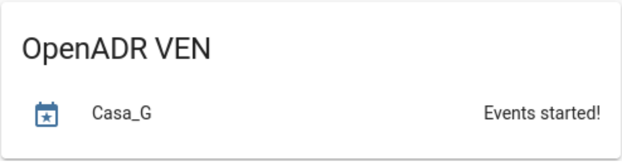
18 seconds ago

New OpenADR event

Event starts at: 18:50 22/09/2021, it last 2 minutes, and it targets the resources: Refrigerador

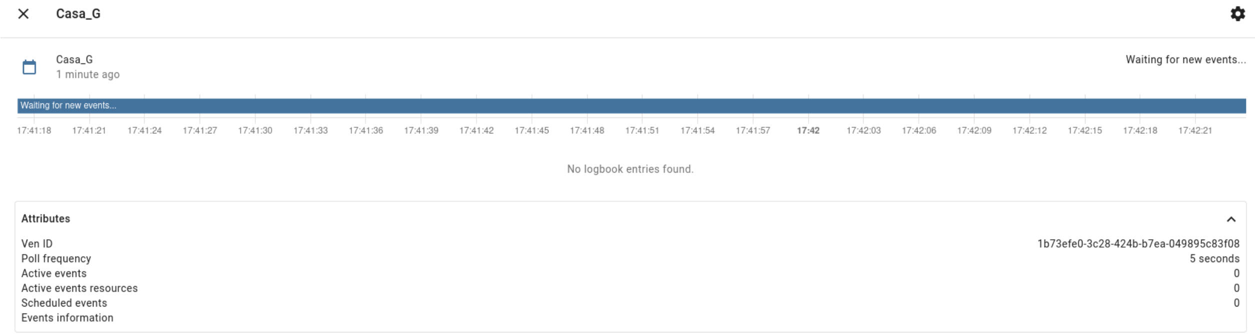
1 minute ago

(a) Start up notification. (b) New event notification.


OpenADR VEN

Casa_G Events started!

(c) User interface card with updated state.



Casa_G
1 minute ago

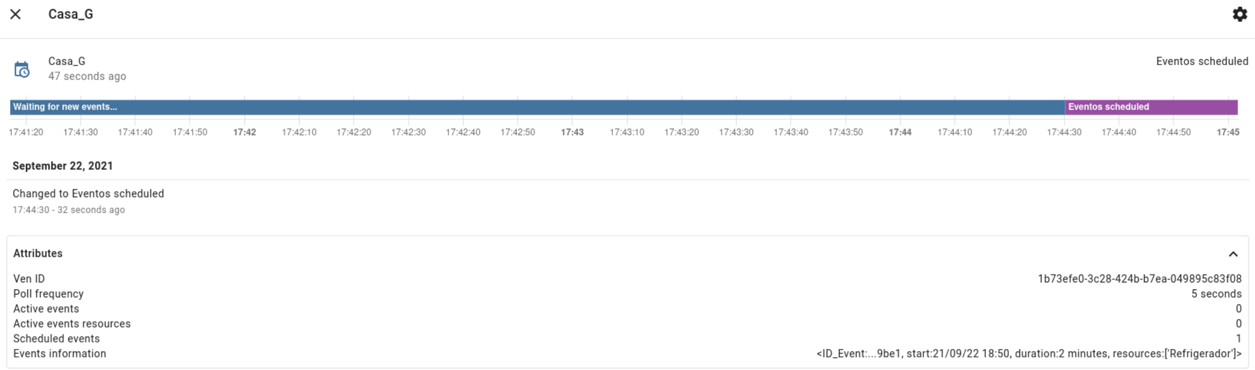
Waiting for new events...

No logbook entries found.

Attributes

Ven ID	1b73efe0-3c28-424b-b7ea-049895c83f08
Poll frequency	5 seconds
Active events	0
Active events resources	0
Scheduled events	0
Events information	

(d) Expanded card with DR signaling information.



