



D3.2-B In-Home energy management strategies development

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Summary

The "In-home energy management strategies development" is a confidential document delivered in the context of WP3, "Task 3.2: Cell-level control and actuation systems" with regard to the energy-management algorithms to be included in the eDIANA cell device concentrator (CDC).

The document describes the energy strategies to be used in the cell level context, in order to manage all devices integrated at the Cell taking into account rules defined for the eDIANA platform

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Abbreviations

CDC	Cell Device Concentrator
eDIANA	Embedded Systems for Energy Efficient Buildings
MCC	Macro Cell Concentrator

1. Introduction

This document describes the control and actuation strategies over the devices integrated in the eDIANA Cell, with the goal of a correct energy management.

In the first section, with the start point of the state-of-the art, an open discussion is presented dealing with the different approaches for energy management. A first approach is presented based on a direct control from an external entity, which could be seen as a negative impact since it represents an intrusion in the user home, and a second approach is also described which focuses on an indirect control, where the loads are controlled entirely inside the Cell itself.

The next section analyzes the system requirements defined in deliverable D1.3-B, together with the inputs and outputs of the energy-management algorithms.

Section 4 describes the energy-management algorithms, based on the management and control of the devices integrated into the domestic environment. These strategies take into account the features of the devices connected, their priorities, the preferences established by the user, and the prices and consumption limits. Simulation models for these algorithms are presented in Section 5, while simulation results are shown in Section 6 for different scenarios.

All partners in Task T3.2 have contributed to the first sections of the deliverable (state-of-the-art, input/output parameters and algorithm description), while simulation models and results have been provided by partners IKERLAN and UNIBO.

2. State-of-the-art on energy-management strategies

There are two main approaches for home energy-demand management. The first one goes for a *direct control* of the domestic loads by an external entity (e.g. the electrical utility, a network manager, or the local transformation centre). This approach is based on the industrial energy-management systems, where the electrical utility may disconnect a series of loads when a variation in the generation-demand pair is observed. These systems are the most beneficial ones for the network manager, as they allow a direct control over the energy demand, but has an impact on the user comfort, as external entities enter his/her home. This is why the second energy-management approach goes for an *indirect control*, where the loads are controlled entirely inside the home itself.

Reference [1] defines energy-demand management as a problem of order and optimization. In order to deal with this problem the control algorithm needs to know the future behaviour of the loads (i.e. the forecast of their power consumption). This forecast may be obtained through measurement, statistics, learning, etc. They divide the loads into three categories:

1. *Active loads*: we know their consumption forecast and we can act on their behavior.
2. *Informative loads*: we know their consumption forecast but we cannot act on their behavior.
3. *Non-informative loads*: we do not know about their consumption forecast and we cannot act on their behavior either.

They propose the following solutions in order to act on the non-active loads:

- To change their control hardware by another one which allows energy-management.
- To follow their behaviour closely by sensors.
- To control their consumption directly with switches.

Even in the cases where it is not possible to act on the loads, their consumption needs to be taken into account, so it is advisable to create a *virtual load* in the management system in order to reflect their behaviour.

2.1 Direct Control

Reference [2] analyzes the home-level electrical-energy consumption in UK. They obtain peak-consumption reductions up to 60% by using control algorithms in the

cooking and washing devices. They evaluate the removal of consumption peaks by integral control (avoiding simultaneous peaks) and thermal storage. On the other hand, the analysis of home-level energy consumption indicates that:

1. The energy consumption is not constant. In most cases, consumption peaks are much higher than the average value.
2. The consumption value depends on the number of inhabitants and their incomes.
3. Consumption patterns adjust to two types, depending on the activity periods:
 - a. People most of the time at home and needing heating system for most of the day.
 - b. People most of the time out of home and needing heating system only in the morning and in the evening.

Cooking, cloth-washing and dishwashing activities have been identified as responsible for consumption peaks, as they make use of high-power electrical heaters for a fast operation. Simultaneity of these activities may generate peaks over 10 kW, so controls have been implemented in order to avoid this.

Electrical kitchens are the ones which generate the biggest peaks of energy-demand. They are normally controlled with on/off cycles; therefore, a control algorithm has been implemented in [2] which minimizes these peaks, avoiding to a certain extent the overlap of the on-cycles of the different cooking plates.

On the other hand, washing machines have a 10-30 minute heating period at the beginning of their 60-90 minute cycle, and dishwashers have two heating periods of 10-15 minutes each. Control algorithms have been implemented which reduce the peak consumption of these devices, reducing the power of the heaters while increasing the duration of the washing cycles.

Other home devices (television, refrigerator, DVD player, etc) individually have low power consumption (10-200 W) and do not have a significant margin for improvement. The same thing happens with lights: even if it can be controlled in a more efficient way (e.g. by the use of presence sensors), peak reduction values are too small. Other devices, such as toasters, microwave ovens, dryers and hoovers have been defined as non-switchable, proposing a warning system which recommends postponing their use.

Finally, [2] proposes the use of a centralized load-management control system in order to smoothen the consumption profile. Depending on the consumption value,

they apply the controls mentioned before and also delay/switching strategies. Load shedding (e.g. switching off alternatively a heater for a short period of time during periods of high consumption) is a suitable way of avoiding peaks for several devices (ovens, cooking plates, washing machines and dishwashers). This option, however, should have low priority in the control hierarchy, as it might go against the user preferences. They suggest that the user should be able to choose long delays instead of short interruptions, or define a specific operation time for certain appliances (e.g. dishwasher).

Reference [3] proposes a method to control the consumption peaks due to electrical boilers. They propose a centralized control which acts on the boiler's thermostat, increasing the water temperature so that a larger amount of energy is stored before the high consumption periods so the user can have enough hot water during these periods.

Reference [4] details energy-demand control strategies which can be applied to different domestic loads, taking always into account that the user can be reluctant to introduce in his/her home an external control system. The strategies are based on switching-off the loads during peak periods and on using intelligent thermostats and a centralized control of water boilers.

2.2 Indirect Control

Reference [5] promotes the use of controllers which analyze the mains frequency and switch on/off devices depending on variations of this frequency. They define as candidate devices for this kind of control those which are used in thermal applications (heating/cooling), which allow a certain degree of flexibility in their consumption. They focus mainly on the refrigerator, as it is a continuous and relatively constant load, with a reasonable storage time. Therefore, they implement a control which changes the operation point of the thermostat depending on the mains frequency.

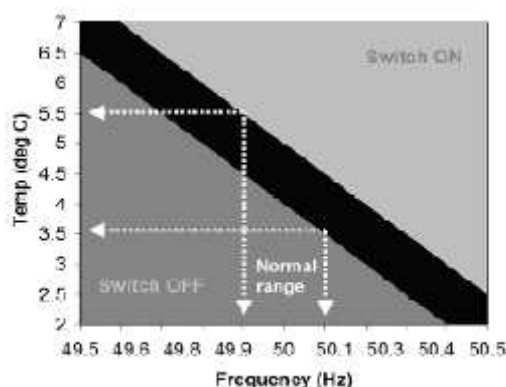


Figure 1: Operation point of thermostat

Reference [6] presents a management scheme which reduces the load peaks based on four main functions, which are activated each time that the user turns on a device:

1. A planner, which calculates the best way of carrying out an action minimizing the consumption, taking into account the available loads that can be optimized (washing machine, dishwasher, dryer).
2. Energy-saving, which manages loads (lamps) according to timers and sensors.
3. A graphical interface which shows the status of each device.
4. Regular use: it guarantees that the devices operate correctly.

The topology of the structure allows several functions to work in parallel. This system works properly as long as a suitable tariffication service and enough optimizable consumption are available, and as long as the user is ready to sacrifice some comfort.

Reference [7] presents a controller which carries out home-level load shedding. The system is based on a microcontroller which controls the on/off switching of the various devices. The controller performs the necessary actions when it receives the control order, which may come from:

1. A signal sent by the network manager.
2. A clock which discriminates the peak consumption periods.
3. The overflow of a consumption level set by the user.

The priority of the loads to be delayed is defined by the user, as well as the duration of the interruption.

Reference [8] presents a control algorithm which allows shifting the operation of domestic loads in order to match several predefined demand profiles. They classify the loads according to the following features:

1. The calculation step for the load monitoring.
2. The power it needs to operate for each step of the calculation.
3. Priority of use, defined by the impact of the load shift.
4. Time that the load can be shifted with minimal effects.

5. Availability for shifting the load, taking into account how long it has been from the last shifting.

The algorithm shifts the loads according to the instantaneous demand.

Reference [9] presents a home management system which takes into account the global home situation and the consequences of the actions. The system comprises the following steps:

1. It gathers the data (sensors, status of devices, electrical prices, etc) and generates the current scenario.
2. It classifies the current scenario taking as a reference those coming from a database of predefined scenarios.
3. It analyzes the actions that can be done in that scenario.
4. It adds these actions to the scenario, obtaining a virtual scenario.
5. It compares the virtual scenario with the actual one. If it is better (higher comfort, less consumption, etc), it performs the actions.

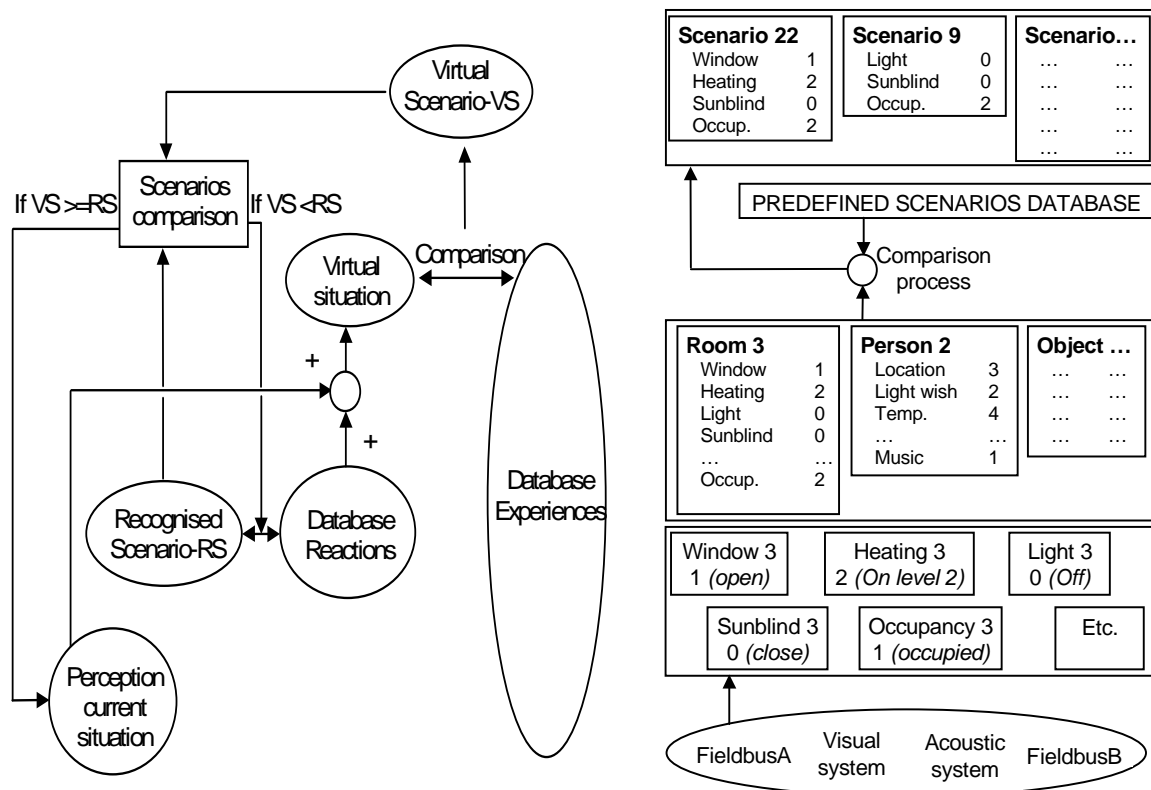


Figure 2: Home energy-management system [9]

In [10] they developed a home energy-management system using a fuzzy controller. The system is made of a central unit which communicates with the device controllers using X10 communication protocol. The control is implemented in the following three units:

1. *Load models*: they are needed in order to calculate the hourly home consumption and to design load-shifting strategies.
2. *User interface*: it allows to introduce the preferences for the devices and to communicate their status.
3. *Load-shedding algorithm*: it determines the shift of the loads based on the price, load, temperature and user preferences. It determines the reference temperature for devices such as thermostats and air-conditioning.

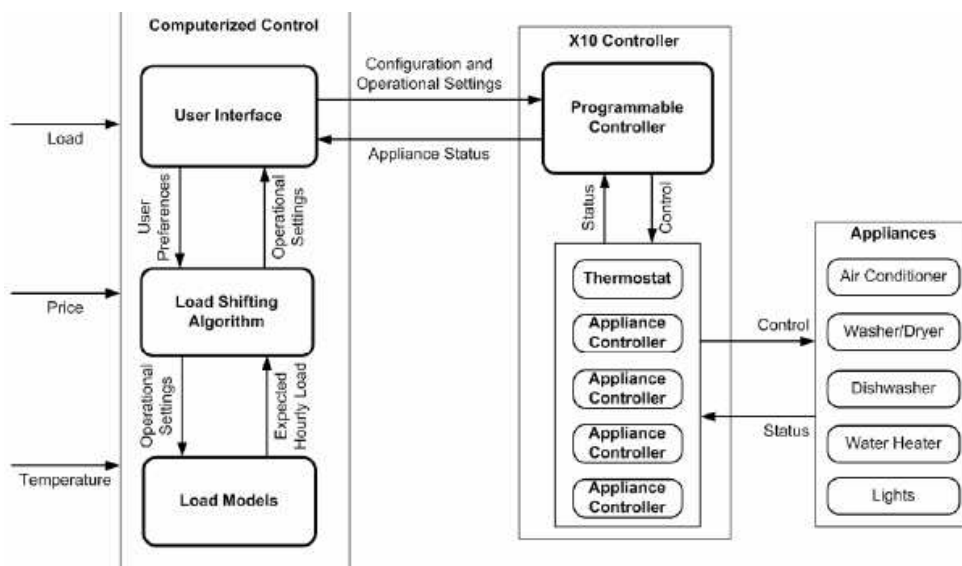


Figure 3: Home energy-management system [10]

The user may select three operating modes: Super-saving, Economic and Comfort. Each mode predefines the following parameters:

1. Price threshold (the load-reduction system is activated whenever the price goes over this threshold).
2. Temperature tolerance (the variation allowed on the air-conditioning thermostat).
3. Minimum light intensity.
4. Minimum use of the boiler.

5. Maximum allowed delay for the washing machine, dryer and dishwasher.

The system divides the day in *peak*, *valley* and *pre-peak* hours, depending on the price, load and temperature. With a notification made in advance, the pre-peak hours may be useful for load-shedding (e.g. rising the activity of the heating system, so that the thermal inertia of the house minimizes the discomfort of a lower thermostat temperature setting during the peak hours).

During peak hours the system tries to redistribute the loads that can be delayed either to a valley-hour or to a cheaper hour, taking into account the maximum allowed delay.

The reference temperatures of the devices that can be controlled will be set following the following fuzzy rules:

1. If the price is low and the load is not high, then set the reference temperatures to the desired levels.
2. If the price is low and the load is high, then the air-conditioning and the boiler go to warm state and the lights dim.
3. If the price is medium and the load is not high, then the air-conditioning and the boiler go to warm state and the lights dim.
4. If the price is medium and the load is high, then the air-conditioning goes to warm state, the boiler goes to cold state, and the lights dim at maximum level.
5. If the price is high and the load is low, then the air-conditioning and the boiler go to warm state and the lights dim.
6. If the price is high and the load is medium, then the air-conditioning goes to hot state, the boiler goes to warm state, and the lights dim.
7. If the price is high and the load is high, then the air-conditioning goes to hot state, the boiler goes to cold state, and the lights dim at maximum level.

3. Definition of input/output parameters

3.1 System requirements

To begin with, requirements included in D1.3-B have been analyzed, as within them it is possible to find different inputs or outputs of the eDIANA system that can be useful for the design of the energy saving algorithms.

Req. 2.2.2.1.1 - *End user preferences*: The system must act according to the end-user preferences.

Req. 2.2.2.1.7 - *Energy saving Suggestions*: The eDIANA system should give suggestions what users should do to save more money/energy.

Req 2.2.1.1.9 - *Standby killer*: The eDIANA system should be able to detect that a device is on standby and cut of the electricity use to save energy

Req. 2.2.2.1a.1 - *Control light and intensity*: The end user must be able to control the lights and their intensity according to the user's desired comfort. When doing that eDIANA should give information about the energy usage

Req. 2.2.2.1b.1 - *Take advantage of tariffication options*: Utilities will offer different tariffication options to their customers depending on the time of the day, or at demand peaks. Some appliances could delay their start, lower the consumption, etc. when the price is higher.

Req. 2.2.2.2.a.1 - *Readjust water boiler temperature setting*: The temperature setting of the boiler can be altered by the energy management system

Req. 2.2.2.2.a.2 - *Interrupt hot water service if occupants are not at home for a long time*.

Req. 2.2.2.2.a.4 - *Full blocking of washing process*

Req. 2.2.2.2.a.7 - *Raise fridge/freezer temperature temporarily*

Req. 2.2.2.2b.1 - *Control light intensity of a television*: The end user must be able to control the light intensity of his television according to his preferences. eDIANA can interact with this by closing the bindings or suggesting to do that.

Req. 2.2.2.3a.1 - *Control ICT network*: In an office, eDIANA should be able to actuate a network during office hours (e.g. starting the printers in the morning). However the end user must have priority when he wants to change something

Req. 2.2.3.3/4/5 - *Feedback on energy usage*: The eDIANA system should be able to predict a consumption pattern of a user.

The eDIANA system can recommend the user to take actions to reduce the amount of consumption or change the consumption pattern

The eDIANA system should allow the user to keep track of their efforts to reduce the amount of consumption or change the consumption pattern

Req. 2.2.3.7 - *User energy consumption and energy reduction comparison*: The eDIANA system enables users to relate their energy consumption and energy reduction and the energy consumption and energy reduction of users having equal conditions. Comparing user energy consumption and energy reduction with others enables to optimize the energy consumption of a user

Req. 2.2.3.9 - *The eDIANA system should be able to register energy delivery*

Req. 2.2.3.11 - *Automatic energy consumption*: The eDIANA system shall provide mechanism to switch on/off equipment or suspend energy consumption

Req. 2.2.3.13 - *Network congestion*: The eDIANA system should provide network congestion prediction information

Req. 2.2.3.14 - *Pricing information*: The eDIANA system shall support various schemes for pricing.

Req. 2.2.4.1.3 - *Daily behaviour setting*: The user must be able to set his daily behaviour into the eDIANA calendar. (e.g. every weekday he wakes up at 7.00h). Next to that he must be able to set exceptional days (e.g. the end user is sick). The eDIANA system will run according to the user's location and activity in the house

Req. 2.2.4.1.4 - *Single device information*: The eDIANA UI must be able to provide the user information about each single electronic device. The end user must be able to interact with it through eDIANA.

Req. 2.2.5.1 - *Handle priorities of electrical equipment*: Handle priorities of electrical equipment in a case of a price signal (from MCC): to turn off only non-essential equipment and not to turn off all equipment (could be a matrix with a priority value for each device).

Req. 2.2.5.3 - *Handle time-scheduled programs*: Handle time-scheduled programs. Turn off certain equipment with a (user-programmable) daily, weekly or yearly period

Req. 2.2.5.4 - *Handle exceptions in turning electrical equipment off and on*: Handle exceptions in turning electrical equipment off and on, for example

- do not turn off the lights in a room where someone is present,
- do not turn off the washing machine during its use,
- do not finish a washing program when nobody will be home for the next four hours

3.2 Inputs/Outputs breakdown

Inputs/outputs identified within Cell scope are summarized in the following table:

Requirement	Related Input/Output	
	Input	Output
Req. 2.2.2.1.1	User preferences. Devices settings, energy use schedule	Orders to the cell level devices involved
Req. 2.2.2.1.7		Energy saving suggestions
Req. 2.2.1.1.9	Stand by signal.	Off signal
Req. 2.2.2.1a.1	Light dimming signal; Light energy consumption.	Lighting consumption information.
Req. 2.2.2.1b.1	Energy Tariffs.	
Req. 2.2.2.2.a.1		Boiler temperature settings.
Req. 2.2.2.2.a.2		Cut out hot water.
Req. 2.2.2.2.a.4		Washing machine control (pause, on, off).
Req. 2.2.2.2.a.7		Fridge control. Raise/decrease temperature.
Req. 2.2.2.2b.1		TV's brilliance control.
Req. 2.2.2.3a.1		Devices on/off control
Req. 2.2.3.3/4/5		
Req. 2.2.3.7	Overall energy consumption	Consumption/reduction balance
Req. 2.2.3.9		
Req. 2.2.3.11		switch on/off equipment
Req. 2.2.3.13		
Req. 2.2.3.14		
Req. 2.2.4.1.3	Occupancy, programmed schedule, associated time stamp.	Energy use short term schedule.
Req. 2.2.4.1.4	Devices priorities	
Req. 2.2.5.1	Energy price from MCC	Turn off equipment depending on priorities
Req. 2.2.5.3	Scheduled program	Turn on/off equipment
Req. 2.2.5.4		

Table 1: Cell-level inputs/outputs

Therefore, the following inputs and outputs can be considered for energy-management algorithms:

Inputs:

- User's settings
 - Occupancy
 - Devices programs
 - Automatic energy saving profile set up
- Devices' status
 - On, off, stand-by
- Devices' consumption [kWh]
- Devices' priorities
- Sensor's data
 - Occupancy
 - Humidity
 - Lighting
 - Temperature
- Energy price

Outputs:

- Devices status
 - On/off control
 - Stand-by control
 - Pause control
- Devices features control
 - Lighting dimming
 - Screen brilliance
 - Temperature control

3.3 Load management algorithm input/outputs

Regarding the load management algorithm, the following inputs can be considered:

- Packet on contract conditions between the user and the distributor/marketer (using the meter as gateway).

