

# IoT for smart home energy planning

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**Abstract.** This article presents a platform combining hardware and software for smart power consumption monitoring and planning in urban scenarios. The system integrates a hardware controller for energy efficiency, a communication protocol to improve data transmission, and a software module for planning and managing home devices. The proposed solution is implemented applying the Internet of Things paradigm, allowing the integration of computational intelligence techniques. A greedy algorithm is proposed for planning, according to user preferences and a maximum allowed power consumption. Results show that the power consumption of a water heater is reduced up to 38.9%, and two water heaters and one air conditioning can be optimized simultaneously without reducing the quality of service. These results suggest that the proposed approach is useful for home power consumption planning.

**Keywords:** Smart grid; energy; demand management

## 1 Introduction

The *smart grid* concept proposes using information and communication technologies for improving the quality and the performance of electrical networks to increase the efficiency, robustness, and adaptability of the network as a whole [6] [5]. This paradigm is usually applied when electricity is generated by means of unpredictable renewable energies, such as wind and solar. Uncertainty poses one of the biggest challenges in terms of the system operation to guarantee appropriate quality of service (QoS) to users of the electrical system.

Systems including mathematical models and algorithms are applied to control electrical devices to properly address issues related to QoS and energy distribution. Specific hardware support is also needed for measurement and management using sensors, data communication, and control devices. These pieces of hardware must be able to communicate and cooperate to properly react to dynamic situations (e.g., peaks of power consumption, valleys on renewable energy generation, price changes). Control devices allow implementing planning techniques to better use the available resources [10].

This article reports the advances on building a system for smart home energy management that includes an energy controller and computational intelligence methods for planning the power consumption on houses, buildings, and

neighborhoods. The main goal of the proposed system is to provide an efficient and intelligent management of electric devices, reducing the power consumption and the monetary cost, while satisfying QoS requirements by users. We plan to implement the system in a distributed platform applying Internet of Things (IoT) and cloud computing paradigms, providing great flexibility on hardware resources and communications. The research is developed within the STIC-AmSud project Cloud Computing for Smart-City Energy Management (CC-SEM) [16].

The article is organized as follows. Next section introduces the home energy management problem and reviews related works. The proposed system for energy management is described in Section 3. Section 4 evaluates the algorithm for home energy planning over two case studies. Finally, Section 5 presents the conclusions and the main lines for future work.

## 2 The home energy management problem

This section presents the home energy management problem and reviews relevant related works.

### 2.1 Problem description

Load management allows users to adjust power consumption according to expected QoS, different energy prices, etc. Planning techniques allow leveling the power consumption in homes. This way, users can apply strategies to shift the load of electric devices from peak hours (having high demand and expensive energy prices) to low demand and cheaper energy price periods [9]. *Demand response* [11] changes the way of managing energy flow for homes and cities to better match the power demand with the power supply, according to the energy production capabilities. Demand response techniques allow reducing peak demand, thus improving the quality of service of the electric grid as a whole.

The home energy management problem proposes using information systems and algorithms to find appropriate energy plannings, i.e., assigning a shared resource (energy) to several tasks or loads (electric devices) that consume energy.

Home devices have different features and power consumption profiles, which affect possible actions to take within a plan to minimize negative effects on the QoS provided to users. *Interruptible* loads, which can be interrupted during periods of time without causing a significant negative impact in the QoS, are very important for energy planning without affecting the user experience. Usually, interruptible loads preserve energy in form of heat (e.g., water heater and air conditioner). Taking into account the load features and the availability of both real-time and historical data (patterns/preferences of utilization for each home device), the proposed system uses a home controller, a specific protocol for load monitoring and controlling, and a planning system for home energy efficiency.

In order to handle the communication of power consumption and control messages in real time, data flow must be optimized to provide a robust and efficient demand management [2], thus the need of an optimized protocol for

communication. A controller is needed because most current home devices do not allow digital/remote controlling. The planning system allows defining specific actions to reduce the energy cost without affecting the QoS provided to the users.