Casa_G
47 seconds ago

Eventos scheduled

September 22, 2021

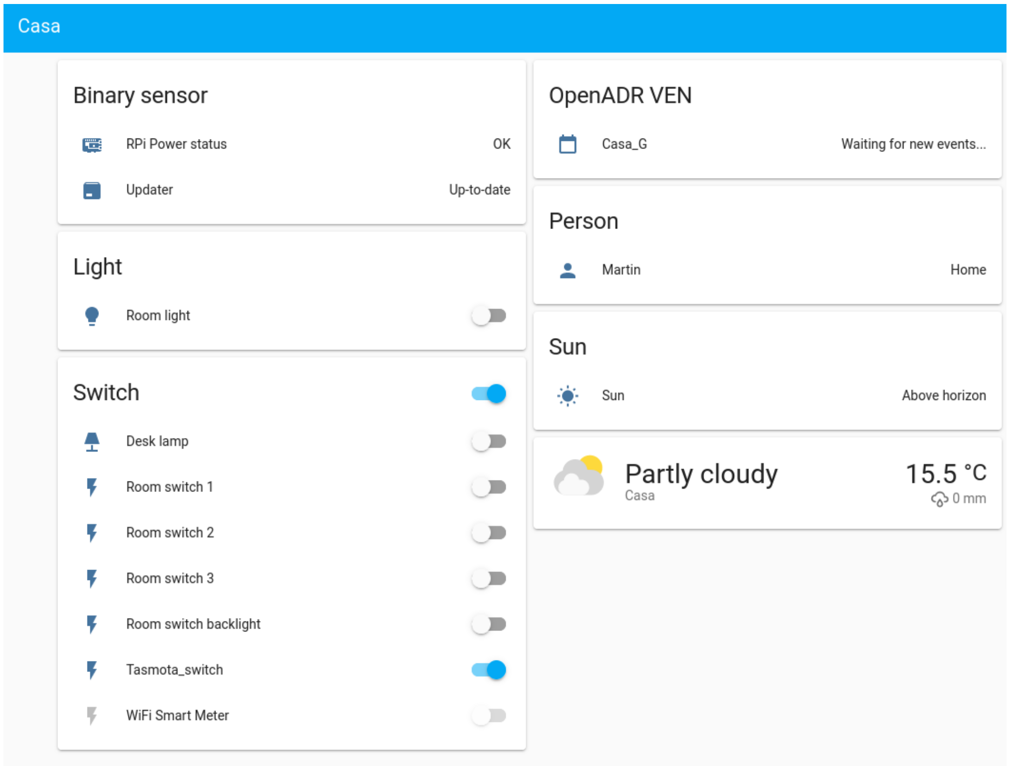
Changed to Eventos scheduled
17:44:30 - 32 seconds ago

Attributes

Ven ID	1b73efe0-3c28-424b-b7ea-049895c83f08
Poll frequency	5 seconds
Active events	0
Active events resources	0
Scheduled events	1
Events information	<ID_Event:...9be1, start:21/09/22 18:50, duration:2 minutes, resources:['Refrigerador']>

(e) Expanded card with DR signaling information with updated state.

Figure 4.5: EMaaS integration graphic components.



Casa

Binary sensor

RPi Power status OK

Updater Up-to-date

Light

Room light ○

Switch ●

Desk lamp ○

Room switch 1 ○

Room switch 2 ○

Room switch 3 ○

Room switch backlight ○

Tasmota_switch ●

WiFi Smart Meter ○

OpenADR VEN

Casa_G Waiting for new events...

Person

Martin Home

Sun

Sun Above horizon

Partly cloudy 15.5 °C

Casa 0 mm

Figure 4.6: EMaaS Integration card in Home Assistant user interface.

4.1.5. Pilot description

The EMaaS system prototype was tested in a household in the Chile Metropolitan Region in a short pilot program. The pilot was originally planned to last for three weeks between March and April, but an extra day was added at the end to overcome some practical challenges, described in section 4.1.5.2.

During the first week of the pilot, no demand response events were sent to the prosumer. This approach was adopted to gather data and establish a baseline for comparison. In the second week, the schedules for the appliances were sent via email, and the user would turn them on and off through the Home Assistant interface. Lastly, in the third week, the EMaaS integration in Home Assistant automatically turned on and off the eligible appliances for automatic demand response, the pool pump and pool heater.

Figure 4.7 shows a diagram of the residential setting where the EMaaS system was deployed. The pilot household had four flexible appliances: a pool heater, a pool pump, a washing machine, and a clothes dryer.