Variable	Size	Description
Rate_price	24 bytes	Indicates the kWh price per hour (24 periods)

Table 2: Algorithm input data (Rates)

- Packet on contract conditions between the user and the distributor/marketer (using the meter as gateway).

Variable	Size	Description
Power limit	24 bytes	Indicates consumable power at each hour (24 periods)

Table 3: Algorithm input data (power limits)

- Packet on changing designation of priorities or preferences for domestic appliances by user.

Variable	Size	Description
Appliance_name	String	Name to identify domestic appliance type (washing machine, oven, dishwasher, etc.).
Appliance_priority	1 byte	Indicates priority of domestic appliance.
User_time_preferences	20 bytes	Variable indicating the periods during which one wants to use the domestic appliance.

Table 4: Algorithm input data (Priorities/preferences of use)

- Packet on changes resulting from action by user on a load.

Variable	Size	Description
Name_appliance	String	Name to identify domestic appliance type (washing machine, oven, dishwasher, etc.).
PL	1 bit	Indicates that the domestic appliance can operate in limited power mode.
Consumption_profile	10x1 bytes	Consumption during each phase of operation of the domestic appliance (10 phases).
Duration_profile	10x1 bytes	Duration of each phase of operation of the domestic appliance (2-minute base) (10 phases).

Table 5: Algorithm input data (user action on load)

And these are the outputs parameters of the algorithm:

Variable	Dimensión	Descripción
T_start	30x5 bytes	Start date and time for the device
Device_code	30x2 bytes	Device identification
Device_status	30x1 bytes	Device status (on/off/continue)

Table 6: Algorithm output data

4. Algorithm description

4.1 Fully automatic algorithms

The function of the load management algorithm consists of generating the operating orders for each of the manageable loads integrated into the domestic environment. These orders indicate the switch-on moment for each domestic appliance (day/month/year/hour/minute). To perform this, the algorithm uses information from

the features of the domestic appliances, the priorities and preferences of use established by the user, and the prices and consumption limits laid down by the contracts.

The algorithm positions the operation of each of the domestic appliances to minimize energy expenditure, bearing in mind how electricity prices are evolving and adhering at all times to the limits on the level of usable power, as well as the levels of priority and preferences of use established by the user.

To fulfil the functionality specifications, an algorithm has been developed for the non-linear mono-objective optimization with equality and inequality restrictions. The function to minimize is:

$$\varphi = \sum_{i=1}^{n^{\text{electro}}} \text{coste_energético}(i) \quad (1)$$

being *coste_energético* (*energy_cost*) (*i*) the cost resulting from the operation of the domestic appliance *i*.

The aim of the algorithm will be to minimize the function φ , taking the following restrictions into consideration:

$$\text{Limite potencia} \geq \sum_{i=1}^{n^{\text{electro}}} \text{Potencia_consumida}(t) \quad (2)$$

$$t_{\text{on_usuario}} \leq t_{\text{inicio}} \leq t_{\text{off_usuario}} \quad (3)$$

$$t_{\text{on_usuario}} \leq t_{\text{final}} \leq t_{\text{off_usuario}} \quad (4)$$

$t_{\text{on_usuario}}$ and $t_{\text{off_usuario}}$ being the user's time preferences regarding the moment in which each domestic appliance functions, while t_{inicio} and t_{final} are the start and stop times of the operation of the domestic appliance.

Figure 4 shows the general flow chart of the algorithm. The steps followed to reach the optimum solution are explained below:

1. Firstly, the domestic appliances are ranked according to their priority, so that the algorithm will start considering first the domestic appliances with the highest priority (the reason is that the moment of operation of a domestic appliance is naturally determined by the moments of operation of the other domestic appliances with higher priority).
2. Once ranked, the domestic appliances will be positioned for operation purposes while minimizing energy cost and complying with the restrictions imposed. To carry out this process, a check is first made to see whether the domestic appliance in question is *on* or not:

- If it is already functioning when the algorithm kicks in, it is regarded as a time restriction and the costs associated with it are evaluated by means of the *Algo7_coste* (*Algo7_cost*) function developed.
 - If the domestic appliance in question is switched off when the algorithm kicks in, a call is made to the *Algo7_coste* function and its results are used to evaluate the *Algo6_min* (*Algo6_min*) function, which returns the switching on moment for the domestic appliance with a minimum energy cost.
3. This operation is repeated in accordance with the number of domestic appliances that are in the system. Once they have all been considered, the total costs are calculated and the nucleus of the optimization algorithm is exited.

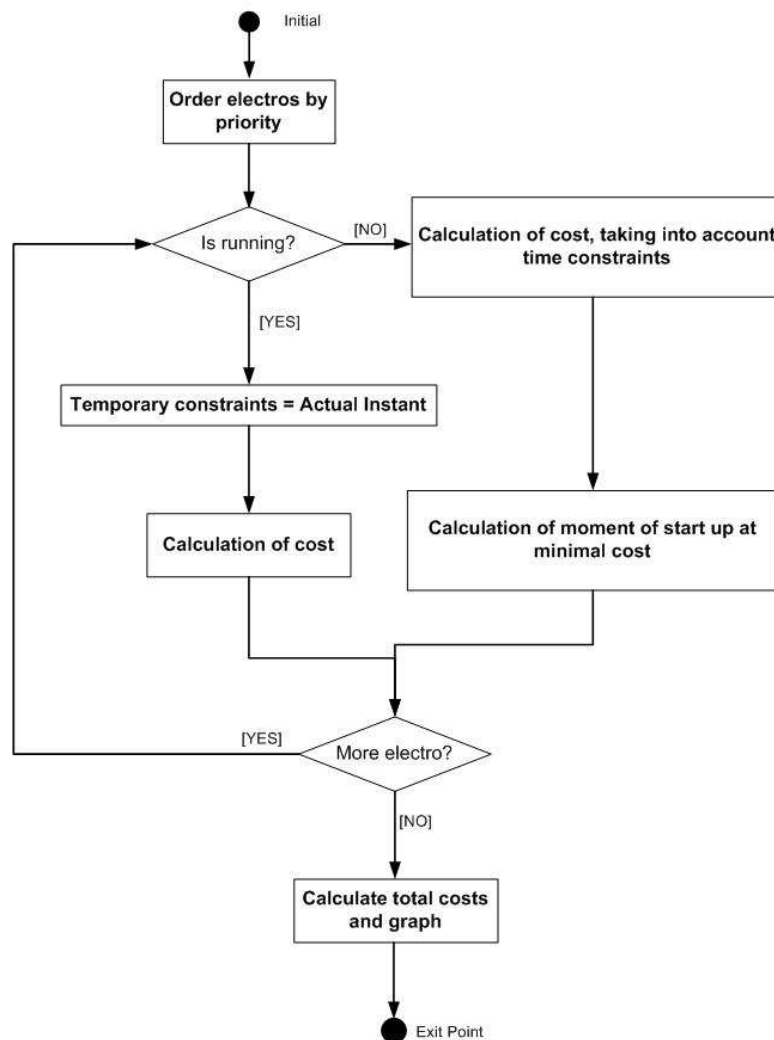


Figure 4: State diagram of the optimization core

The *Algo7_coste* function undertakes to calculate all the costs associated with the functioning of the domestic appliances.

- Should a domestic appliance already be switched on, it calculates the cost that is going to be incurred by the remainder of the operating cycle.
- Should domestic appliance be switched off, the function calculates the cost that would be incurred in switching it on at each of the moments within a 24-hour period, as long as the time restrictions are adhered to.

The *Algo6_min* function calculates the moment for turning on the domestic appliance bearing in mind the power limits and time restrictions. To clarify how this works, the diagram of states followed by this function is shown in Figure 5:

1. Taking the cost data provided by *Algo7_coste* as the starting point, the moment of minimum cost is first selected for turning on the domestic appliance. So, assuming that the domestic appliance comes on at that moment, the total used power is calculated and it is compared with the power limit. If the power limit is exceeded at any moment while the domestic appliance is on, that moment for being on is rejected, and the next possibility is sought, always bearing in mind the final aim of minimizing energy cost.
2. When the iteration reaches an operation starting point in which the power limit of the installation is adhered to at all moments, that will be the solution of the algorithm for minimizing energy costs, and that is therefore the end of the calculation. Once all the possible moments provided by *Algo7_coste* have been considered, should it turn out that none complying with the limited power restriction is forthcoming, a message is sent advising that it is impossible to switch on the domestic appliance through lack of sufficient power to carry out the whole operation, and the calculation is thus regarded as terminated.

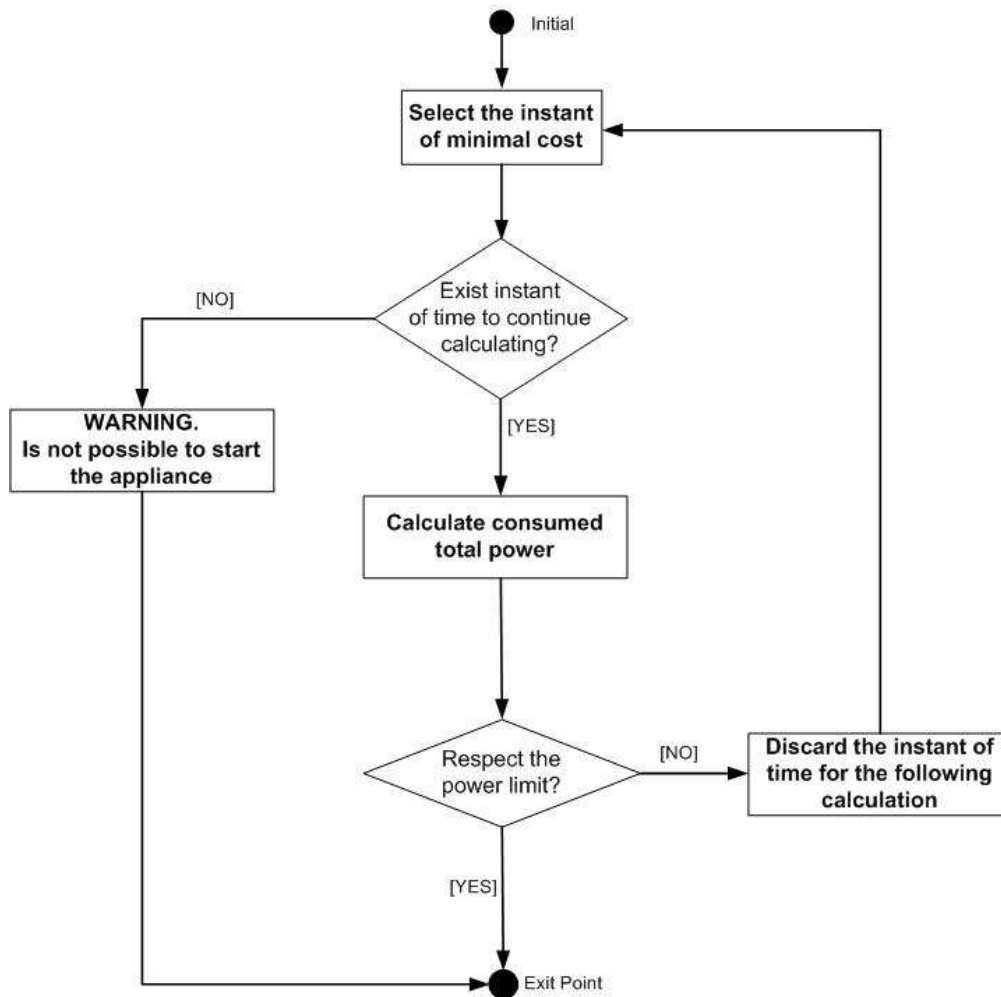


Figure 5: State diagram for calculating the moment for optimum functioning

4.2 User-centered algorithms

The user-centered algorithm is needed for an home energy-demand management system that is centred around the end user. His feel of comfort will improve if the user has control on the energy-demand management system. At first, he needs to have in sight on his current energy usage.

A photo display can be used show the current energy usage, which is input for the end user to change his usage pattern or give commands to the system to optimize the energy demand without loss of comfort in an intuitive way.

First the user needs to get a general in sight in its daily energy consumption, see Figure 6.

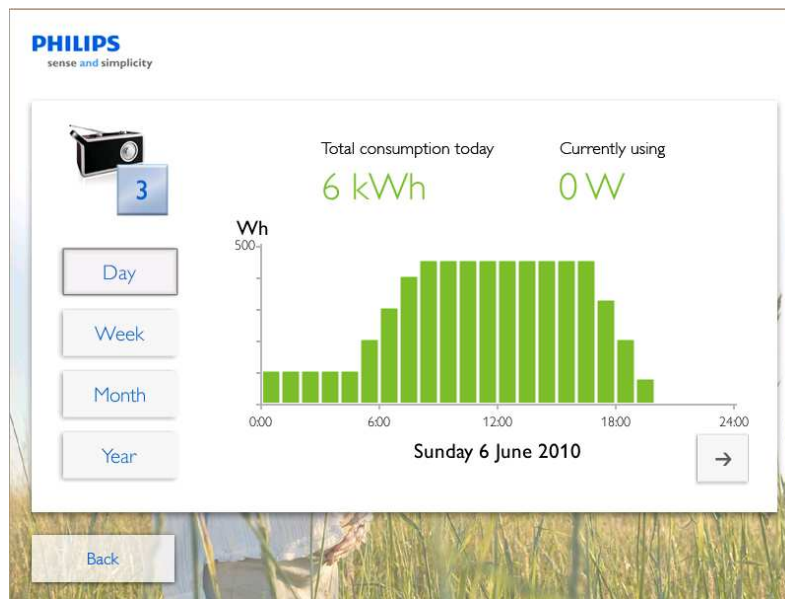


Figure 6

In Figure 7 the energy consumption is given per group of devices. The user can act on this information and give commands to reduce power consumption.



Figure 7

The photo display is using a web interface to get information on the power consumption from the plug wise network. The same information can also be displayed on a web enabled TV set.

5. Simulation models

5.1 Cell Model

To determinate the Macro-Cell pattern is required to start from the Cell ones and create the Macro-Cell pattern take into account the modularity and scalability. In this report we will refer to a Cell like a private flat and to a Macro-Cell like a condominium. We need to consider a Cell both like a energy consumer and energy producer, in eDiana terms "PROSUMER". For this reason a first high level division of the Cell pattern can be in consumption part and in production part (Figure 8). The external input of the consumption part is temperature, the outputs are the thermal energy consumption and the electrical energy consumption. For the generation part the inputs are wind speed, number of the day and cloudy factor (a parameter that indicates the intensity of cloud in a determinate time for a determinate place). In fact, how we will see better in the next pages, the energy generation is possible in two ways: wind generation and photovoltaic generation. The output of generation part is the electrical energy generation.

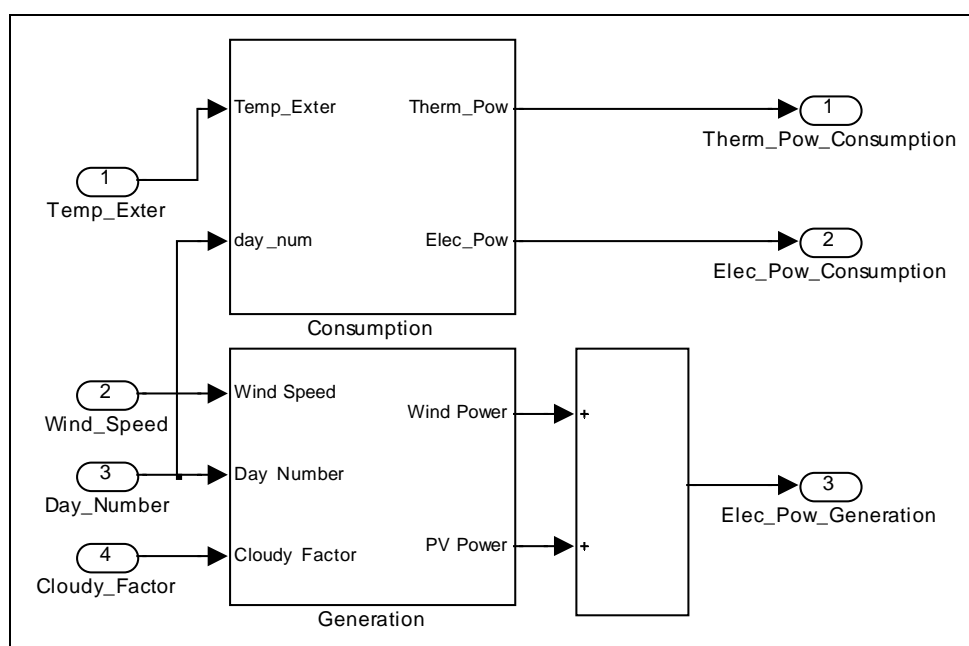


Figure 8

5.1.1 Consumption Model

In Figure 9 there is a first view of the consumption model (high level). The pattern is divided in two parts, one thermal and one electrical. Outputs are the thermal power and the electrical power. Inputs are warm water request, household appliance activation, and lighting activation.

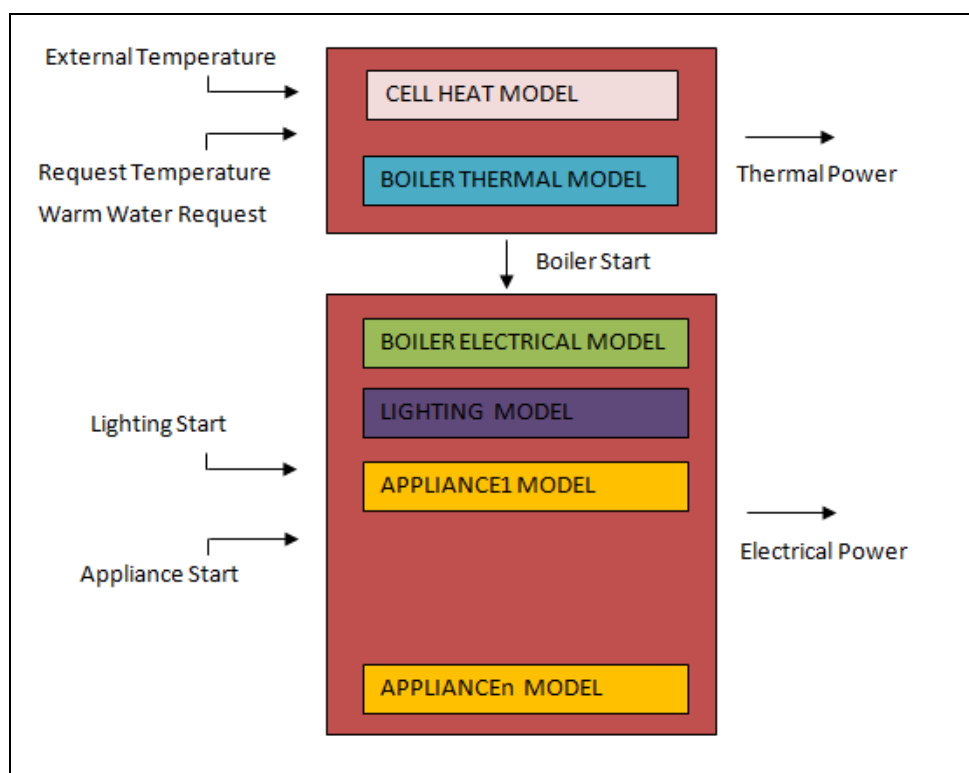


Figure 9

In Figure 10 we see a breakdown of the cell in two parts, heat and electricity. The heat system receives in input the external temperature and the current day number. Outputs of this subsystem are thermal power, the start boiler request (understood in terms of electricity), temperature inside the cell and conditioner electric power. Regarding the electrical system the only input is the signal "Enable boiler" representing the start request of the boiler. In this case the output is electrical power. There is also a block called "calendar" which generates a signal responsible to discriminate if the day simulated is a working day or not. In fact it is reasonable to consider different consumption for a working day or a holyday. The total electrical and thermal power represents the two outputs of the system Cell. They will be added together with the corresponding powers of the other Cells and form electrical and thermal power of the Macro-Cell. It is necessary to specify the dimensions of the cell (surface and height) for the heat subsystem. There is also a noise block to simulate the constant loss of energy due to imperfect calibration of the electrical plant and to constant consumption of appliances that are always connected to the network (TV, VCR, cable box, alarm, etc.). Same thing for the thermal plant.