## 2.2 Related work

There are a few examples of home automation devices for energy efficiency. Most of them are set to control specific environment parameters (e.g., heating/cooling), like Nest devices [1] or perform basic automation (e.g., turning devices on/off according to a user schedule). These devices lack a global view on the consumer profile and devices. Consumption meters are also becoming smart, like *ElectriSense* [4] that can identify the families of devices, or *Linky* [18] a connected device deployed by *Électricité de France*. None of these systems are open-source and their capabilities are often restricted to data acquisition and basic automation.

Gomes et al. [3] studied a scenario using several micro generation units (MGU) in a low tension distribution network. MGUs cause voltage fluctuations when switching on/off home devices, thus demand response is useful to preserve the quality of the network. Specific techniques were proposed for shifting the power consumption of washing/drying machines and dish washers; reducing the temperature of water heaters in peak hours; and shifting the use of water heaters. A simple scenario was studied, considering 10 MGUs with and without demand management. The analysis showed that the quality variations due to MGUs and demand management are important, but can be kept under acceptable values.

Soares et al. studied demand management for homes and categorized home devices, according to their behavior and the different management strategies to be applied [13] and presented a model and an algorithm for planning the power utilization to reduce the cost [14]. A non-linear integer programming problem formulation was introduced and Evolutionary Algorithms (EA) were applied to minimize the bills and the violations to the maximum contracted power. The proposed EA allowed reducing up to 40% the energy cost for users with respect to a reference scenario without demand management. Later, a multiobjective EA was applied to find a set of plans for minimizing cost and maximizing user satisfaction [12]. Plans are evaluated according to user-defined preferences for different times of the year. The main results showed that the cost reduction is between 22% and 24%, depending on the satisfaction levels. However, the experiments are based on synthetic data and no real system for implementing demand management in homes was proposed.

The analysis of the related works indicates that there is still room to contribute with solutions focused on developing a system to implement home demand management. The system proposed in this article combines a hardware controller and computational intelligence methods for power consumption management and planning.

### 3 A system for smart home energy management

The proposed system integrates three components, implemented in independent modules: EFEN for defining/storing user actions and preferences, and compute plannings; the home CONTROLLERS, and KHIMO for communication with the home controllers. These modules allow changing the electric flow in real time, controlling the devices according to specific rules. The modules and their interactions are shown in Fig. 1 and described next.

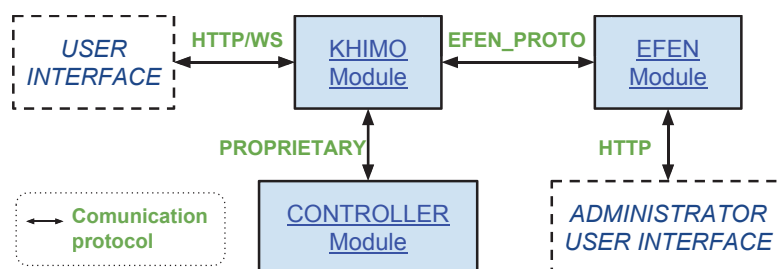


Fig. 1: Architecture of the proposed system.

*EFEN*. EFEN is the central module of the system, which defines the devices, stores the power consumption data, provides an interface for device control, and computes the planning. EFEN groups homes in buildings and buildings in neighborhoods, allowing energy planning at different levels.

EFEN also provides an Application Programming Interface (API) to integrate computational intelligence algorithms for big data analysis/pattern recognition and energy planning. Further details can be found in <https://www.fing.edu.uy/inco/grupos/cecal/hpc/EFEHO>.