This household generates some of its energy needs using photovoltaic panels in the backyard. The electrical feed for the entire household comes from a hybrid inverter, which converts solar energy from DC to AC. When the energy generated by the panels is not sufficient, the inverter imports energy from the grid. It is important to note that the inverter can not feed power from the panels back into the grid.

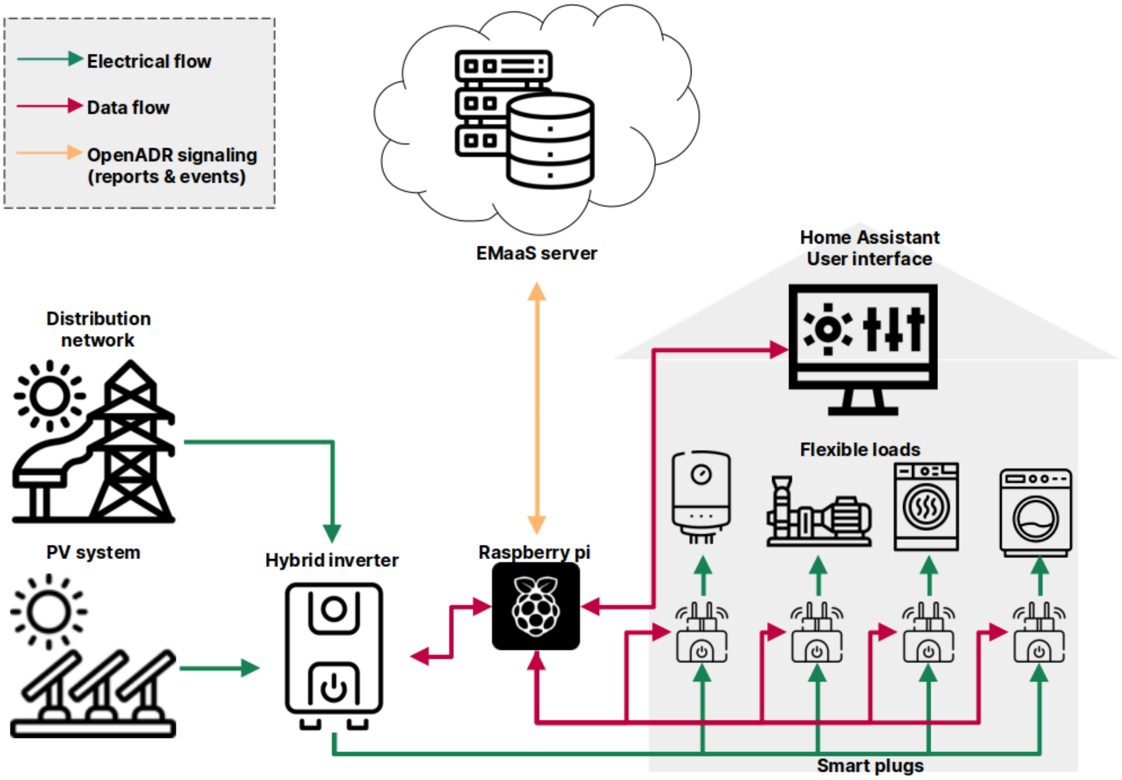


Figure 4.7: Prosumer setting in the pilot program.

Table 4.3: Hardware used in pilot program.

Device	**Model**	**Details**
Solar panels	Unknown	Array of 3kWp.
Hybrid inverter	Axpert MKS II 5000-48	Hybrid inverter with 5kW capacity.
Raspberry pi	Pi 3 Model B+	Single board computer with quad core 1.4GHz processor, 2 GB RAM, Ubuntu 20.04 Operative system and Home Assistant running inside a docker container.
Smart plugs	Sonoff POW R2	WiFi switch with real time power consumption monitor measurement.

The EMaaS prototype's client side runs on a Raspberry Pi with Home Assistant. Each flexible appliance is connected to a smart plug that has power metering and switching capabilities. The household-wide consumption and generation data is acquired through a serial port available in the inverter and is integrated into Home Assistant as regular sensors. A comprehensive list of hardware used in the pilot household is available in table 4.3.