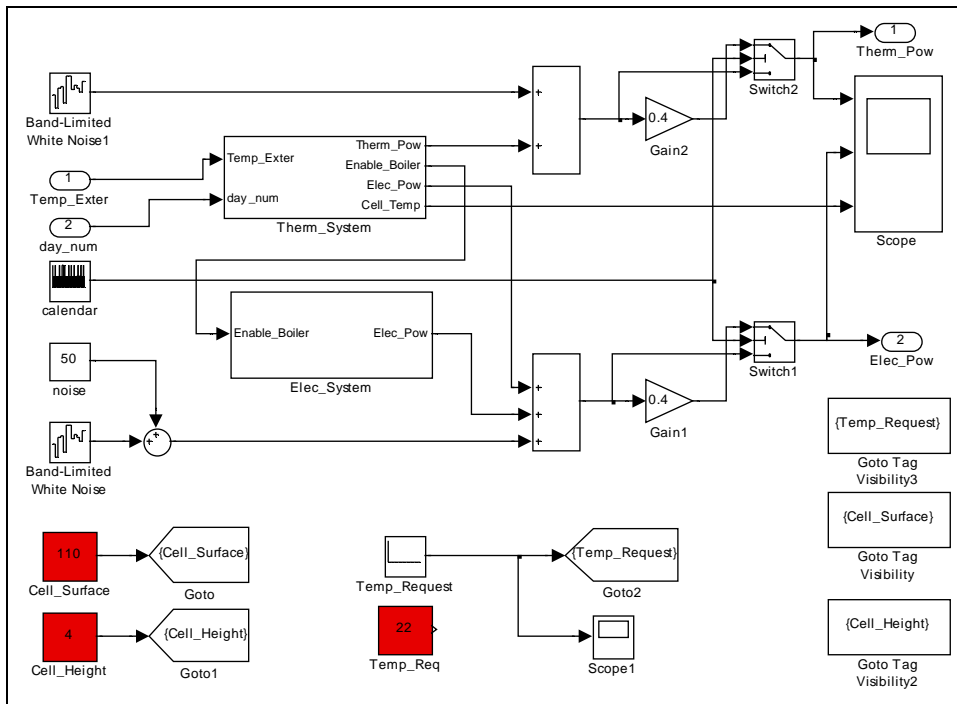


Figure 10

5.1.1.1 Electrical System Pattern

In Figure 11 we see the electrical subsystem of the Cell. It was decided to understand a Cell as a medium sized apartment within the following appliances: fridge, vacuum cleaner, hair dryer, oven, computer, television, and washing machine. It is also considered the lighting. The total electrical capacity of the Cell is the sum of the individual electrical appliances. The only input of this subsystem is "Enable_Boiler", the output "Elec_pow". The appliances are modeled very simply. To start and stop using a square wave signal with period equal to a day. For the exact time of day and duration it is used the phase and the width of the wave. This signal then arrives at a gain block that represents the electrical power of the appliance. In Figure 12 we see an example of appliance subsystem. It is the example of a hair dryer. There is a first block for the generation of a wave signal and a second block (gain block) which represents the hair dryer power. It is possible monitoring the power signal using a scope block. In every appliance model there is also a generation random signal block. The reason is that it is not realistic consider the uses of all appliance every day. This block generates a random signal with average 1 and change value with time sampling of 24 hours. If the value is more than 1 the appliance will be used during the day, in contrary case not.

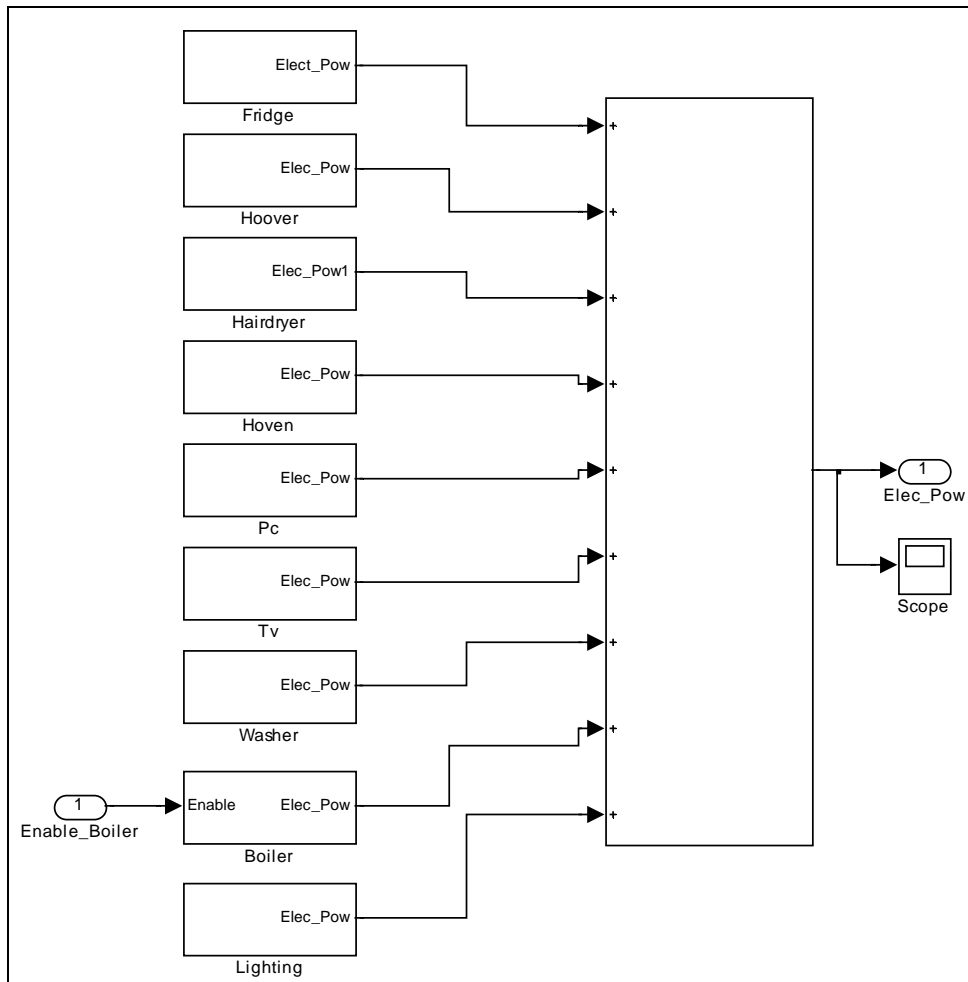


Figure 11

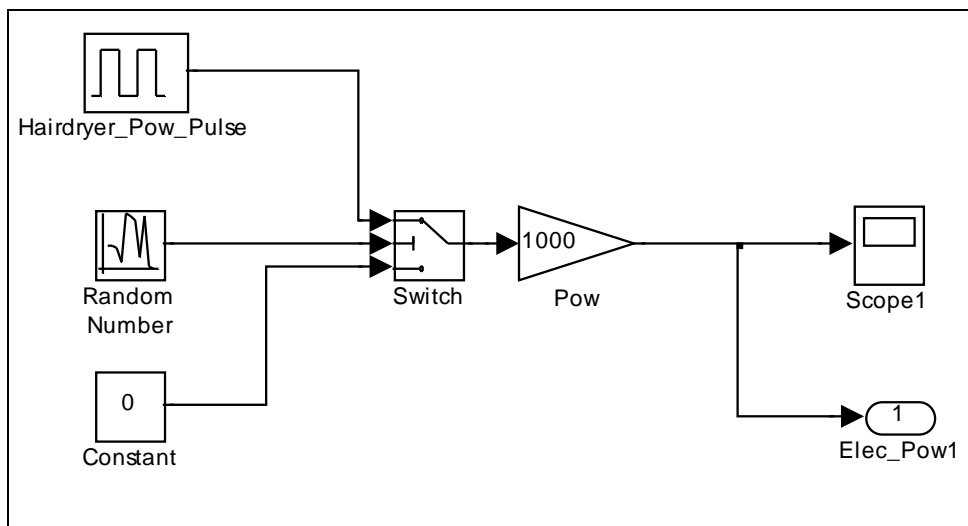


Figure 12

A model like the one showed in Figure 12 is used also for Hoover, oven, PC, TV, washer and lighting. For boiler model it is not used the random block because the start signal arrives directly from the heating subsystem or from the warm water subsystem (Figure 13). Different speech for the fridge model. In this case there is neither an external input signal nor the random signal. In fact a fridge has its periodical cycle of activation and cannot depends from the user (Figure 14).

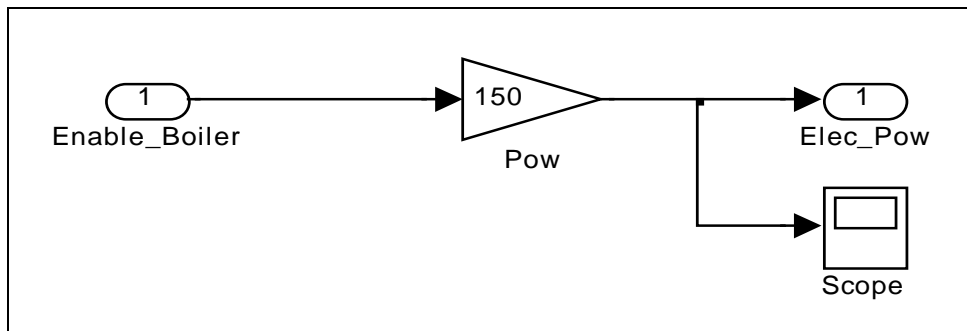


Figure 13

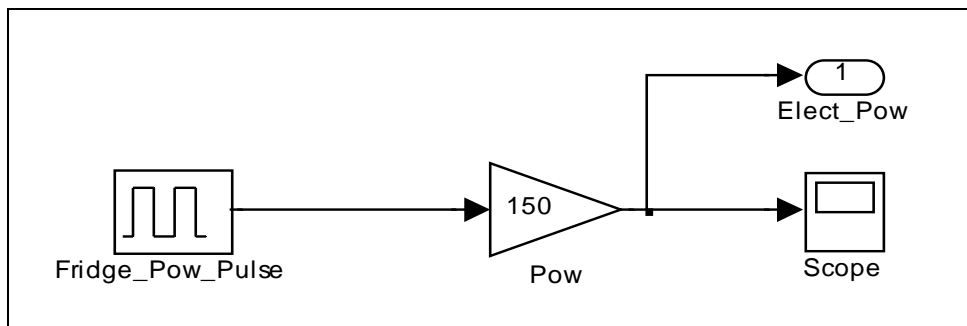


Figure 14

5.1.1.2 Thermal System Pattern

The thermal model of a Cell is show in Figure 15. It has been divided into heating, air conditioning and hot water system. Inputs of this system are the temperature outside the Cell, the temperature required by the user, and the number of current day. Outputs are the thermal power, the electrical power of air conditioner, the temperature inside the Cell and a signal called "Enable_boiler" representing the start request of the boiler.

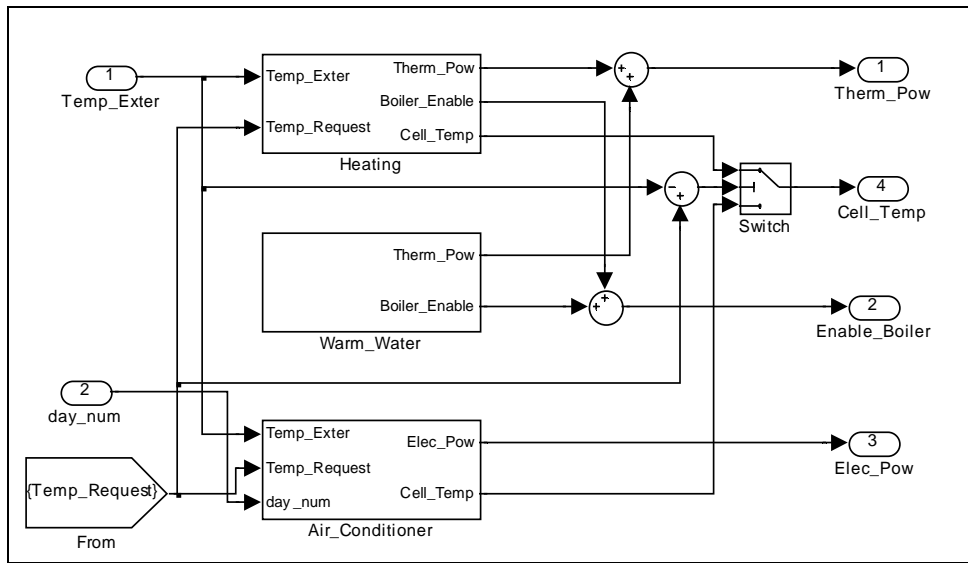


Figure 15

5.1.1.3 Hot Water Plant

In modeling this system, it was considered the daily health consumption. In Figure 16 we see the pattern of this model. The outputs are the thermal power and a signal called "Boiler_Enable". This signal can have value 1 or 0. It will be 1 when the hot water plant will be active, 0 otherwise. "Boiler_Enable" is used to activate the boiler every time there is a hot water demand.

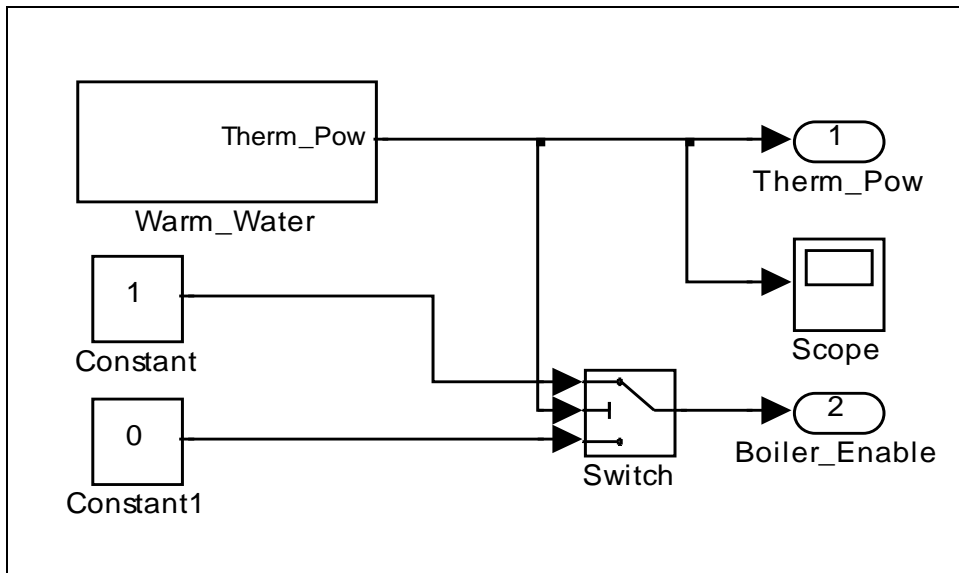


Figure 16

In Figure 17 has been reported the exploded view of the "Warm_Water" subsystem. As mentioned, it is the pattern for hot water daily consumption. It is assumed that

there are six long hot water requests a day. For representing the start and the stop of a certain warm water use, step block are used. For activation a positive step, a negative step otherwise.

5.1.1.4 Heating Plant

Before going into details of heating pattern we need to define typical sizes of thermal system:

- *Heat Capacity*: a measurable physical quantity that characterizes the amount of heat that is required to change a temperature of a body by a given amount. (J/°K)
- *Specific Heat*: it is the amount of heat per unit mass required to raise the temperature by one degree Kelvin. (J/Kg* °K)
- *Thermal Conductivity*: it is the property of a material that indicates its ability to conduct heat. (W/m*K)
- *Thermal Resistance*: it is the temperature difference across a structure when a unit of heat energy flows through it in a unit time. (°K/W)

For the Cell model it was necessary to calculate thermal resistance and thermal capacity of the Cell and of the radiator. The quantities used are:

$C_{sa} = 1008 \text{ J}/(\text{Kg} \cdot ^\circ\text{C})$	<i>Air Specific Heat</i>
$C_{sr} = 880 \text{ J}/(\text{Kg} \cdot ^\circ\text{C})$	<i>Radiator Specific Heat</i>
$\gamma = 0.08 \text{ W}/(\text{m} \cdot \text{K})$	<i>Thermal Conductivity of the Cell</i>
$d = 1.2928 \text{ Kg}/\text{m}^3$	<i>Air Density</i>
$m = 1.6 \text{ Kg}$	<i>Radiator Column Mass</i>
$p = 150 \text{ W}$	<i>Radiator Column Thermal Power</i>

To respect the bonds of modularity and scalability we decided to approximate the Cell to a single room, although it represents a whole apartment. The reason is to have a valid model regardless of the numbers of rooms. The idea is to design a model that requires as inputs only the total area of the Cell (square meters) and its height. For example, if we want to model a building (Macro-Cell), we can simply combine several models of flat (our Cell). When you add a new apartment you take the standard model and initialize the only two variables area and height, without worrying about the number of the rooms and their place inside the apartment.

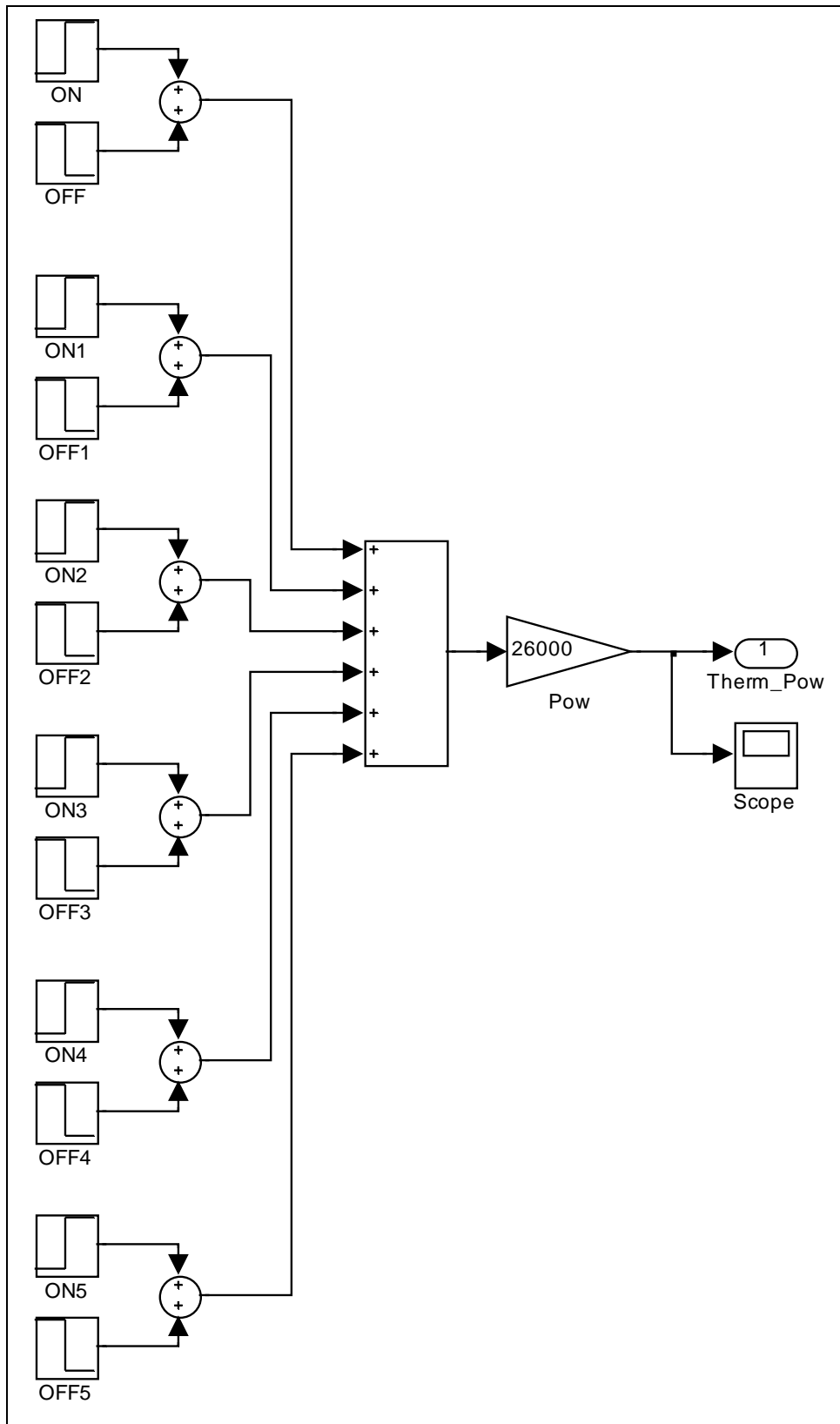


Figure 17

We tried to use the equivalence between thermal and electrical systems in order to use a more favorable physical domain. The equivalent circuit is shown in Figure 18.