Big data algorithms allow extracting useful information from raw power consumption data, to be used by machine learning and planning tools. This approach ensures scalability and portability of the developed solution, allowing a smooth transition from the prototyping/validation phases to a production phase. Basic ETL (Extraction, Transformation, Load) of data are implemented using MapReduce, while more advanced operations can be conducted with high-level tools (e.g., Pig or Apache Spark). Storage and access to the data are improved by using NoSQL databases, which allow storing data from sensors and other data sources (e.g., power generation, historical consumption charts, weather forecast). Due to its lightweight and efficient communication protocol, EFEN is capable of controlling over 50 devices per building within a neighbor context. Computational intelligence methods allow identifying correlated patterns and situations to be used on the optimization algorithms [17]. In EFEN, pattern analysis is performed to determine device utilization and cycle of power consumption at home/building/neighborhood levels. EFEN also allows the user to define preferences for using each device in a day or in a week.

Planning defines specific actions to be taken on the devices (an *agenda*), considering power consumption, pricing, user preferences, and user satisfaction. Other features included in EFEN are: feasibility check of agendas, evaluation of the energy stored in form of heat (for water heaters and air conditioning systems), cost evaluation, and user satisfaction estimation. User satisfaction is evaluated according to the features and services provided by each load. For example, for a water heater, satisfaction is related to the deviation from the water temperature the user expects when using it. These features are critical when evaluating the impact of interrupting a device that generates heat. For verification purposes, a tool to simulate historical power consumption time series is also included in EFEN.

**CONTROLLER.** The controller includes a module for power measuring, a relay for power supply control, and a Single Board Computer (SBC) that controls the measures and the relay, and communicates with KHIMO.

A raspberry Pi (rPi) is used as SBC, providing a flexible and portable solution. Additional hardware include a relay and a STPM01/10 module [15] for power measuring using the SPI protocol. Figure 2 shows the connections between the rPi and the relay. The red wire controls the state, purple is the ground wire and blue connects to the power source (5V).

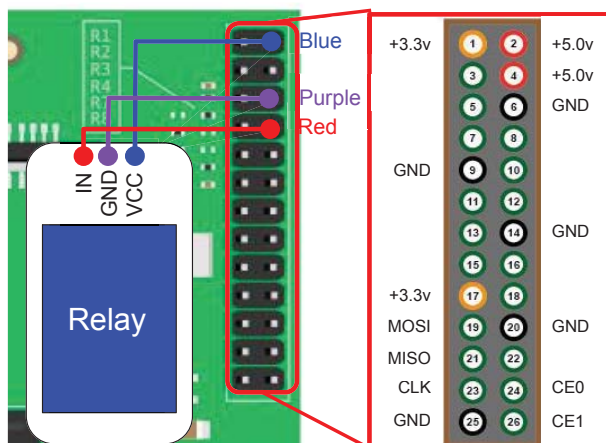


Fig. 2: Connections between the rPi and the relay.

The STPM01/10 chip was integrated using the steval-ipe016v1 board. Figure 3 shows the connections between the rPi and the SPI module, including MOSI, MISO (purple), and CLK (grey), the signal for read/write the channel (pin 22, green), the ChipSelect signal (pin 18, blue), the ground wire (pin 9, pink) and the VCC wire (pin 17, mustard).

The controller is presented in Fig. 4 (a male connector is on the rear side). Further details can be found in <https://www.fing.edu.uy/inco/grupos/cecal/hpc/EFEHO>.

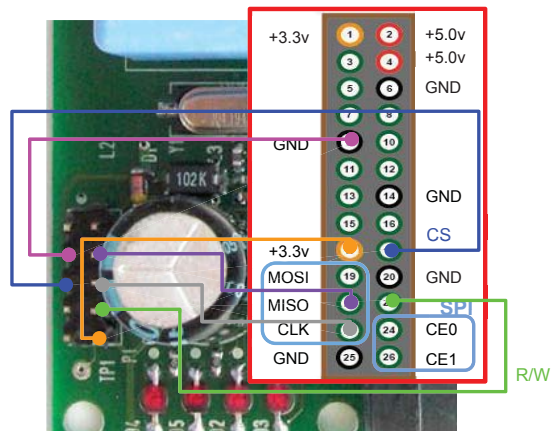


Fig. 3: Connections between the rPi and the STPM01/10.