4.1.5.1. Pilot prosumer problem

The optimization problem inputs, fixed demand, allowed hours to turn on appliances, and required energy, were obtained from the baseline week. These values were determined through averaging sensed data and considering customer-declared preferences. To address the interdependence of appliances, additional constraints (see 4.1 and 4.2) were introduced to the prosumer problem. Specifically, the pool heater relies on the pool pump cycling water, and the clothes dryer depends on the washing machine completing its tasks before starting the drying process. The prosumer problem was solved daily using a 30-minute time step and a satisfaction parameter (ω) set to 0. It's worth noting that, since the inverter cannot feed energy into the grid, the selling price parameter (λ_{sell}) used in the problem was fixed at 0.

$$u^{APP}_{\text{Pool heater}}(t) \leq u^{APP}_{\text{Pool pump}}(t) \quad \forall t \in\in [L_{\text{Pool heater}}, U_{\text{Pool heater}}] \tag{4.1}$$

$$1 - u^{APP}_{\text{Dryer}}(t) \geq u^{APP}_{\text{Washing machine}}(j) \quad \forall t \in [j, U_{\text{Dryer}}] \quad \forall j \in [L_{\text{Dryer}}, U_{\text{Dryer}}] \tag{4.2}$$

4.1.5.2. Practical challenges

During the execution of the pilot program, the prototype faced several practical challenges. For instance, power outages occurred throughout the three-week period, caused by inverter overloads. This became problematic, particularly when the pool heater operated in automatic mode, as it could trigger the shutdown when turning on. Then, after power was restored and the Raspberry Pi rebooted, the EMaaS integration would fail to activate the pool heater again, because the scheduled control had already occurred.

Another challenge was the unreliable Wi-Fi connection of the smart plugs located outside the house. This inconsistency in the connection resulted in inconsistent automatic responses from the pool appliances throughout the week.

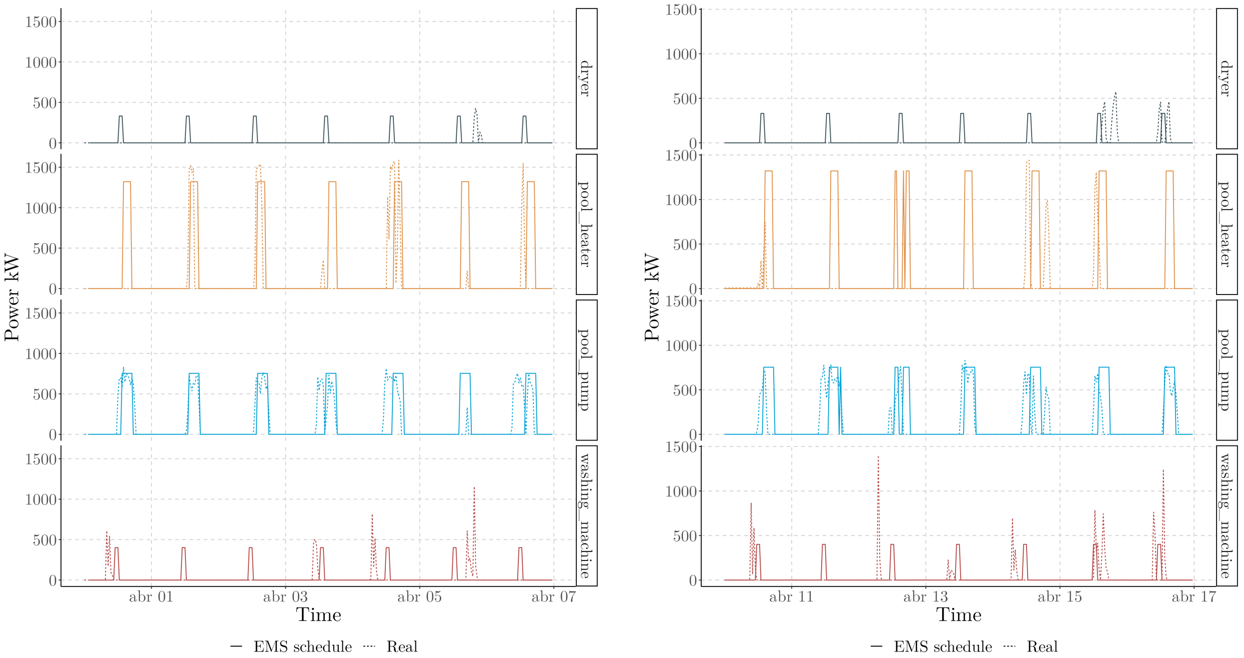
Furthermore, during the pilot program, there was a shift in the country's time from summer to winter hours. This adjustment wasn't incorporated into the automated scripts until the final day, resulting in a one-hour difference between the scheduled time and the automated signals. Additionally, solar radiation levels varied significantly over the three weeks, and the time shift impacted energy consumption patterns. Due to these conditions, it's important to note that the quality of the results may be limited for making accurate comparisons between modes of operation or assessing cost savings.