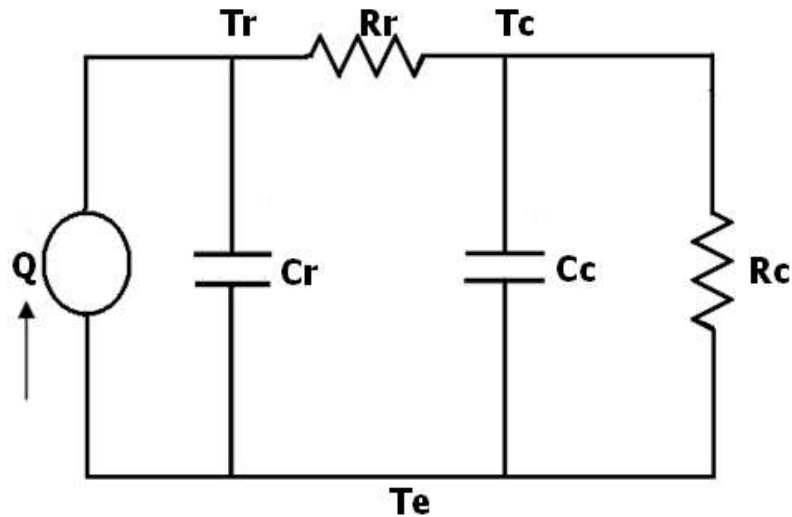


Figure 18

The thermal capacity will be considered as electrical capacity and the thermal resistance as electrical resistance. The radiator will be treated as a current source. Then using the convention of typical circuits the state variables will be assigned at the voltages across the two capacitors. The two states of the system will be the temperature difference between outside and radiator and the temperature difference between outside and Cell environment. The system equations are:

$$\dot{X}_1 = \frac{Q}{C_R} - \frac{X_1}{R_{RA} * C_R} + \frac{X_2}{R_{RA} * C_R} \quad \dot{X}_2 = \frac{X_1}{R_{RA} * C_A} - \frac{X_2}{R_{RA} * C_A} - \frac{X_2}{R_{AE} * C_A}$$

In Figure 19 it is showed the heating pattern. To simulate a typical thermostat controlling it is used a simply hysteresis control (+/- 1 degree of required temperature). This means that the heating plant is active when the temperature is less than one degree of temperature required by user and turn off when the temperature exceeds one degree. During the activation the signal "Boiler_Enable" is brought to value 1. This signal is used in the electrical system to simulate the boiler start. The inputs of thermal system are the outside temperature and the temperature required by user. There is also a subsystem used to calculate thermal capacity and resistance of Cell and radiator and thermal power of radiator. The outputs of the system, in addition of the signal to simulate the boiler start, are the Cell temperature and the thermal power. The last one is calculated by going to see when the heating is on. If yes, we known that boiler is working. Knowing the boiler thermal power we can know what is the thermal power consumed.

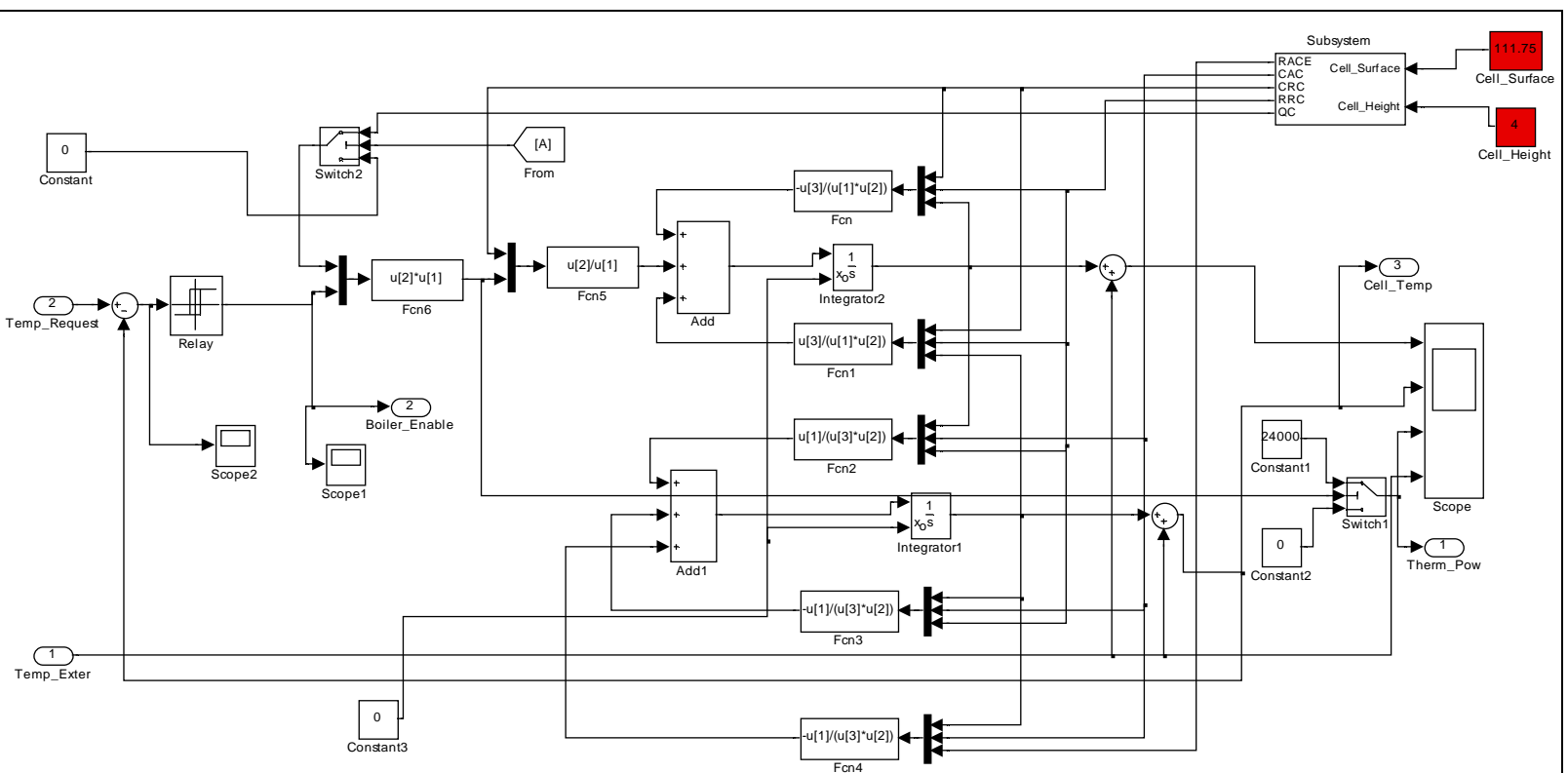


Figure 19

5.1.1.5 Air Conditioning Plant

Regarding the air conditioning system it is used a model similar to the heating one. In technological terms heating and air conditioning are completely different, but in terms of thermal effects they play two similar functions. For this reason the air conditioning was added in the thermal system. Of course, the output will be electrical power, not thermal. Remembering that our goal is to calculate the consumptions, electricity consumption in this case, we only want a model that, with a temperature request, furnishes the required electrical power to satisfy it. From this perspective it makes no sense a detailed electrical model of air conditioner. We will use the same Cell thermal model used for heating. Reasoning in terms of equivalent electrical circuit (Figure 20), we understand the operation of air conditioning as assuming a current opposite to the one used for heating. What is done is consider a thermal "negative" power for the air conditioner that decreases the temperature of the Cell. In Figure 21 there is the thermal Cell model changed in air conditioning point of view. Inputs are still outside temperature and temperature required by user. Outputs are the temperature of the Cell and the electrical power consumed by air conditioning. In add to the heating system there is also a switch block to disable the air conditioning plant. The switching depends to the number of current day. The plant is active only during the Summer days.

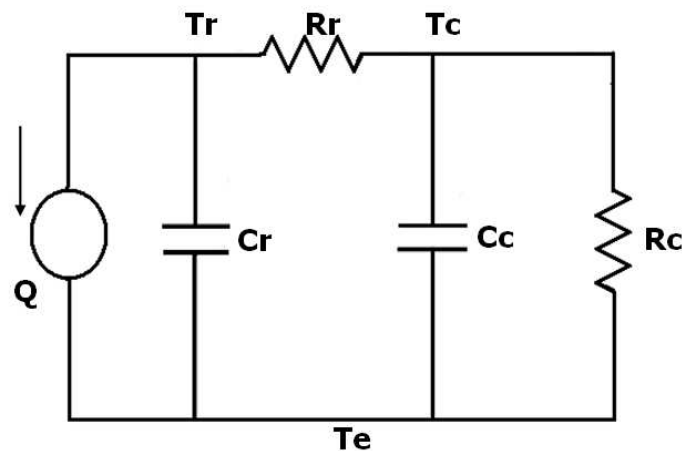


Figure 20

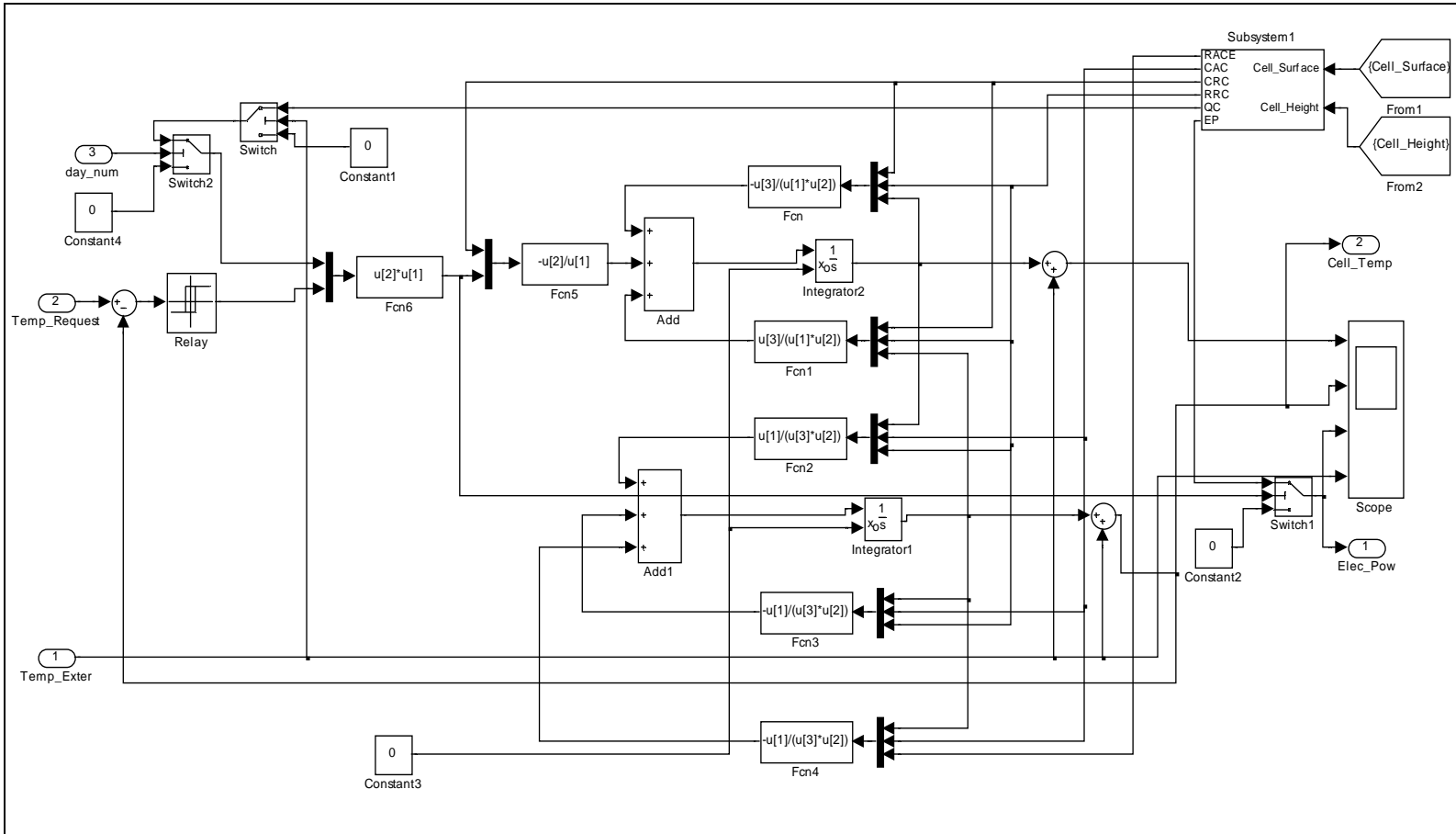


Figure 21

To conclude the part on the thermal subsystem should be noted that heating and air conditioning will not work simultaneously. As can be seen in Figure 22 what we have decided to do is to compare the temperature outside the Cell and the temperature required by user. If it exceeds the first one the heating will be active, otherwise the air conditioning system will be active.

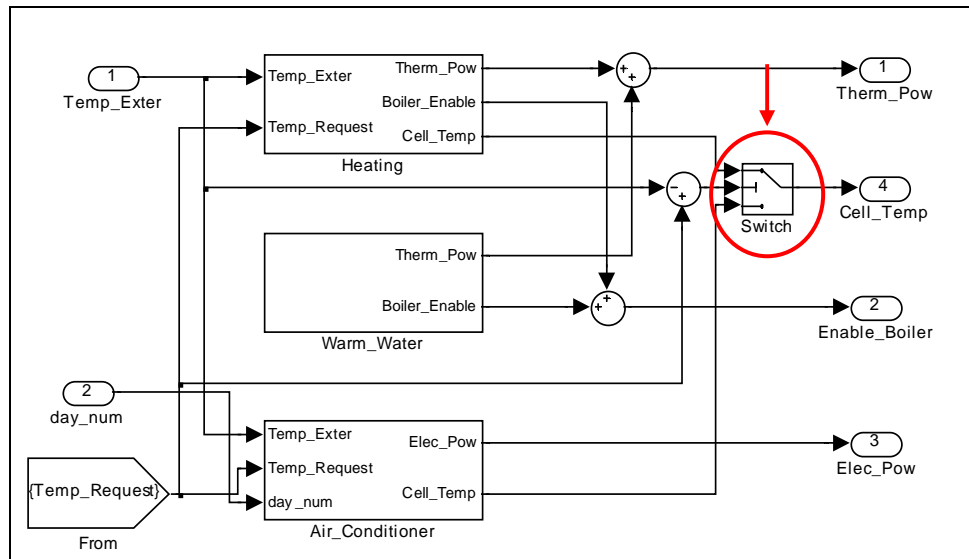


Figure 22

5.1.2 Generation Model

In Figure 23 there is a view (high level) of electrical generation system. It is divided in wind subsystem and photovoltaic subsystem. The inputs are wind speed, day number and cloudy factor. The output is the electrical energy generated.

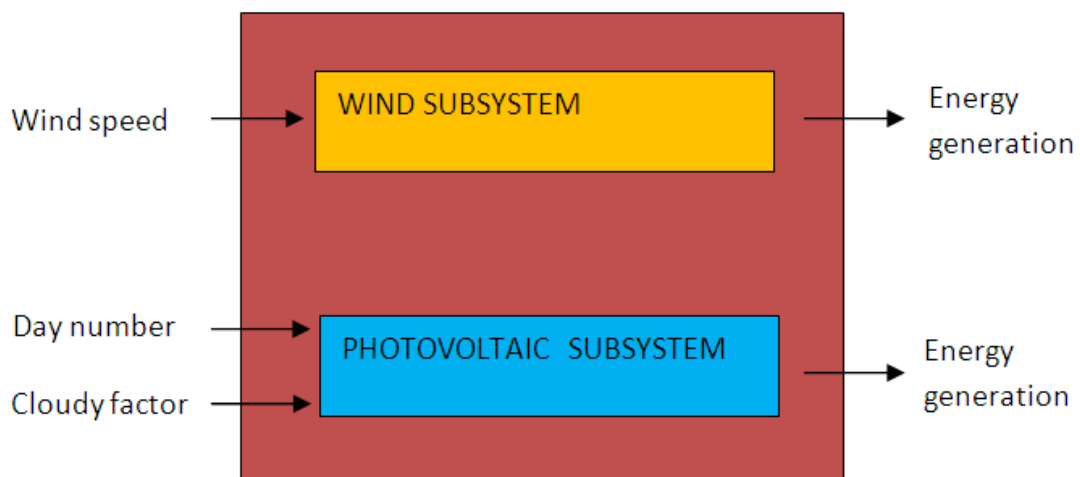


Figure 23

5.1.2.1 Wind Generation

A first way to generate energy is using wind. The wind speed v is the key variable for the production of wind energy. The power incident on the rotor blades of length r (and area $A = \pi r^2$) it is given by :

$$P = \frac{1}{2} Adv^3$$

Where d is air density (approximately $1.3 \text{ Kg} / \text{m}^3$).

But all this power cannot be used. According to Betz's law, no turbine can capture more than 59.3 percent of the kinetic energy in wind. The ideal or maximum theoretical efficiency n_{max} of a wind turbine is the ratio of maximum power obtained from the wind to the total power available in the wind. The factor 0.593 is known as Betz's coefficient (from the name of the man who first derived it). It is the maximum fraction of the power in a wind stream that can be extracted.

Others power losses occur naturally in the mechanical parts and in the electromagnetic conversion, bringing the total return to a value between 20% and 40%, depending on the model.

In the Cell Generation Model it is supposed to insert a wind plant. In Figure 24 there is the pattern used. The radius of the blame is supposed 1.5 meter. It is the average dimension for a micro-eolic plant.

The total efficiency system is 20%. The value of v^3 is divided by 10. This correction parameter is used because the wind speed used as input is an daily average speed and not the real instantaneous speed.

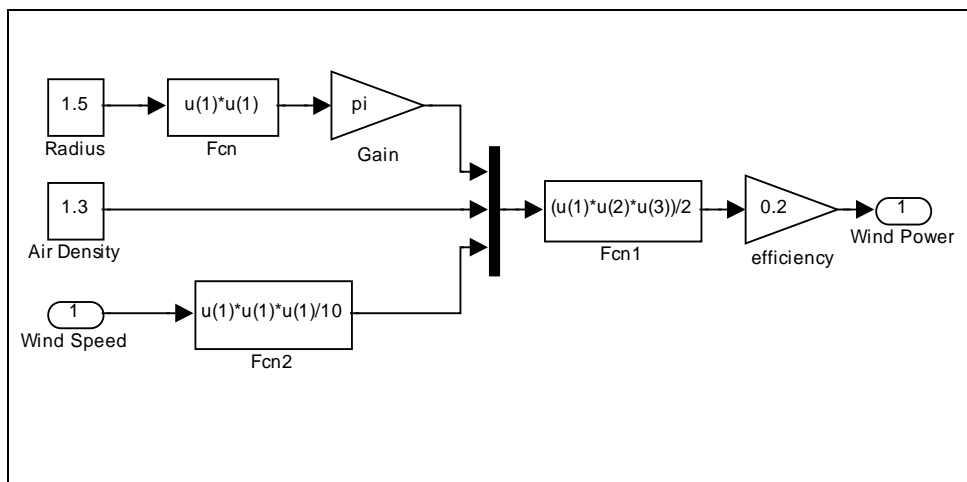


Figure 24

5.1.2.2 Photovoltaic Generation

The amount of solar radiation in the surface of Earth depends primarily by two factors:

GEOMETRIC FACTORS: The distance between the sun and the Earth, latitude, longitude...

METEOROLOGICAL FACTORS: Clouds, fog, dust in the air. Indirectly also rain snow, wind...

The solar constant I_{sc} is defined as the incident solar energy per unit time on a unit area placed normal to the direct radiation. Currently the most reliable value of solar constant is:

$$I_{sc} = 1366 \text{ W} / \text{m}^2$$

Since the distance between the Sun and the Earth varies periodically during a year, I_{sc} is the mean value. We can approximate the solar power for the n day by:

$$I_n = r I_{sc}$$

Where the parameter r is:

$$r = 1 + 0.33 \cos\left(\frac{360n}{365}\right)$$

In Figure 25 there is the variation of direct radiation during a year.