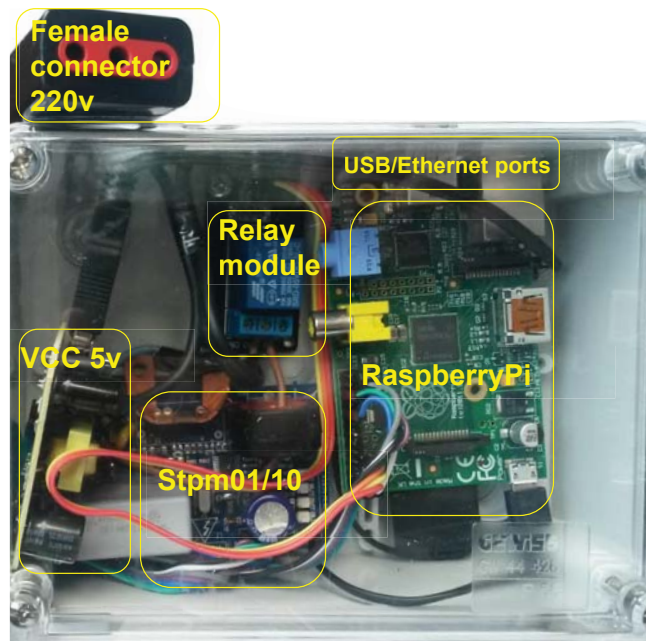


Fig. 4: Overview of the smart home energy controller.

*KHIMO*. The system is controlled by communications applying the IoT paradigm [8] to guarantee ubiquitous access using a wide range of communication devices (smartphones, tablets, web interface, etc.). The Khimo platform [7] is used to implement the communications between the home controller and the management system. Khimo provides the user interface that allows remote monitoring and controlling of several devices in real time.

The communication between KHIMO and EFEN is performed using EFEN\_PROTO, a protocol specifically developed to guarantee efficiency and different functionalities for device control. EFEN\_PROTO provides a channel for bidirectional communication to define actions to be performed on the loads and gathering information about the state and power consumption of the loads. Efficiency is achieved by enabling event subscription and avoiding intermittent queries (*polling*) to each device. Possible events to subscribe are state changes, power consumption changes, and connection events. In addition, message delivering (i.e., all pending actions) is performed simultaneously for all required devices via action grouping. EFEN\_PROTO groups the loads according to the actions to perform and not viceversa. This mechanism avoids redundancy, thus improving the communication efficiency.

## 4 Experimental evaluation

This section presents a sample application of the proposed system for managing two scenarios including water heaters and an air conditioner. We focus the analysis on relevant interruptible loads that generate energy in the form of heat, as they are frequently used (especially in Uruguayan homes) and have a significant impact on domestic power utilization [13].

### 4.1 A greedy algorithm for defining agendas

A greedy algorithm is proposed to minimize power consumption and maximize user satisfaction by taking local decisions to build a global agenda. The maximum power available is a hard restriction of the planning problem.

The greedy algorithm applies the following steps:

1. Create an action considering the utilization periods defined in EFEN. The first action intends storing the total expected heat, and the following actions intend maintaining the heat in acceptable ranges. Each action is assigned a priority according to the probability of utilization of the corresponding load.
2. If the defined action generates a conflict with previously defined actions, priorities are taken into account to shift (anticipate or delay) the actions in conflict.
3. If there are time steps in the utilization periods that are not covered by an action, go to step 1
4. Store the actions in EFEN, to be applied when appropriate.

The proposed greedy algorithm is a simple but reasonable method for defining agendas. It is based on keeping the expected heat (and thus, the expected QoS) in a reasonable range for all time steps and shifting loads when needed, according to the user preferences. Furthermore, the proposed greedy algorithm can be used as an initial solution for applying more powerful optimization techniques (machine learning, EAs, etc).