To tackle these challenges, I analyzed an additional day using automatic demand response. This extra day underwent close monitoring to ensure the uninterrupted connection between the appliances and the Raspberry Pi, and to prevent overloads that could trigger a shutdown.

4.2. Results

4.2.1. Three-week pilot

The pilot program results are categorized based on the corresponding week within the program. The energy data from flexible appliances is presented alongside the schedule recommended by the EMaaS service in figure 4.8.



(a) Flexible appliances' profiles in week 2: manual operation.

(b) Flexible appliances' profiles in week 3: automatic operation.

Figure 4.8: Appliances profiles during pilot.

The cost of energy for each pilot week, including the baseline week without EMaaS, is displayed along with additional information on solar availability, energy generation, and energy usage in table 4.4.

Table 4.4: Three-week EMaaS pilot summary.

Metric	**Baseline**	**Manual**	**Automatic**
Avg. cost [$/day]	2.81	3.13	3.03
Avg. consumption [kWh/day]	25.3	27	24
Energy cost [¢/kWh]	11.1	11.6	12.6
Avg. forecasted generation [kWh/day]	15	17.7	15.6
Avg. solar generation [kWh/day]	9.8	9.67	7.21

4.2.2. Additional day with automatic response

Regarding the additional day of automatic operation, I included estimated data for a case without energy management to compute an estimation of the economic savings achieved by the EMaaS system. To estimate the demand profile without energy management, I shifted pool appliances profiles back to their original schedule. Additionally, to estimate solar generation, I used the average ratio between forecasted energy production and real production to define the value for hours when solar production is less than total demand (when importing energy from the grid and generating as much as possible). Similarly, I used the average ratio between solar production and total load to define a value for hours when solar potential is greater than total load (when the house is primarily being powered by solar production). The resulting estimates and real data from the additional day of operation are shown in figure 4.9. A summary of the additional day of automatic operation is presented in table 4.5.

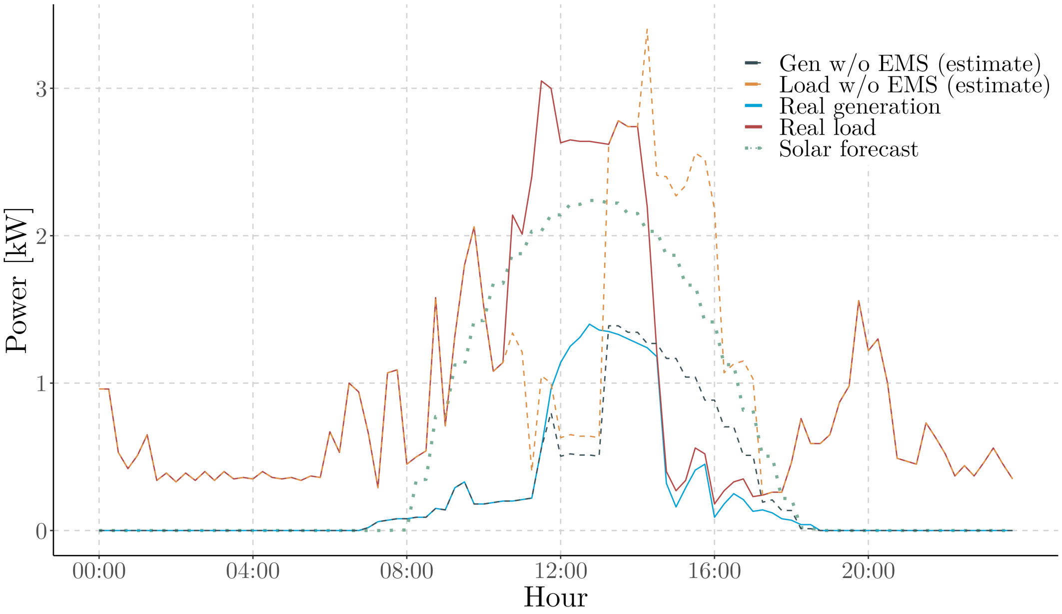


Figure 4.9: Profiles of the additional pilot day.