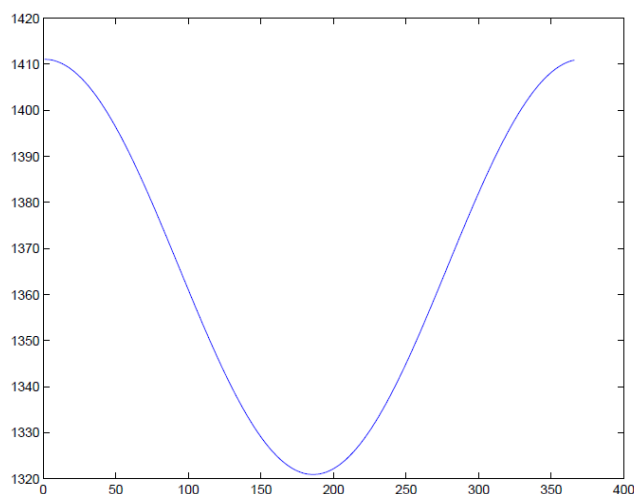


Figure 25

We also need to define the following parameters:

- LATITUDE (ϕ): Equator zero, Nord positive, South negative.
- HOUR ANGLE (ω): Midday sun zero, positive in the morning, negative in the afternoon. 15° per hour.
- INCIDENCE ANGLE (ϑ): Angle between the solar radius and the normal at the surface.

We can define the intensity of solar radiation I_0 incident on a surface in absence of atmosphere, for an angle of incidence ϑ as:

$$I_0 = rI_{sc} \cos \vartheta$$

- DECLINATION (δ): Angle between the solar radius and the equatorial plane. There is a relationship to calculate the variation depending on the day n of the year:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right)$$

The angle of sunrise and sunset are symmetrical to the solar noon and can be calculated in correspondence at an angle of 90 ° of the solar radius with a horizontal surface:

$$\cos \omega_s = -\operatorname{tg} \phi \operatorname{tg} \delta$$

So we can calculate the solar day length T_g :

$$T_g = \frac{2}{15} \omega_s \quad (\text{h})$$

In this way is possible to calculate the daily solar radiation H_0 , incident on a horizontal surface:

$$H_0 = \frac{24}{2\pi} \int_{-\omega_s}^{\omega_s} I_0 d\omega$$

$$H_0 = \frac{24}{2\pi} rI_{sc} \int_{-\omega_s}^{\omega_s} (\cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta) d\omega$$

$$H_0 = \frac{24}{\pi} rI_{sc} (\cos \phi \cos \delta \sin \omega_s + \frac{\pi}{180} \omega_s \sin \phi \sin \delta)$$

With this expression is possible to calculate the solar daily power without atmosphere. All the previous calculations refers to an horizontal surface tilted towards the south.

Not all solar radiation arrives to the surface of the Earth. Part is reflected back into the space, part is absorbed by atmospheric molecules. The remaining part is separated into direct radiation and diffuse radiation.

The global radiation at ground level is the sum of direct radiation and diffuse radiation. The fraction of diffuse radiation depends on the height and latitude of the locality, but also on the day of year and atmospheric factors.

Therefore, to forecast the solar energy available, measured past data must be used for a certain location. It is also possible to use a parameter, called Cloudy Factor, which varies according to location and time of year.

$$H = kHo$$

It is possible to find the average monthly Cloudy Factor for a determinate place in several website (e.g. ENEA website).

In Figure 26 the is the pattern for the Cell photovoltaic generation plant. The inputs of this system are the number of the day, latitude of Cell location and cloudy factor. The first two inputs come in a subsystem called "Duration/Radiation" which calculates the daily solar radiation. This values is then multiplied by cloudy factor and by total plant efficiency. The size of photovoltaic panel is 1 m². In the pattern it is possible to chose the number of panel to consider.

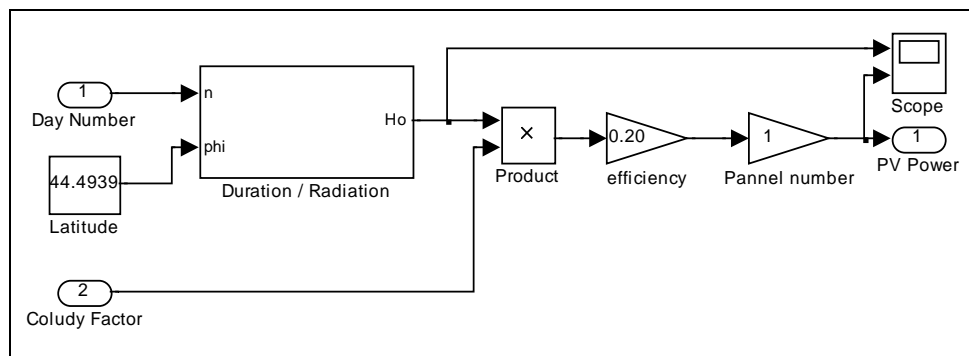


Figure 26

In Figure 27 there is the exploded pattern of subsystem "Duration/Radiation". This subsystem calculates the daily solar radiation Ho. It receives as inputs the number of the day and the latitude of the Cell. The equations described previously are used to calculate the parameter r, declination δ, the sunrise and sunset angle ωs and daily solar radiation Ho.

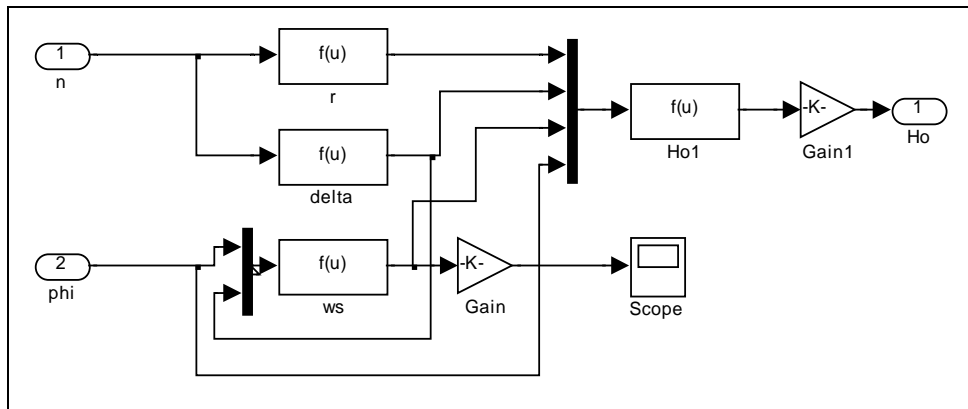


Figure 27

5.2 Macro-Cell Model

Once we have a model of the Cell we can create a model of Macro-Cell simply connecting Cell models. In Figure 28 there is the higher level view of Macro-Cell pattern. The inputs are external temperature, wind speed, number of day and cloudy factor. Of course all these inputs are vectors. The length of vectors is equivalent to the length of the simulation period. The sample interval is 24 hours. The outputs of system are Macro-Cell thermal consumption, Macro-Cell electrical consumption and Macro-Cell electrical generation.

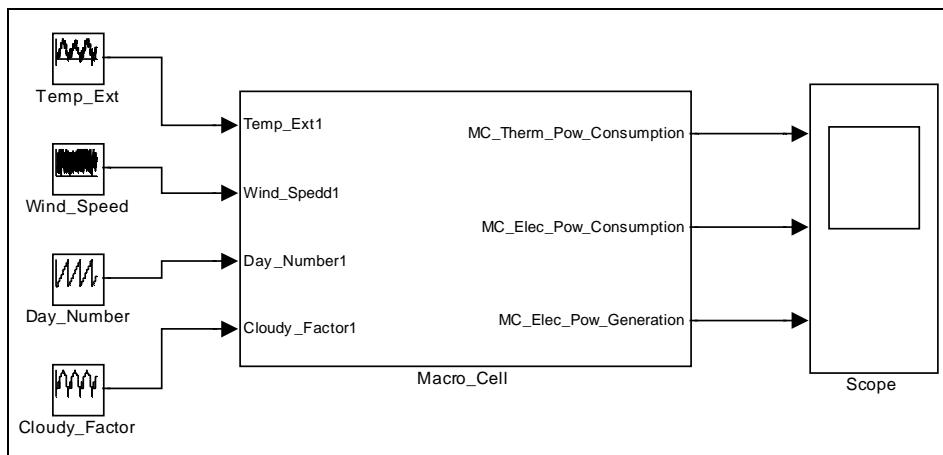
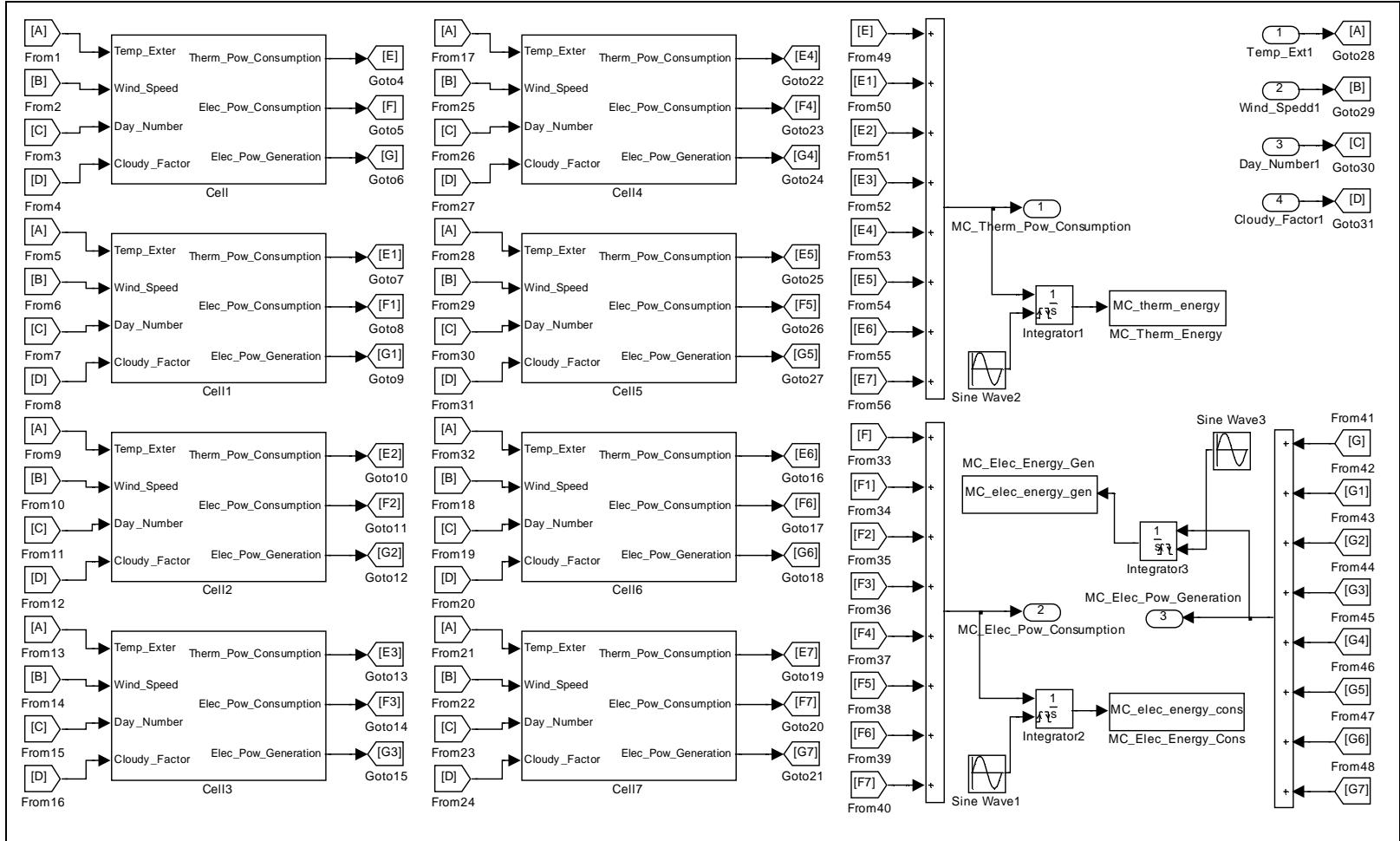


Figure 28

In Figure 29 there is a Macro-Cell view.

Figure 29



This Macro-Cell is consisting of eight Cell. Each Cell receives external temperature, wind speed, number of day and cloudy factor. To calculate consumption and generation of Macro-Cell it is done the sum of each Cell consumption and generation.

5.2.1 Data for Simulation

With the Macro-Cell model it is possible to obtain several statistical data. Knowing the trends of its inputs (temperature, wind speed...) for a determinate time period we can determinate the trends of outputs. From this point of view the first step necessary is to find input data. The only way to recover them is using internet website. In the web there are many weather sites which contain an archive with past collected data. In table 2.1 there is an example of possible data recovered in the web. In this case we have a collection of temperature, humidity, pressure and wind speed with time sampling of 24 hours. These data refer to the first ten days of January 2007. For Macro-Cell model it is used data from 01-01-2007 to 30-04-2010, 1216 samples.

2007	Temp. (°C)			Humidity (%)		Pressure (hPa)		Wind (km/h)	
	High	avg	low	High	avg	high	avg	high	avg
January									
1	6	2	-1	100	98	1034	1027	19	5
2	8	5	1	100	76	1021	1015	26	5
3	12	7	1	65	44	1027	1024	27	16
4	6	3	0	81	56	1026	1023	16	10
5	10	5	1	87	74	1025	1018	13	5
6	10	5	0	93	80	1028	1024	11	6
7	10	5	0	100	84	1026	1026	11	2
8	7	5	2	100	94	1023	1021	11	3
9	10	7	5	100	90	1027	1021	11	10
10	8	5	1	100	94	1029	1027	10	6
.....

Table 7

For others inputs (calendar, day of years, cloudy factor) it has been necessary to create a function which, starting from the first day of simulation, generates the signals. Regarding the day number the function is simple. It generates the number day (from 1 to 365 or 366 for leap year) with sampling time of 24 hours. Of course it need to receive in input the first day of simulation. For cloudy factor the function need to memorize each monthly values. Starting from the first simulation day (input), it generates a sequence with cloudy factor parameters. The monthly average cloudy factor values can be find in several web site (e.g. ENEA website). Regarding

calendar signal it is necessary because there are different behaviors for a working day or a holiday. The function generates a signal which value 1 or 0. In this way the Cell model can know in the current day is or not a working day (0 for a working day 1 for holiday). The function, starting from the first day of simulation, automatically know the day of week and can make the signal at value 1 for Saturday and Sunday. Furthermore user can inserts its forecasted holiday and the function can make the value 2 for that period. In table 2.2 there are examples of values generates with the functions described. The first day is 25-01-2007. We can see (calendar column) that this day was a Thursday, in fact after two days there are two not working day (Saturday and Sunday).

DAY NUMBER	CLOUDY FACTOR	CALENDAR
25	0,4603	0
26	0,4603	0
27	0,4603	1
28	0,4603	1
29	0,4603	0
30	0,4603	0
31	0,4603	0
32	0,5020	0
33	0,5020	0
34	0,5020	1
.....

Table 8

In the following pages there are some figures that show examples of inputs signals.

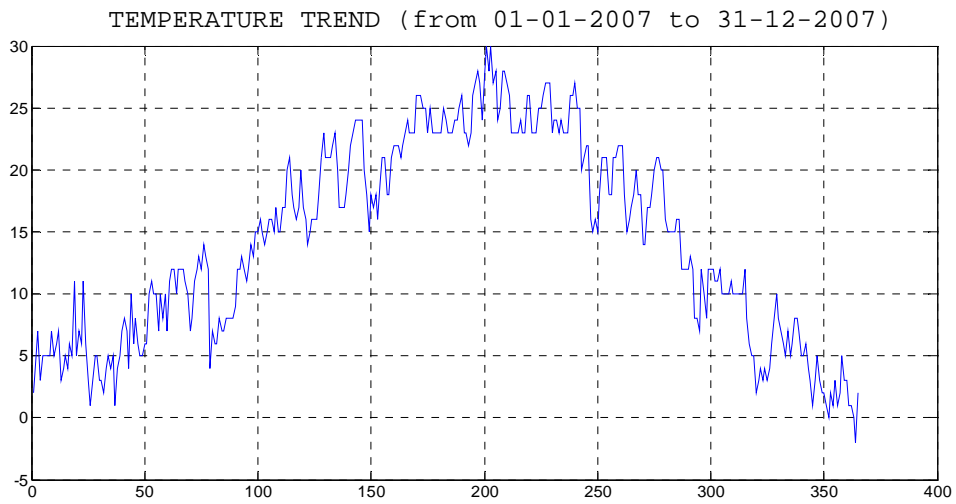


Figure 30

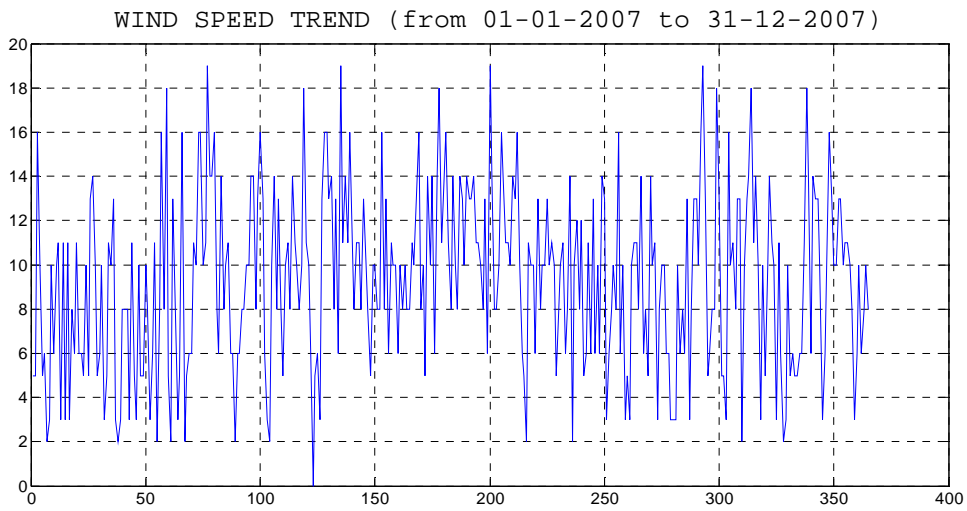


Figure 31

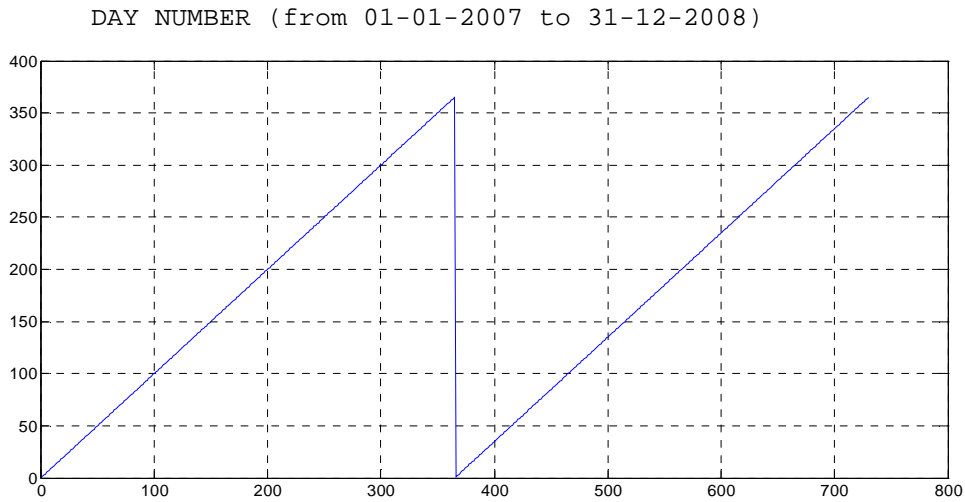


Figure 32

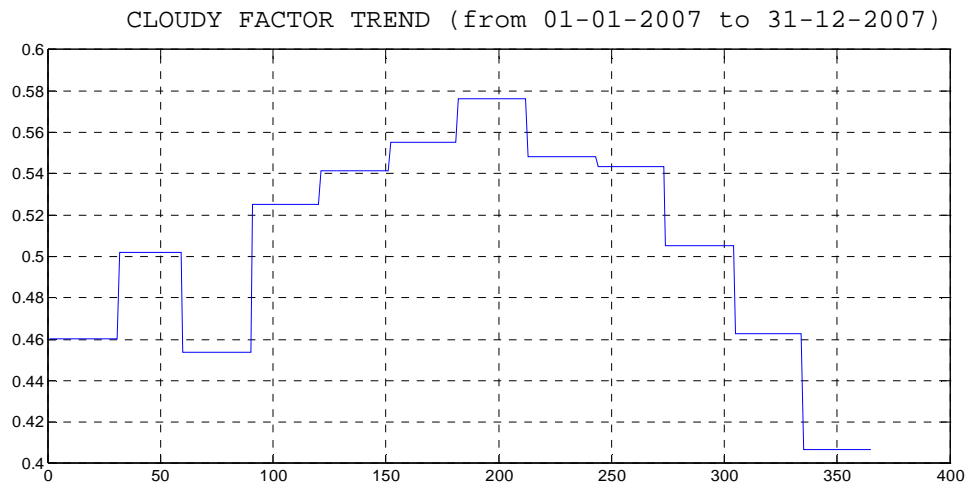


Figure 33

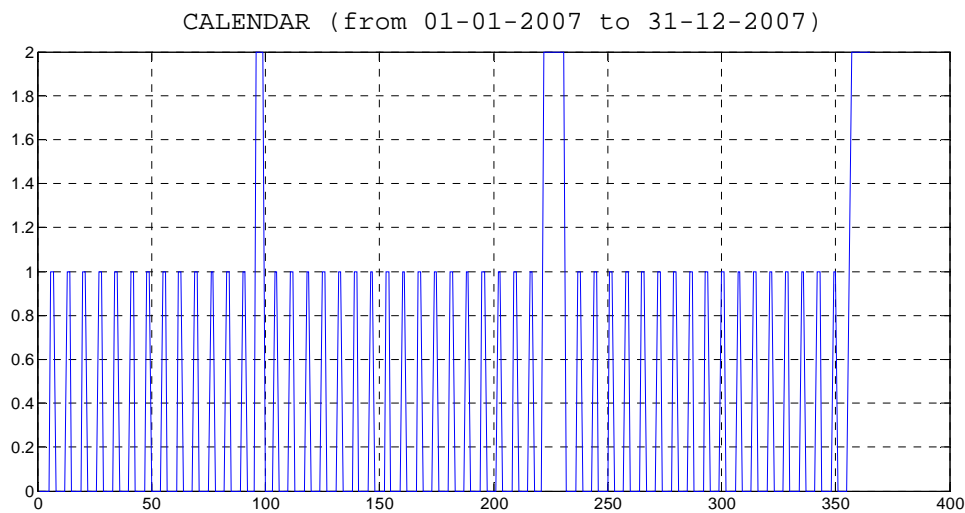


Figure 34

The time sampling of all these signals is 24 hours.