## 4.2 Experimental analysis

The evaluation of the proposed algorithm for load planning focus on shifting power consumption of interruptible loads trying to fulfill the user satisfaction and not exceed a maximum power limit. The evaluation scenarios involve two simulated water heaters and one simulated air conditioner. Table 1 presents the features of the devices defined in EFEN. The tolerance for temperature is 10%.

Table 1: Features of the devices defined in EFEN.

	<i>water heater</i>	<i>air conditioner</i>
Power consumption (W)	1500	2000
Time to reach target temperature	40 m	25 m
Time to lose all heat	480 m	80 m
Maintenance frequency	48 m	14 m
Time for maintenance	4 m	2 m

*Scenario 1: power consumption optimization for a water heater.* According to the defined device, the water heater must be on for 4 minutes each period of 48 minutes to keep the temperature in the accepted range. According to the agenda computed for the water heater between 8:00 and 12:00, it is necessary to turn on the water heater for 56 minutes to guarantee the required QoS. The agenda allows reducing up to **38.9%** (88 minutes less) the time that the water heater is on, when compared with the non-optimized scenario.

*Scenario 2: simultaneous optimization of power consumption for two water heaters and one air conditioner.* This scenario sets a maximum instant power of 2200 W, to analyze a situation when a low power value is available, thus devices cannot be on at the same time. Devices are set to be used between 8:00 (minute 480) and 12:00 (minute 720). Water heaters have higher priority than the air conditioner.

Figure 5 shows the agenda computed by the greedy algorithm. Air conditioner is shifted to the beginning of the period, and water heater actions are shifted after that, according to the defined priorities. Water heaters interleave between 7:00–8:20, and no overlapping is observed. The graphic also shows short periods of power consumption to maintain the temperature.

Some agendas do not fulfill the QoS requirements at 100%. However, power consumption is less than when no automatic load management is applied and QoS is within the tolerance.

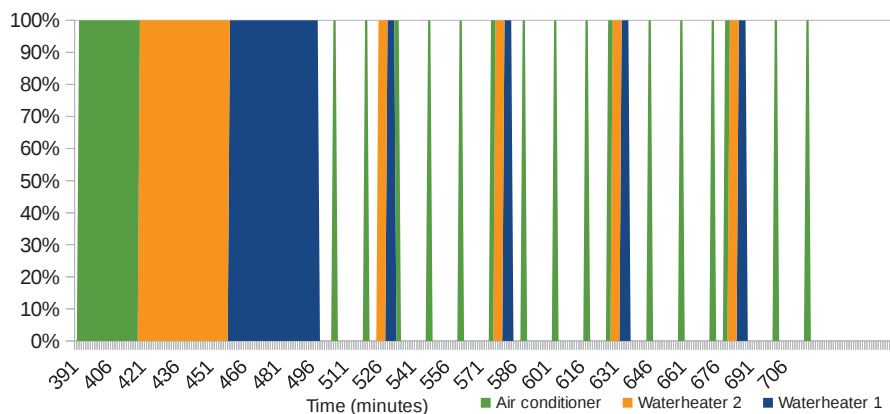


Fig. 5: Power consumption (agenda defined by EFEN for scenario 2)

## 5 Conclusions and future work

This article presented a hardware and software system for smart power consumption monitoring, controlling, and planning in urban scenarios. The system integrates a hardware controller for energy efficiency in homes, a protocol for efficient data communication, and a software module for planning and managing home devices and controllers.

The home energy management problem was studied by integrating cutting-edge technologies (computational intelligence, IoT, and cloud computing). A greedy algorithm was introduced for planning, according to user preferences and maximum allowed power consumption. The main results show that power consumption of a water heater can be reduced up to 38.9%. In addition, two water heaters and one air conditioning can be optimized simultaneously without reducing the QoS.

Results suggest that the proposed system is useful for home power consumption planning. It provides a robust platform that can be integrated to the Uruguayan power network for demand response and power consumption leveling.

The main lines for future work are related to improving the automation features of the proposed system, integrating computational intelligence/machine learning for pattern detection, and developing more powerful planning algorithms. The proposed system can also be extended to other public services.

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