Table 4.5: Additional pilot day summary.

Metric	Value
Energy cost [$]	2.92
Consumption [kWh]	22.5
Energy cost [¢/kWh]	13
Estimated cost w/o EMS [$]	2.81
Estimated energy cost w/o EMS [¢/kWh]	12.5
Solar forecast [kWh]	14.94
Solar generation [kWh]	5.35

5. Discussion

This chapter discusses the results presented in sections 3.2 and 4.2, with a focus on the findings related to the hypotheses proposed in the first chapter. Additionally, other interesting findings from the results of both experiments are mentioned. To improve readability, the hypotheses are restated as follows:

H_1: Consumers with solar production (prosumers) can achieve greater savings by adopting an EMS. Particularly those who rely on electricity as their main energy source.

H_2: Moving the main functions of an EMS to the cloud can ease its implementation in residential settings.

5.1. About the Effect of an EMS on Savings

The simulation results indicate that implementing an EMS does not provide significant benefits for conventional prosumers who are subjected to the BT1 tariff, as shown in figure 3.4.

Meanwhile, for prosumers with an air conditioner, the EMS achieved some savings as shown in figure 3.6. However, as we can see in figure 3.7, the average room temperature is higher than the reference for most of the daytime, which means the savings are mainly driven by sacrificing thermal comfort under BT1.

On the other hand, prosumers who have air conditioners and water heaters can leverage the thermal inertia of the water tank to make smaller sacrifices in hot water thermal comfort after periods of intensive use, such as showering. We can observe this in figure 3.11, where the water temperature drops in the morning before gradually increasing until it reaches the set-point once again. This provides a driver of saving that do not affect severely on comfort for BT1 prosumers.

Following, when households are subject to BT1 tariffs, the inclusion of electric vehicles alongside air conditioners and water heaters provides little to no additional savings, as seen in figure 3.13. This can be attributed to the fact that households would charge their electric vehicles at night when there is no solar generation. Consequently, electric vehicles contribute minimally to the increase in self-consumption which is the primary driver of savings with BT1 tariffs and net-billing regulations.

Regarding results with TOU3 tariff. Tables 3.16 and 3.18 reveals that conventional prosumers and those with air conditioners do not seem to benefit significantly from the EMS under TOU3 tariff. As air conditioner consumption usually takes place during the same hours as solar generation, household demand from the grid is low, and energy prices are at their lowest. Therefore, there are very limited room for managing peak shedding or load shifting with air conditioning units. This makes it difficult for the EMS to offer significant advantages, without sacrificing thermal comfort. To the point where it sacrifices less temperature for the same satisfaction parameter ω_2, than the cases of BT1 tariff.

On the other hand, flexible appliances that operate outside solar hours offer better management potential when the tariff is TOU3. tables 3.18 and 3.21 show that, with $\omega_2 = 0.5$, impact of the EMS jumps from \$36 to \$138 (+102) going from air-conditioned households to prosumers with both air conditioner and water heater. In contrast with the jump from \$74 to \$116 (+42) in the case of BT1. Furthermore, for households with air conditioner and water heater, the EMS achieves greater savings in TOU3 while sacrificing less thermal comfort. Curtailing 14 kWh from the water heater per year, against 33 kWh . And curtailing 74 kWh from the air conditioner (see table 3.22), against 490 kWh (see table 3.19).

Likewise, for fully flexible households (air conditioner, water heater and electric vehicle) with TOU3, the impact of the EMS on savings increases from \$138 to \$195 (+57) when compared to thermal-electric households. This is in contrast to the small jump from \$116 to \$118 (+4) observed when utilizing the BT1 tariff (see table 3.25).