5.3 Load Control Algorithm

MATLAB-SIMULINK environment has been used for developing the model of the home scenario. Figure 35 presents the blocks included in this model.

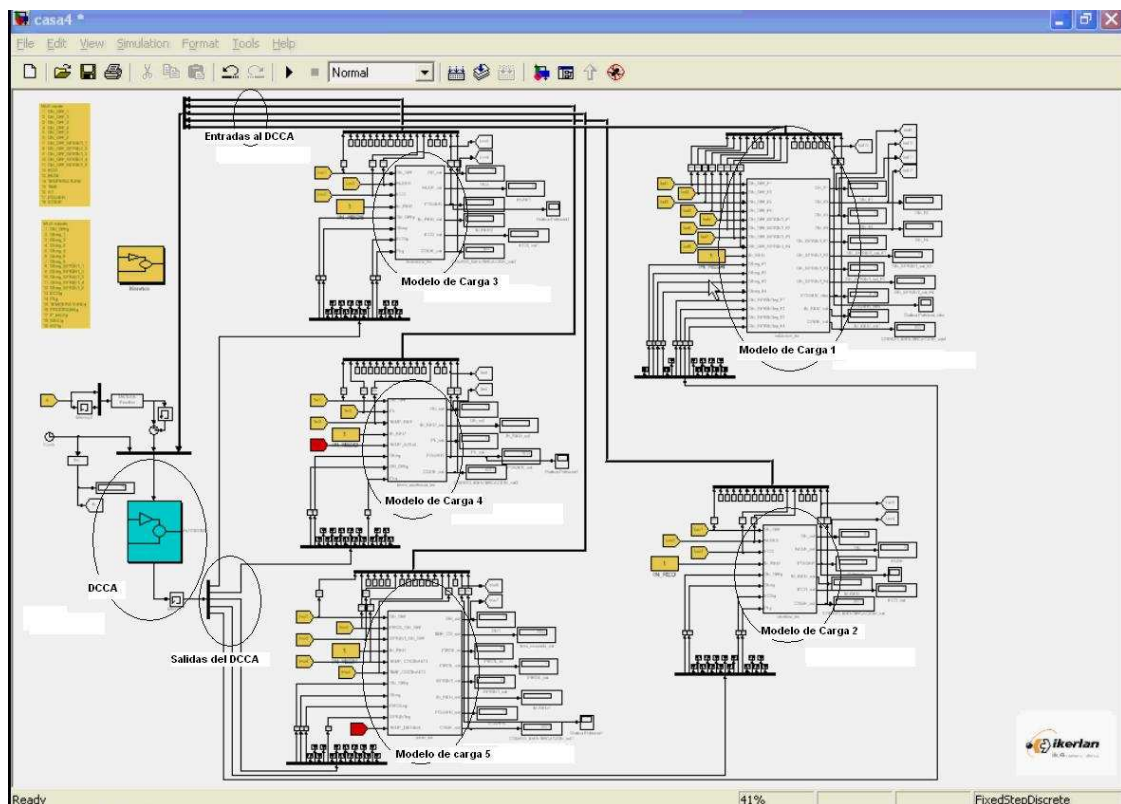


Figure 35: MATLAB-SIMULINK model of home scenario

The load models in Figure 35 have been developed from the analysis of the behaviour of the domestic loads. The communications between the central management device and the loads are identified (input/outputs of the management device). The management device is the one which contains the load-scheduling algorithm.

The sampling period of the simulation is 0.5 seconds. Every 0.5 seconds the management device checks if there is any change in its inputs and updates its outputs.

6. Simulation results

6.1 Cell Model Simulation

With the Cell model we can make several simulation to see the trends of some interesting values. In the following three figures we can see an example of daily Cell electrical energy consumption, an example of daily Cell thermal energy consumption and an example of daily Cell energy production. In the first figure we can see the periodical fridge start and stop and two peak: the first caused by washer machine and the second by hairdryer.

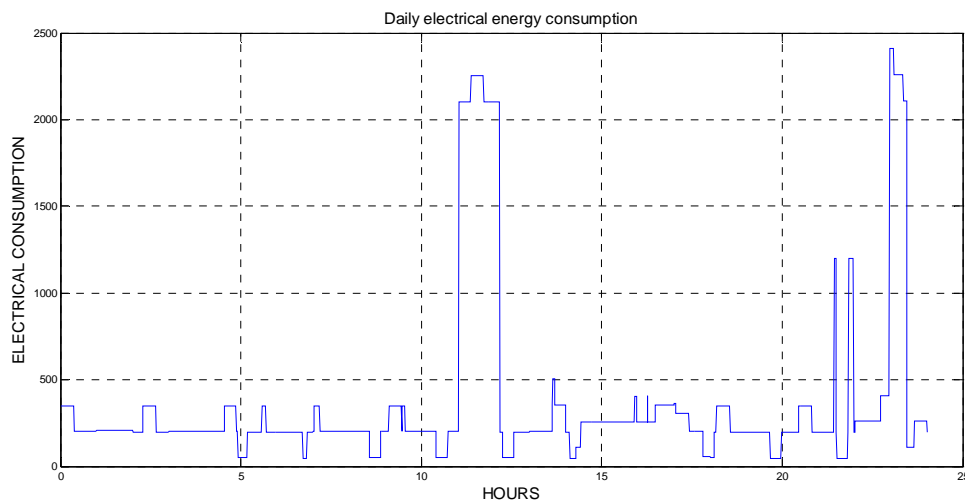


Figure 36

From the second figure we can detect that the day analyzed is a wintery day. In fact we can note the continuous activation of boiler necessary to keep the Cell at the desire temperature.

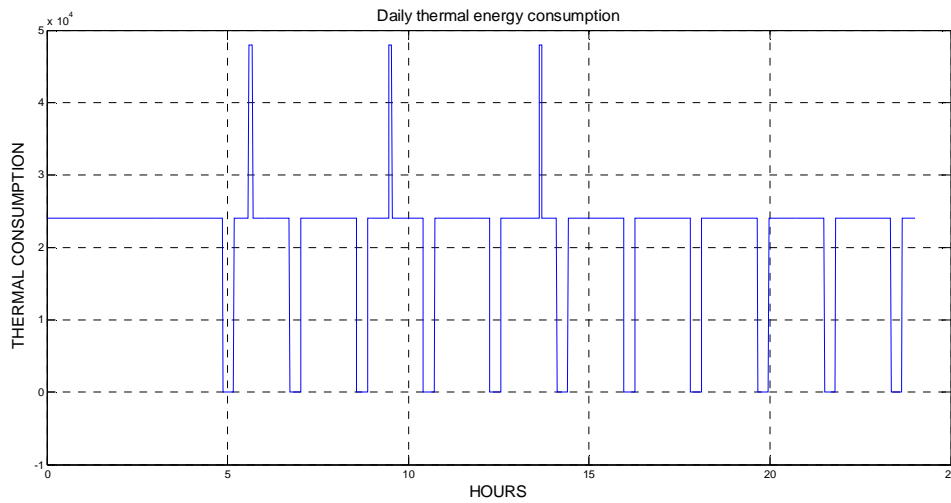


Figure 37

Also from the last figure we can deduce that the day analyzed is a wintry day. In fact the energy production is few and it do not have a bell trend. This means that the photovoltaic production is very few and it is a typical situation for wintry day.

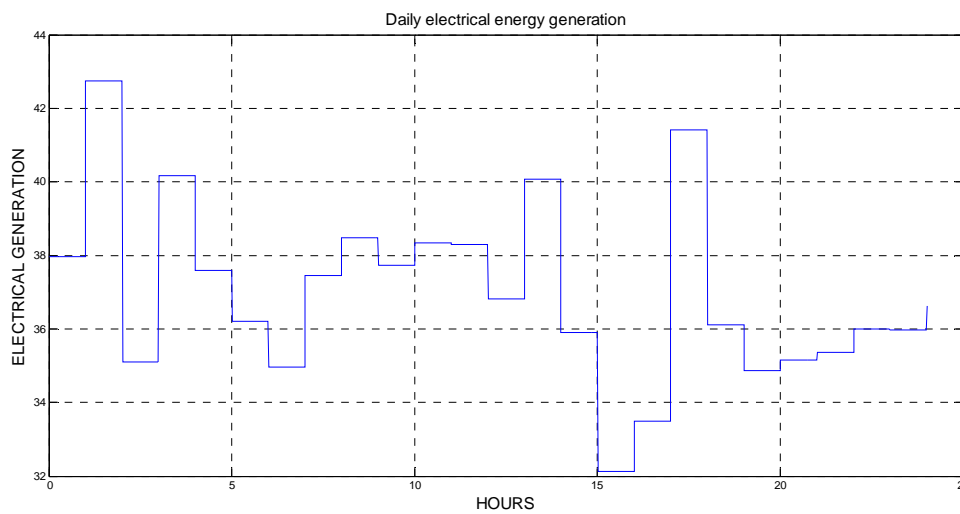
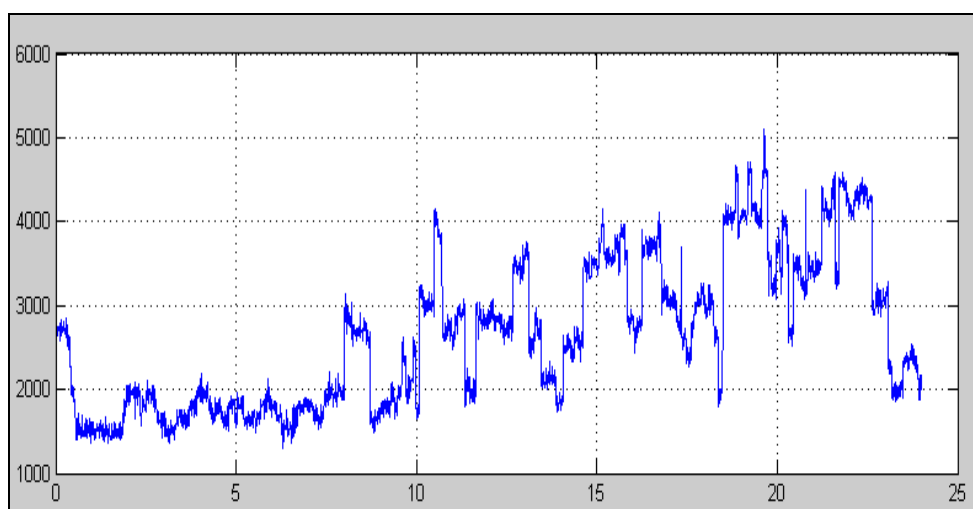
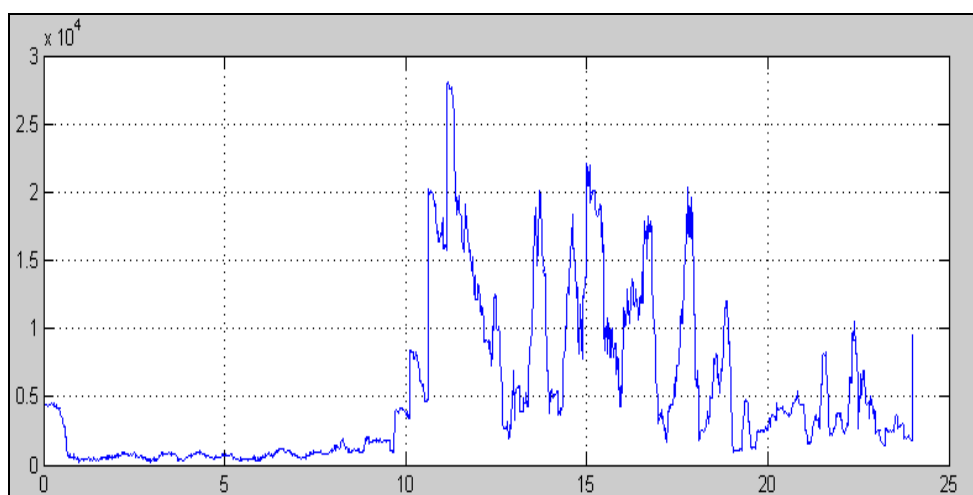


Figure 38

Another example of Cell model simulation is showed in the following two figures where there are the trends of the daily average electrical energy consumption. The first is the daily average consumption of January, the second of August.

*Figure 39**Figure 40*

The two electrical average consumption is very different. We can see how in January the we have a more regular consumption during the day, with a little increase in the evening hours. On the contrary, for August, we see a big electrical consumption in the middle of the day. It is caused by the use of air conditioning system.

6.2 Macro-Cell Model Simulation

We can use the MacroCell model to make several simulation and see the trends of signal of our interest. Of course we need to use the inputs signal described in the previous chapter. The interesting trends to monitor are the thermal energy consumption, the electrical energy consumption, the wind energy production and the photovoltaic energy production. In the following pages we can see some examples of model simulation.

6.2.1 Energy consumption annual trends

In the following two figures there are two example of annual Macro-Cell energy consumption (thermal). The first one refers at the year 2007, the second one at the year 2008. We can see that the two signals have similar trends. There is the maximal thermal consumption during wintry months. During the Summer there is only the consumption for warming water and not for heat-system.

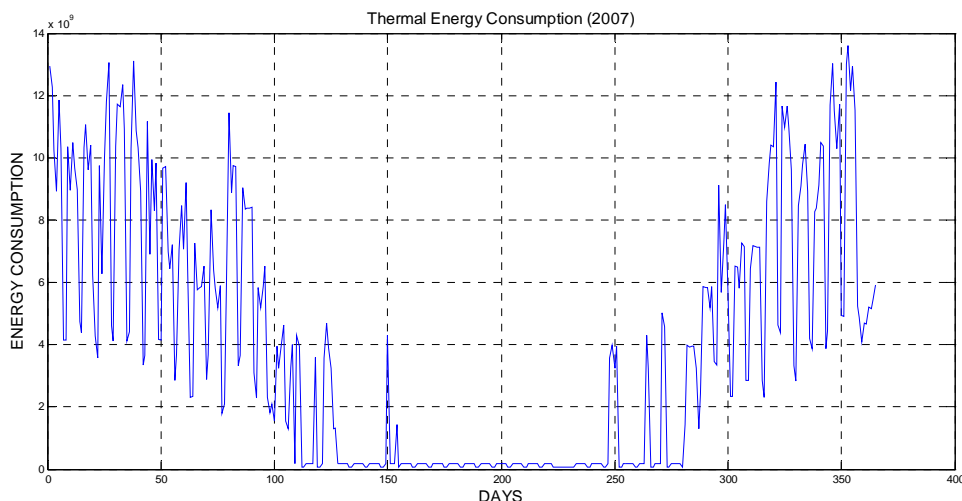


Figure 41

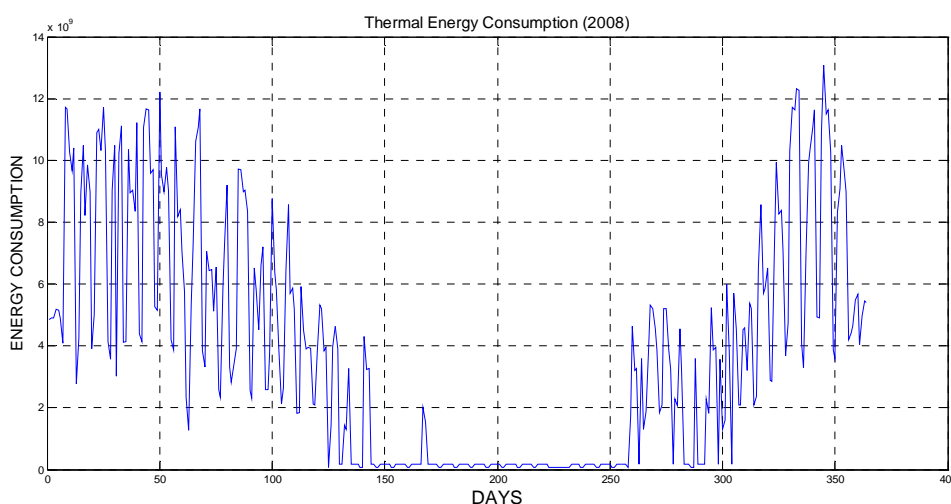
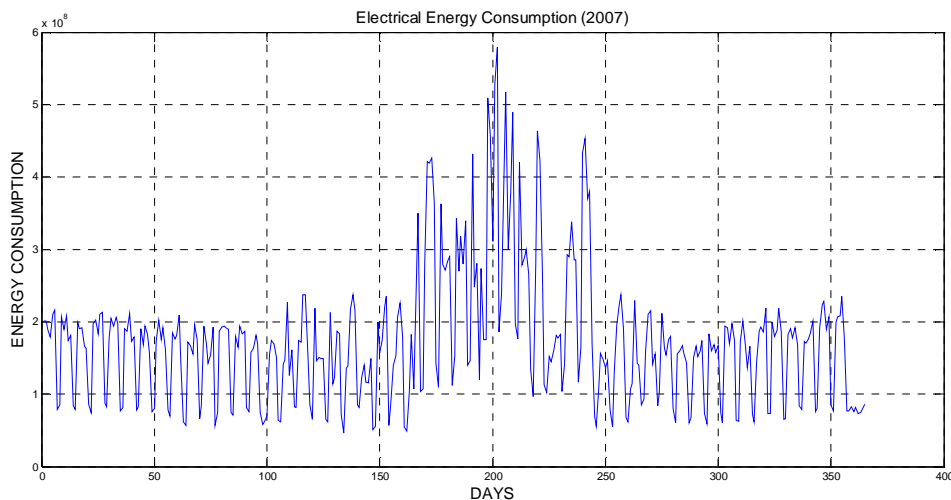
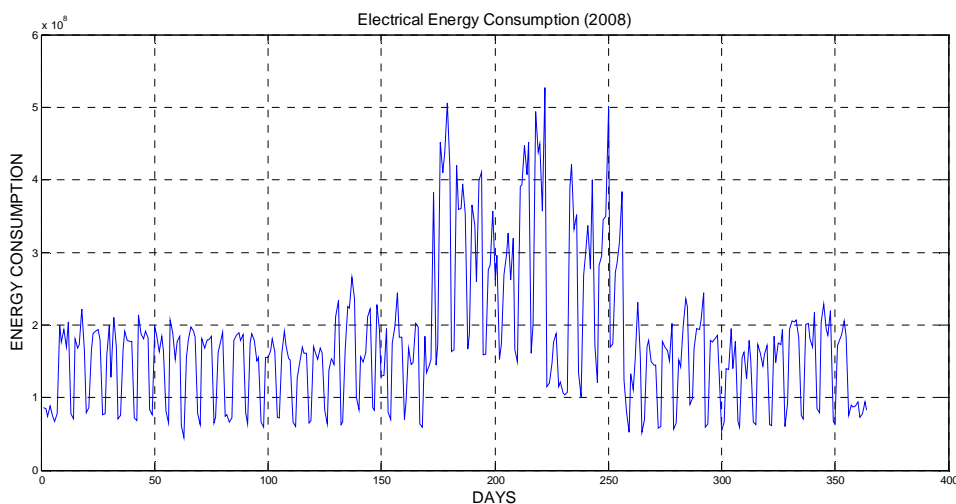


Figure 42

Same speech for the annual Macro-cell electrical consumption. In this case we have the maximal consumption during the Summer months, when temperatures are higher and the air conditioning system is on.