In summary, the simulation results indicate that the economic benefits provided by an EMS for prosumers do not necessarily increase as they rely more on electric energy. For example, the inclusion of an air conditioner is unlikely to increase the impact of the EMS, unless the prosumer is willing to sacrifice comfort. However, the benefits of the EMS do increase as prosumers incorporate more flexible uses of energy, such as water heaters and electric vehicles. This effect is more pronounced with dynamic tariffs than volumetric ones.

5.2. Other System-wide Benefits of EMS

Besides the economic benefits that EMS can provide for prosumers, the simulation results raise some interesting findings about the potential effects on the grid that massive adoption of DER and EMS can bring.

The average load figures 3.3, 3.5, 3.8 and 3.12 show that as prosumers incorporate more electric uses, such as air conditioning, water heating, and electric vehicles, their demand profile reaches greater peak loads, and the ramp from solar hours to sunset gets steeper. In these figures, we can see how, even with a high level of satisfaction ($\omega_2 = 0.5$), the EMS produces some level of demand flattening. This effect is increased when the tariff scheme considers charges for peak demand, as TOU3.

Additionally, energy cost figures 3.4, 3.6, 3.9 and 3.13 show that when a tariff like TOU3 is in place, we see a decrease in the benefit of having solar generation without an EMS against not having solar generation at all. This can lead one to believe that if a tariff like TOU3 is put in place, it will impact the adoption of distributed generation. For this reason, I think it is important to get ahead of the regulatory reforms and explore EMS solutions that could have an impact on the economic benefits of households' solar projects in the near future.

5.3. About the Convenience of the Cloud-based EMS

The experience of developing and deploying the Energy Management as-a-Service prototype suggests that decoupling the EMS from the physical site offers convenience for the prosumer. The prosumer simply provides preferences for hours of operation and automation, without having to deal with the technical details. Although this convenience is not specific to cloud-based EMS, as an all-in-one solution could also provide a comparable experience.

The main advantage of the cloud-based approach is that the DR signaling is not linked to the switches or the Home Assistant platform, and likewise, optimization is not linked to DR signaling. This means that if the provider or the prosumer needs to update the system on one side, it can be done completely separate from the other.

If the client decides to switch to a different brand of a smart plug, the system will still function as long as the new smart plugs are integrated with Home Assistant.

Alternatively, it is possible to develop a client implementation that does not depend on Home Assistant and instead uses a different automation platform, like the ones from Google, Apple, and Amazon. Using these types of platforms could make it possible to operate the EMaaS just from the cloud, without additional hardware on the client side.

Furthermore, on the server side, we can enhance the HEMS optimizer, the email notification system, and the overall VTN implementation while maintaining the service operational with the existing client.

From the developer perspective, leveraging an existing platform to abstract the control and communication of devices with the client node offered clear advantages when compared to previous approaches. First of all, the whole platform user interface is already there, which reduces the development effort. Second of all, it provides support for a wide range of devices and manufacturers from the start, which further reduces the development effort.

To summarize, moving the functions of the EMS to the cloud, decoupling the optimization from the control signal, and dissociating it from the physical devices can simplify the implementation of EMS systems. This technique holds the potential to increase the adoption of EMS and make it easily accessible, particularly in residential settings.

5.4. About Energy Costs in the Pilot Program

Firstly, the pilot duration was too short to derive any meaningful conclusions about the effectiveness of the prototype in reducing costs in the long run.

However, figure 4.8 suggests that the more adaptable appliance, the pool pump, generally adhered to its intended schedule. Despite the fact that the start times and shutdowns of the pool pump in the automatic week were erratic and did not fully adhere to the schedule. Regarding the other adaptable appliances, the prosumer turned on the pool heater around the recommended hours in the manual week in the days the pool heater was used. Also, the pilot client used the washing machine and dryer during the recommended hours on some days of the program.

This begs the question: why did energy costs worsen compared to the baseline, despite having even more forecasted generation (as shown in table 4.4) during the manual and automatic weeks? One would expect the costs to keep similar or decrease, if the optimal schedule was partially adhered.

One possible answer to this question arises from the results of the additional day of automatic operation. In figure 4.9, we can observe that the EMS shifted the pool appliances from around 4 PM, as per the baseline schedule, to around 12 PM. This shifting makes sense in the optimization process as it would utilize more available generation, which is crucial in the pilot case since the inverter cannot feed electricity into the grid, rendering the selling price to be zero in the optimization problem.