*Figure 43**Figure 44*

6.2.2 Energy production annual trends

In the following two figures there are two example of annual Macro-Cell energy production. The first one refers at photovoltaic energy production for the year 2007, the second one at wind energy production for the same year. All these simulations have as inputs data concerning at Bologna city. About photovoltaic production we can see the increase of it during the summer days. On the other hand, about wind generation, we cannot find particular trends during the years

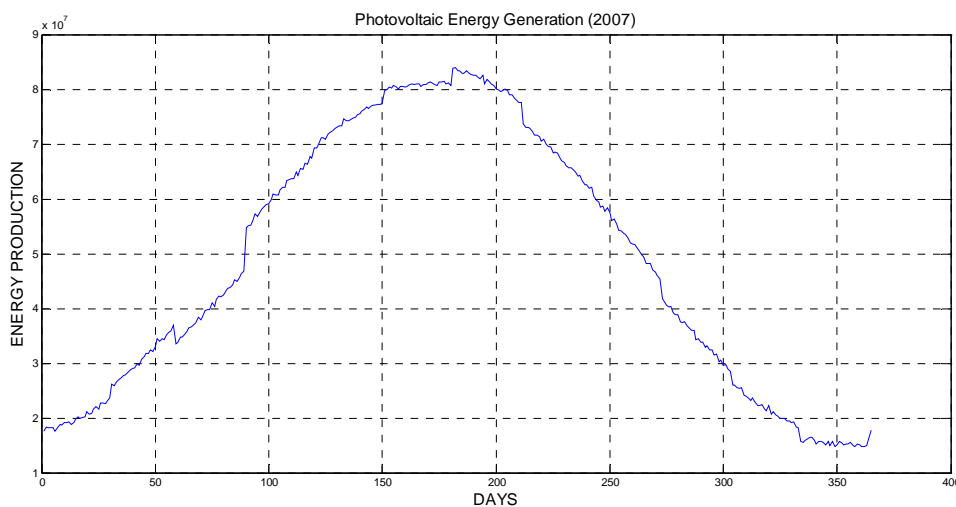


Figure 45

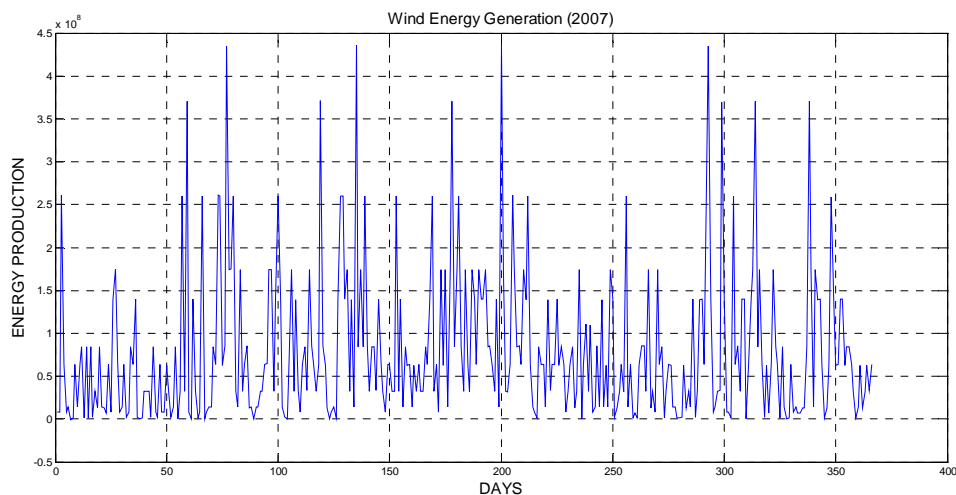


Figure 46

In the following figure we can find the comparison between a Macro-Cell electrical energy production (blue) and generation (green). It has supposed to have a photovoltaic energy generator and a wind energy generator for each Cell. In the figure beneath, red signal, there is the difference between consumption and production of the same example. We can see that in some days of the years the Macro-Cell energy production is enough and there is no need to buy energy from provider.

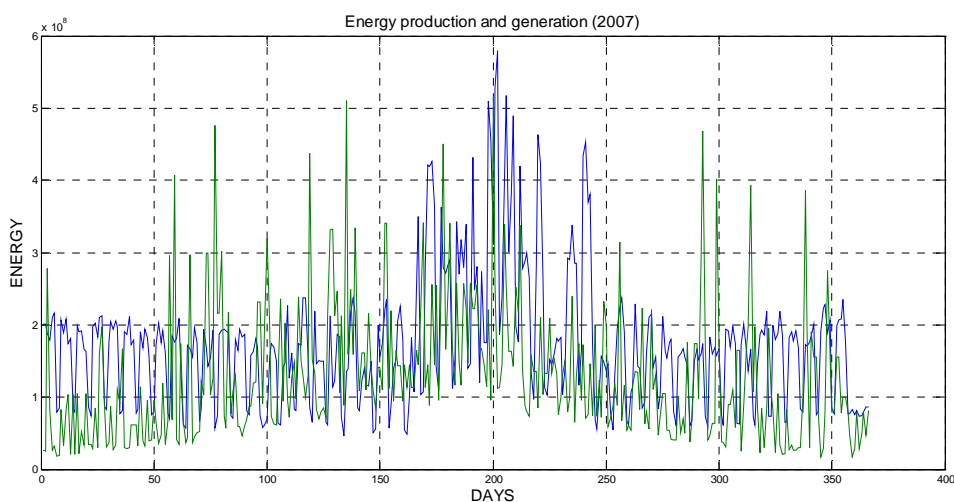


Figure 47

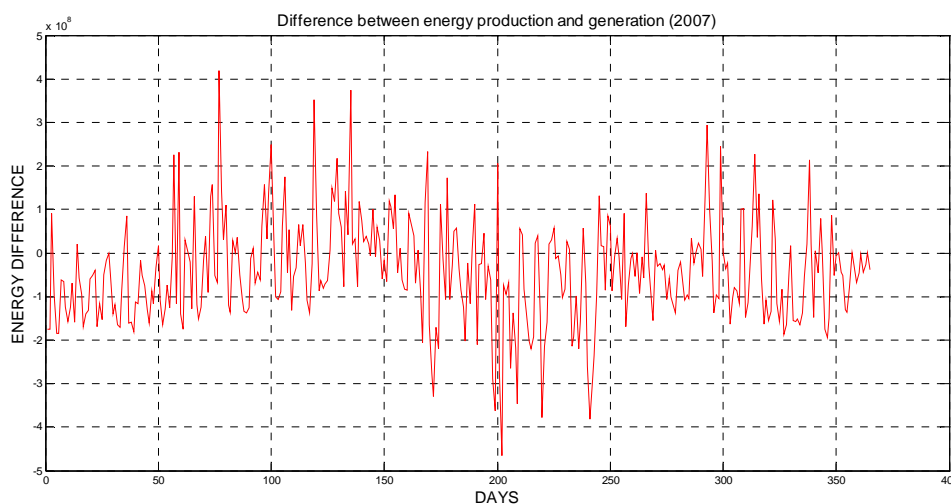


Figure 48

6.3 Load scheduling algorithm

The possible simulation variants that can be made with the scenario model presented in Section 5.3 are infinite. That is why the results presented here are the ones corresponding to the cases that have been specified as best representing the operation of the algorithm when dealing with special situations (e.g. exceeding the value of the power used above the limit of usable power or the positioning of the loads according to the prices and priorities established by the consumer).

6.3.1 Scenario 1

This scenario operates with a *dispersion index* that simulates three different rates for each time period (there are 5 periods). Depending on the level of power used, the

use of the dispersion index enables the operation of the domestic appliances not to be accumulated within one time zone, thus avoiding operation at points close to the power limit.

- Under 2 kW
- Above 2 kW and under 3.5 kW
- Above 3.5 kW

The rate not only differs in each period on the basis of the power used, it also differs depending on the time period during which power is used.

The user in this scenario has also specified his/her preferences of the deferrable domestic appliances in the following way:

- The washing machine (*code 3501*) can be switched on between 8 am and 12 midnight.
- The dishwasher (*code 4001*) can be switched on between 12 midday and 9 pm.

Figure 49 shows:

- In the top graph: the prices applied during the different periods into which the day is divided up.
- In the middle graph: the power limit and the total consumed power programmed by the algorithm.
- The bottom graph shows the consumption profiles of the domestic appliances.

In the bottom graph in Figure 49 it can be seen how the load management algorithm puts the deferrable domestic appliances into the periods in which the electricity rate is more advantageous within the time preferences specified by the user. So, the washing machine is programmed to come on at 2 pm, while the dishwasher is programmed to be turned on at 4 pm. This system of management adheres to the preferences established by the user and makes the domestic appliances function in a cheaper way. The existence of different prices in each period depending on the consumption prevents, as far as possible, the operations of several domestic appliances overlapping at the same moment. Thus, it can be seen that the dishwasher does not come on until the washing machine has finished its operation.

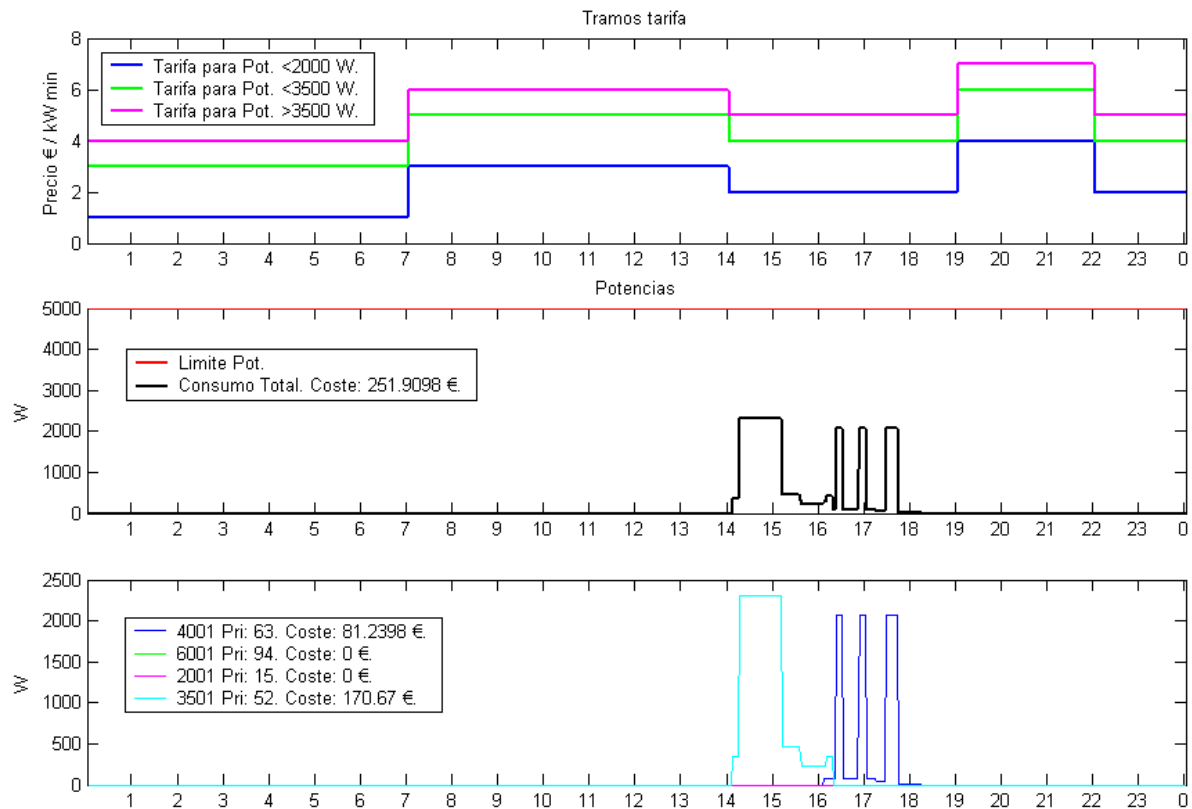


Figure 49: Rates, power limits and positioning of domestic appliances

6.3.2 Scenario 2

Figure 50 shows the same domestic appliances, with the same time preferences, but with different rate periods. In this example, the period with the lowest rate lasts until 10 am, rather than until 7 am only.

This way the washing machine has been programmed for 8 am, because it is the cheapest moment within its time preferences. The dishwasher, however, has been programmed to be turned on at 2 pm, as at that point there are no problems of overlapping with the washing machine, which is set at a more advantageous starting time with the new rates. The effect of the *dispersion index* that simulates three different rates in each period depending on the power consumed is clearly shown here.

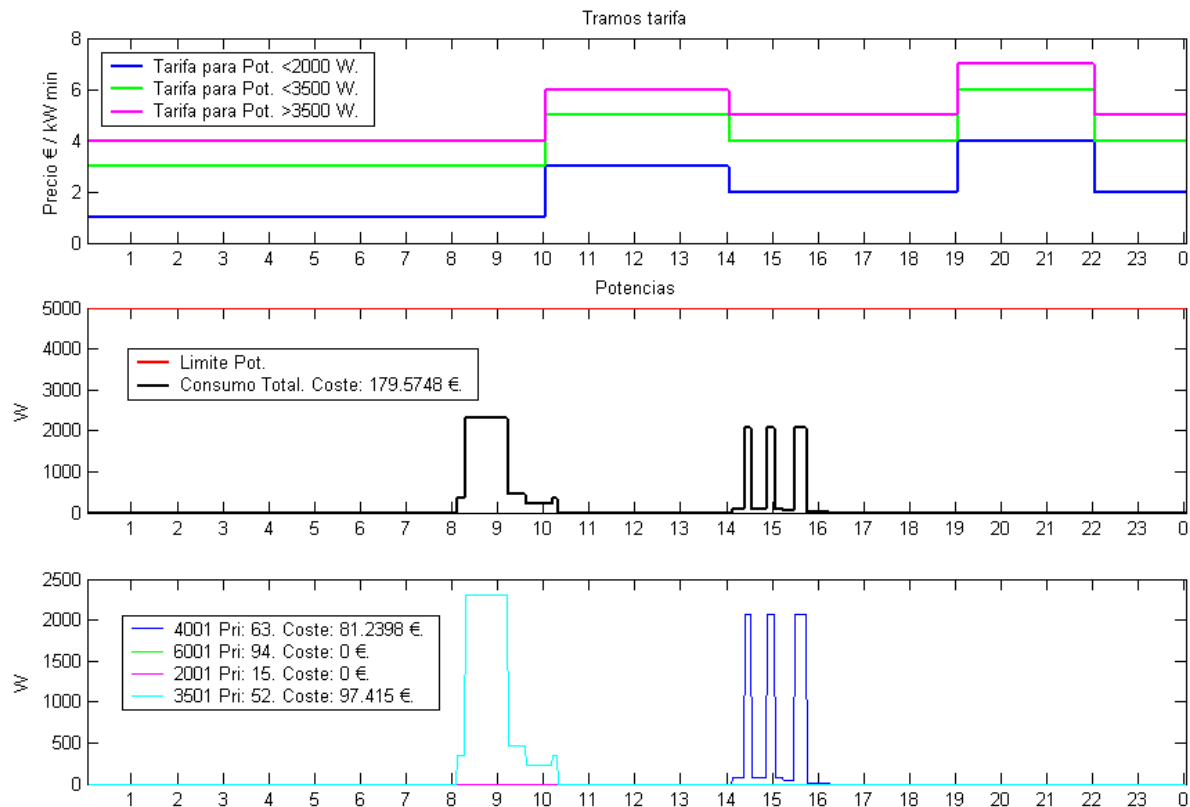


Figure 50: Rates, power limits and positioning of domestic appliances

6.3.3 Scenario 3

Scenario 3 simulates the operation of the algorithm when there are different limits of consumable maximum power. The starting point is the situation described in the previous Section, Figure 50: the washing machine is programmed to come on at 8 am and the dishwasher at 2 pm, in accordance with the rates and the user's preferences.

A contracted power limit is entered. From 9 am to 3 pm the power limit changes from 5 kW to 2 kW. As a result, and as shown in Figure 51, both the washing machine and the dishwasher alter their operation starting times, as they do not have sufficient power to function. The algorithm reschedules the domestic appliances in this new situation. As the algorithm seeks the optimum solution, it defers the moment in which the domestic appliances come on. It should be pointed out that this solution is more expensive than the previous one. Most of the times, when restrictions are entered, the cost increases when the number of possible solutions are restricted.

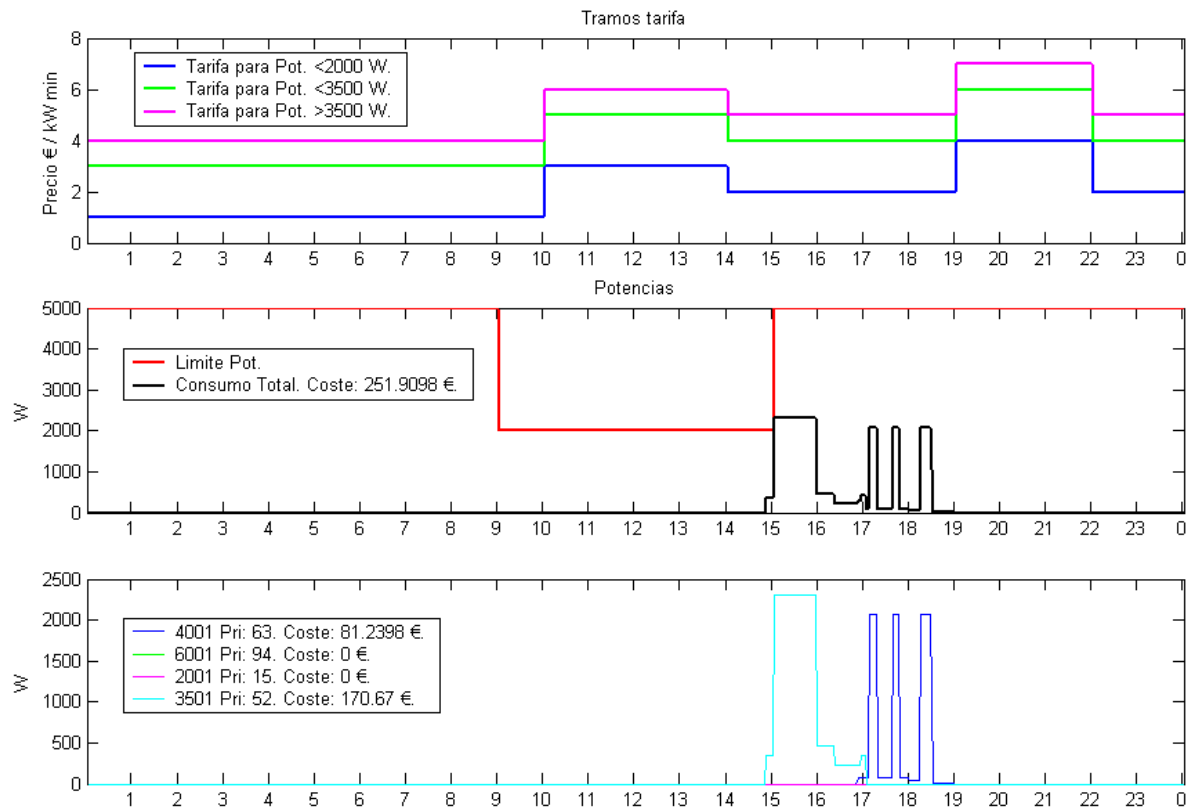


Figure 51: Rates, power limits and positioning of domestic appliances

6.3.4 Scenario 4

In this scenario the situation shown in Figure 52 is taken as the starting point:

- The washing machine (*code 3501*) is scheduled to come on at midnight.
- The dishwasher (*code 4001*) is scheduled to come on at 2 am.