However, the issue is that real solar production deviates from the forecasted trend before 12 PM, as observed in the solar generation profile presented in figure 4.9. Upon inspecting the location of the panel array, I discovered that some trees cast shadows on the array in the morning. This indicates that shifting the load towards the middle of the day may result in more solar generation being lost during the afternoon than what is gained in the morning. This observation aligns with the analyzed energy cost for this specific day, where the cost of the day was \$2.92, while the estimated cost without the EMS was \$2.81. Both costs are shown in table 4.5.

6. Conclusions and Further Work

6.1. Conclusions

The aim of this thesis was to evaluate the potential of cloud-based EMS for reducing energy costs for prosumers in the residential sector. The objectives were to characterize residential consumption and generation in the Metropolitan Region of Chile, simulate achievable savings with an EMS, design and develop an Energy management as-a-Serive prototype, deploy it in a residential setting, and analyze the results of both the simulation and the prototype operation.

Those objectives where followed through, and the simulation results indicate that the economic benefits that an EMS provides for prosumers do not necessarily increase as they rely more on electric energy. However, the benefits of the EMS do increase as they incorporate more flexible uses of energy, such as water heaters and electric vehicles. This effect is more pronounced with dynamic tariffs than volumetric ones.

The results also showed that a change in the tariff scheme, from the typical volumetric BT1 to a multipart one that incorporates capacity charges, like the TOU3 tariff designed for this research, could discourage investment in solar distributed generation within the metropolitan region, as it would reduce the economic benefits of solar generation for residential prosumers.

Additionally, the development of the Energy Management as-a-Service prototype suggest that moving the functions of the EMS to the cloud can ease the implementation of EMS systems, by dividing the principal functions into separate and individual components. As it was done for this research.

The execution of the pilot program and deployment of the EMaaS prototype in a residential setting allowed us to identify practical challenges when implementing a EMS in the real world, and lay out a clear path for improvement for the tools developed in this research.

Overall, this study provides insights into the potential of cloud-based EMS as an effective solution to reduce energy costs. Although further research is required to investigate its performance in different settings and with different flexible loads, the results suggest that cloud-based EMS can play a critical role in the future of energy management and sustainability for residential prosumers.

6.2. Further Work

There is plenty of room for improvement in the work presented in this research. Beginning with the simulation, it would be interesting to replicate the methodology using more regions of Chile, as all the data is available for regions beyond the Metropolitan Region.

Additionally, it would be valuable to study the economic benefits of the Energy Management System for various values of ω_2 and to better define the comfort parameters ϵ of each appliance, to get a better grasp of when the EMS sacrifices comfort. This could be achieved through surveys or by studying the real comfort-price elasticity of users for different appliances.

Other improvements can be done by expanding the modified ALPG, so it could generate more flexible profiles, such as water pool pumps or phone and laptop chargers. Also, more sources of generation, like small wind and hydro turbines.

Lastly, it was challenging to obtain reliable public information on commute distances, so this parameter could be better determined if the data is found.

Regarding the prototype, the first proposed improvement is to enhance the reliability of the client implementation. The current implementation assumes that the client would maintain a 100% up-time and internet connection, which is not a reasonable assumption. Secondly, the graphical components could be improved after some iterations with potential users, and the configuration file could be replaced by a configuration process with a user-friendly interface to select the self-signed certificates and to define the rest OpenADR parameters.

On the server side, a graphical interface for the EMS Provider is missing, and support for more OpenADR signal types is needed, in order to test complex demand response schemes. Moreover, the optimizer should include some inference from historical data to complement the solar forecast, enabling it to account for specific characteristics such as shadowing hours.

Lastly, the EMS would benefit from being less intrusive on the prosumer site. Therefore, future iterations on this idea should necessarily consider Non-Intrusive Load Monitoring algorithms. This would reduce the cost of sensors, and also enable us to monitor those appliances that can hardly operate with automatic scheduling, thus would definitely not be connected to smart plugs or sensors, such as vacuum cleaners and phone chargers.

Regarding the pilot itself, future iterations of the system should be evaluated over longer periods of time, and with more pilot clients. Implementing alerts to detect service failures, such as sensor disconnections and overloads.

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