The boiler (*code 6001*) is scheduled to be *on* all day (24 hours). It is expected to consume the nominal 1.6 kW throughout the day.

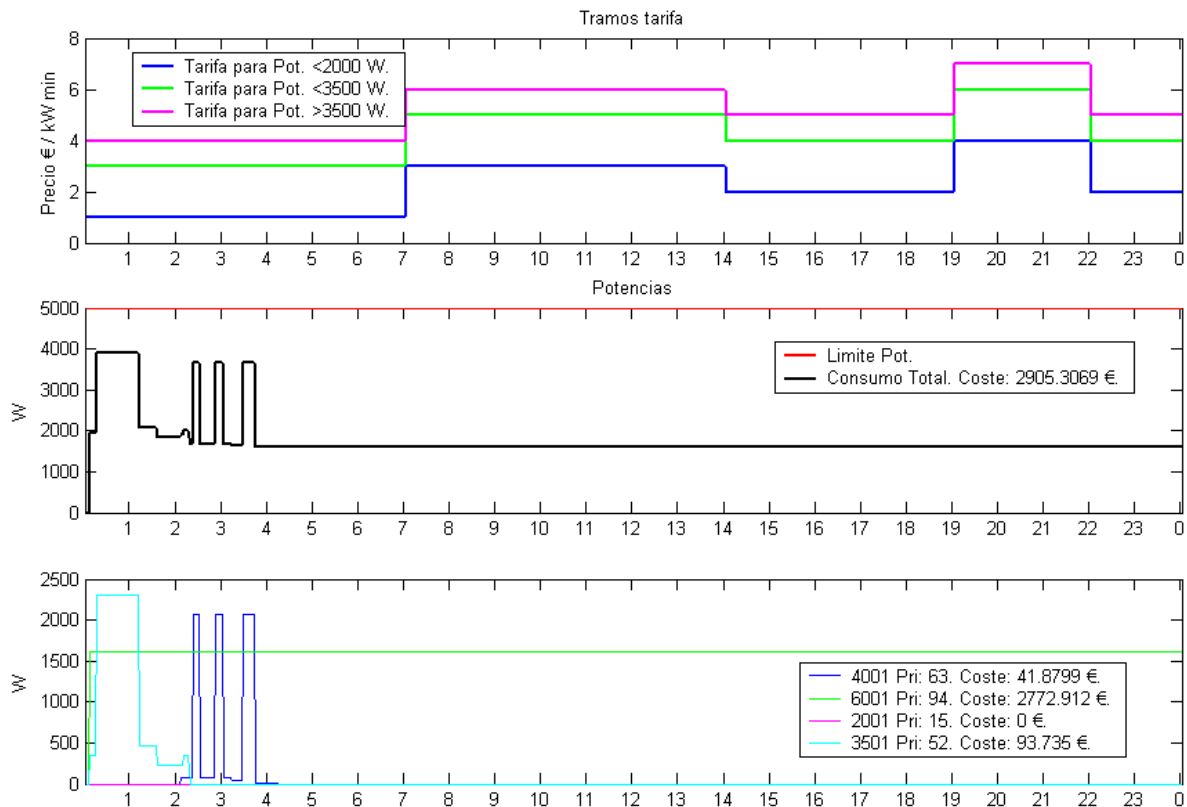


Figure 52: Rates, power limits and positioning of domestic appliances

At quarter past midnight, while the washing machine is on, the oven (*code 2001*) switches on. The oven is a high priority, instantaneous, and non-deferrable domestic appliance. As there is not enough power available, the algorithm carries out the following actions.

- It moves the boiler to “limited power” consumption mode, in which it consumes half of its power.

There is not enough power available yet.

- It moves the washing machine to “limited power” consumption mode, in which each phase consumes half the power, but takes twice as long.

There is still not enough power available.

- It orders the boiler to switch off.

With the boiler switched off and the washing machine in “limited power” mode, there is sufficient power available for the oven. The dishwasher is rescheduled for an optimum cost. Since the washing machine cycle is now longer (because it is in

“limited power” mode), the switch-on of the dishwasher scheduled for 4 am is deferred (Figure 53).

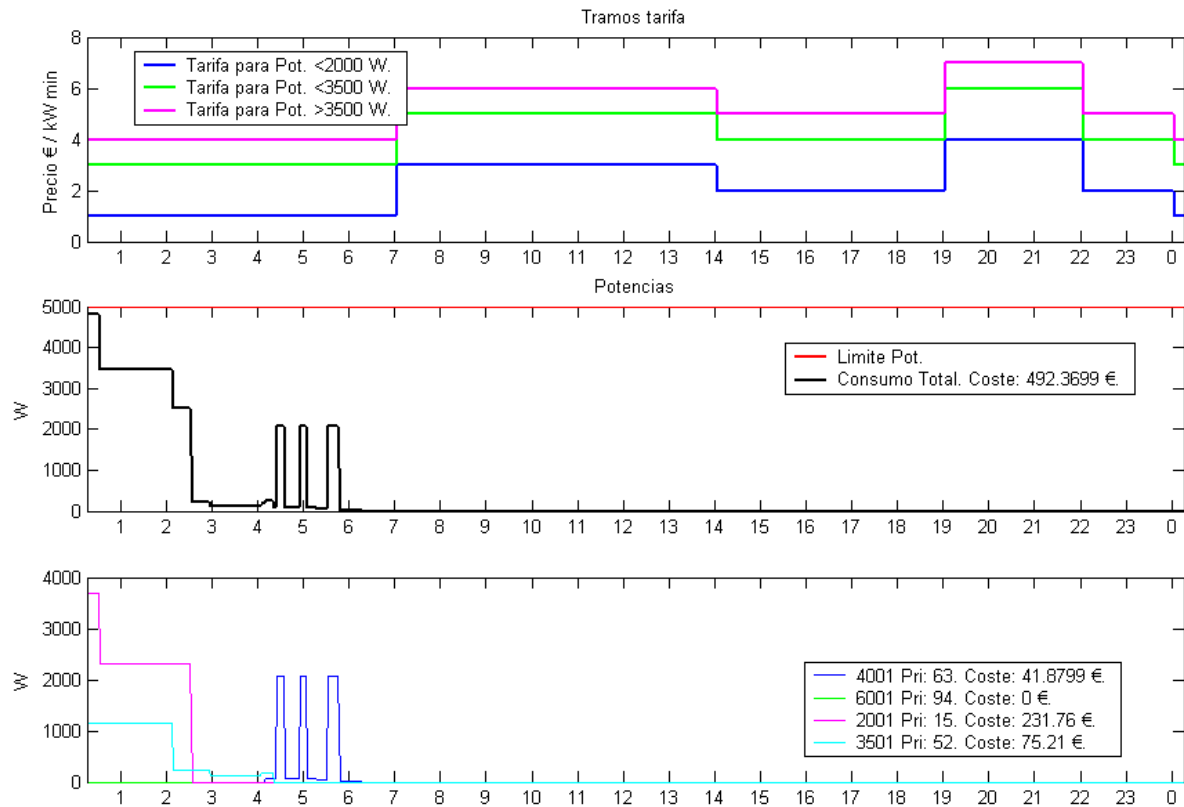


Figure 53: Rates, power limits and positioning of domestic appliances

If the algorithm kicks in again once the oven has finished, it then carries out the following actions (Figure 54):

- It sets the washing machine into normal consumption mode.
- It orders to the boiler to turn on.
- It reschedules the dishwasher to turn on at 3 am.

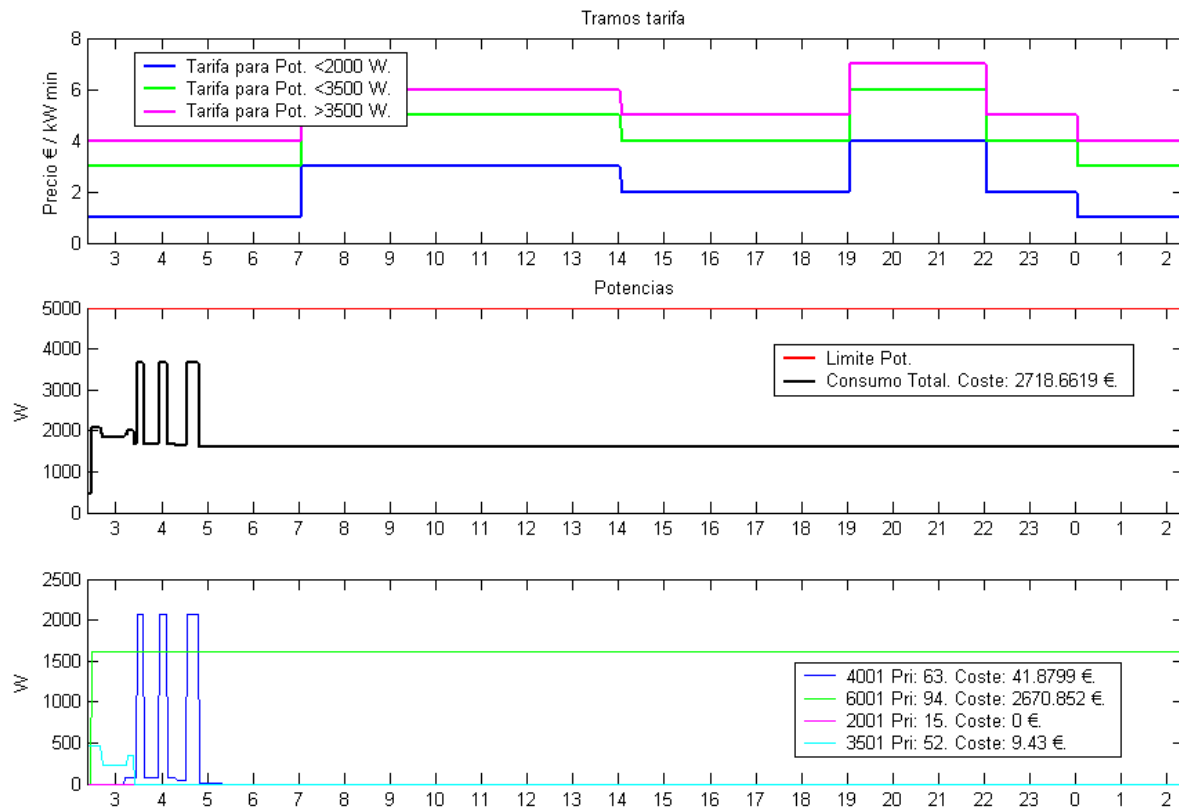


Figure 54: Rates, power limits and positioning of domestic appliances

6.3.5 Scenario 5

The priorities of the domestic appliances are a critical feature when:

- Scheduling the moment in which the domestic appliance should switch on, the highest priority ones are scheduled first.
- Ordering "limited power" consumption mode, the ones with the lowest priority are ordered to do so first.
- Ordering switching off, the lowest priority ones are ordered to switch off first.

The starting situation in Figure 55 is analogous to the one in Figure 52, but in this case the boiler has greater priority than the washing machine.

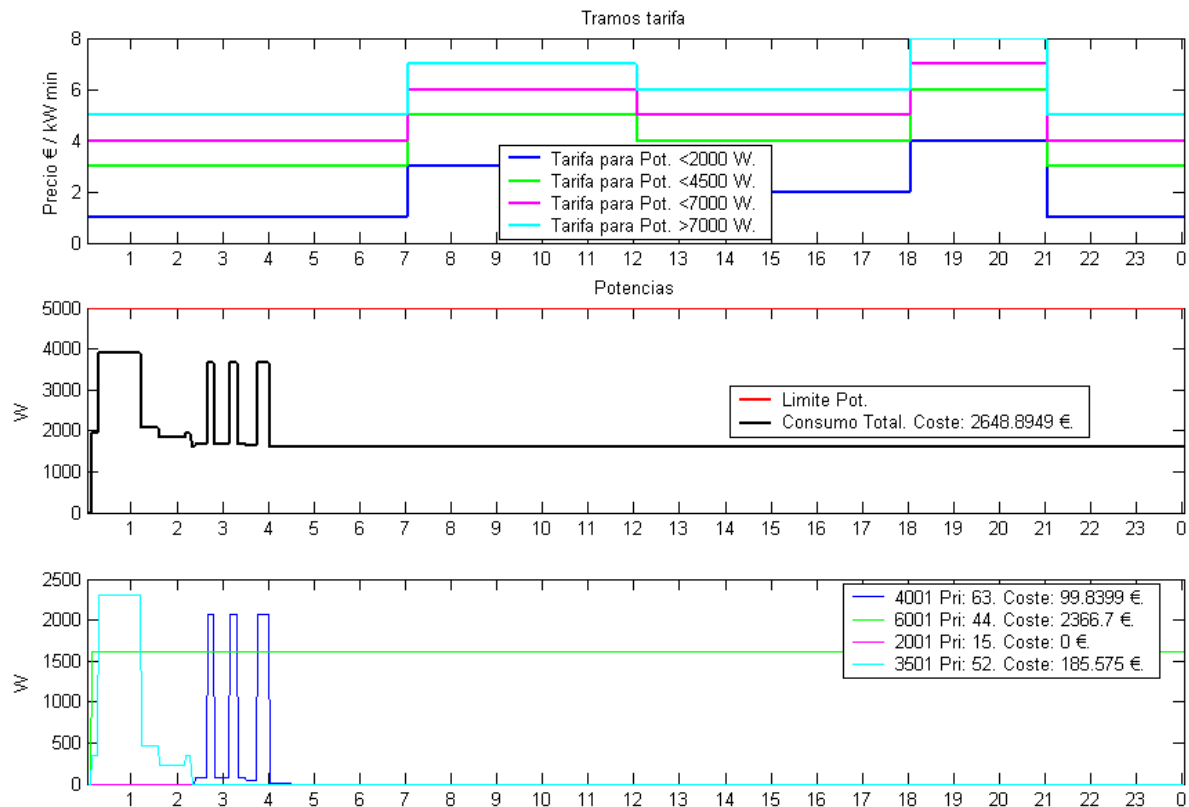


Figure 55: Rates, power limits and positioning of domestic appliances

In this case, when the oven is switched on (Figure 56), the sequence carried out by the algorithm is as follows:

- The washing machine is moved to “limited power” consumption mode, because it has lower priority.

There is not enough power available yet.

- It moves the boiler to “limited power” consumption mode, in which it consumes half of its power.

There is still not enough power available.

- It orders the washing machine to switch off.

With the washing machine switched off and the boiler in “limited power” mode, there is sufficient power available for the oven.

It reschedules the unfinished cycles of the washing machine and the dishwasher for optimum cost. Since the washing machine has higher priority than the dishwasher, when scheduling it, it comes on earlier (Figure 56).

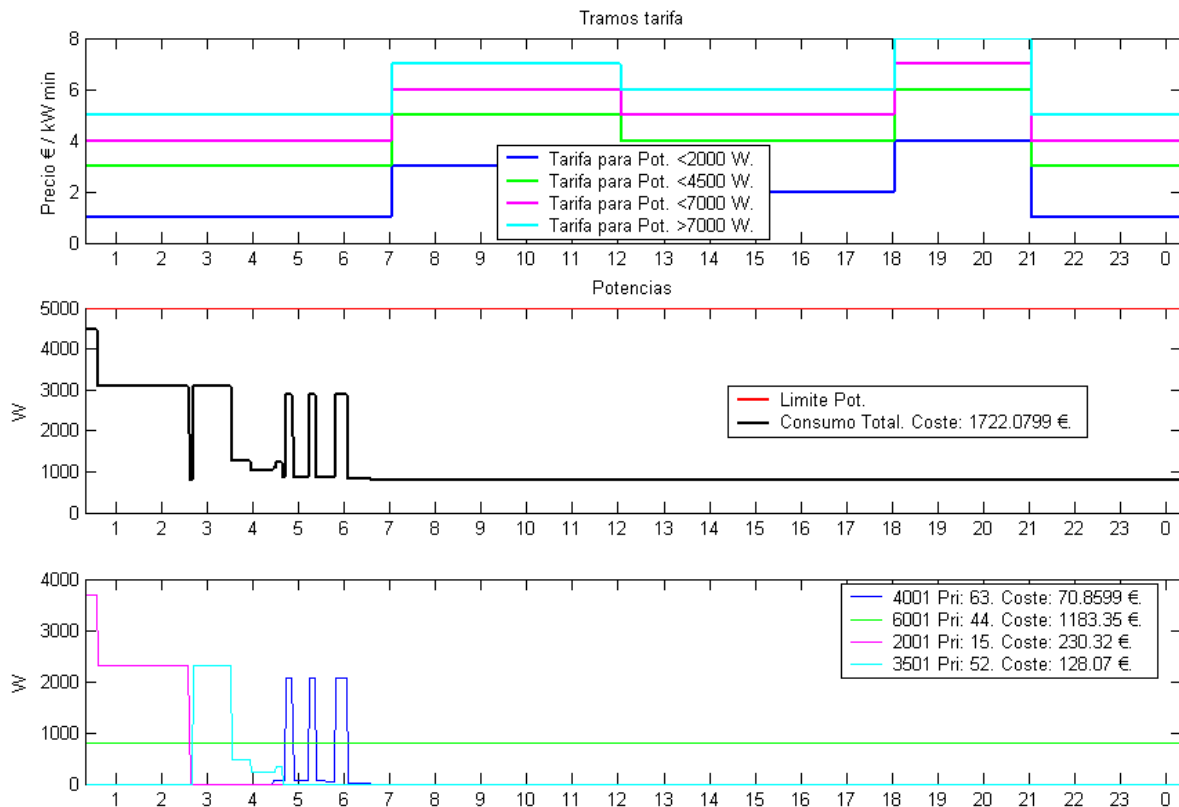


Figure 56: Rates, power limits and positioning of domestic appliances

6.3.6 Scenario 6

This scenario shows the behaviour of equipment like air conditioning, radiators, etc. A scenario with a total of seven domestic appliances is considered. One of them is the air conditioning, and it is considered to have a nominal power of 4 kW. The power limit is set at 5 kW, and it is constant throughout the day. The user establishes a set point of 20° with a margin of $\pm 3^{\circ}$. The outside temperature is considered to be constant 30° throughout the day.

Figure 57 shows, from top to bottom, the rate for each level of power according to the time period, the total power consumed in the home, and the power limit and scheduled consumption for each domestic appliance. In this case, the only domestic appliance connected is the air conditioning. Figure 58 shows the temperature evolution

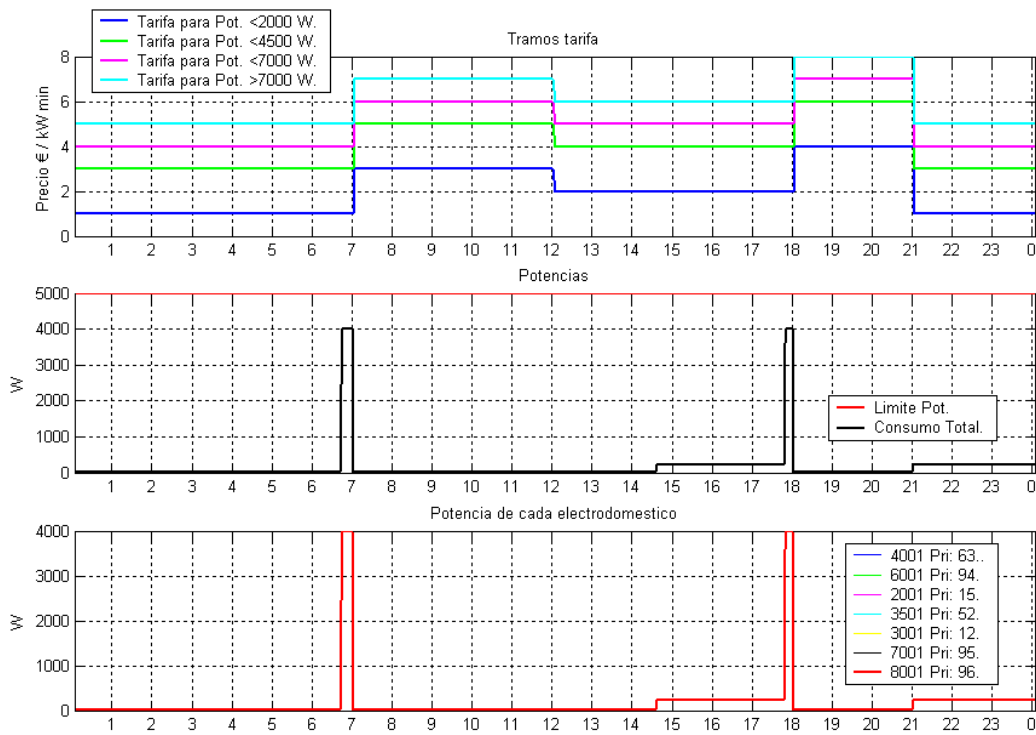


Figure 57: Consumption of air conditioning

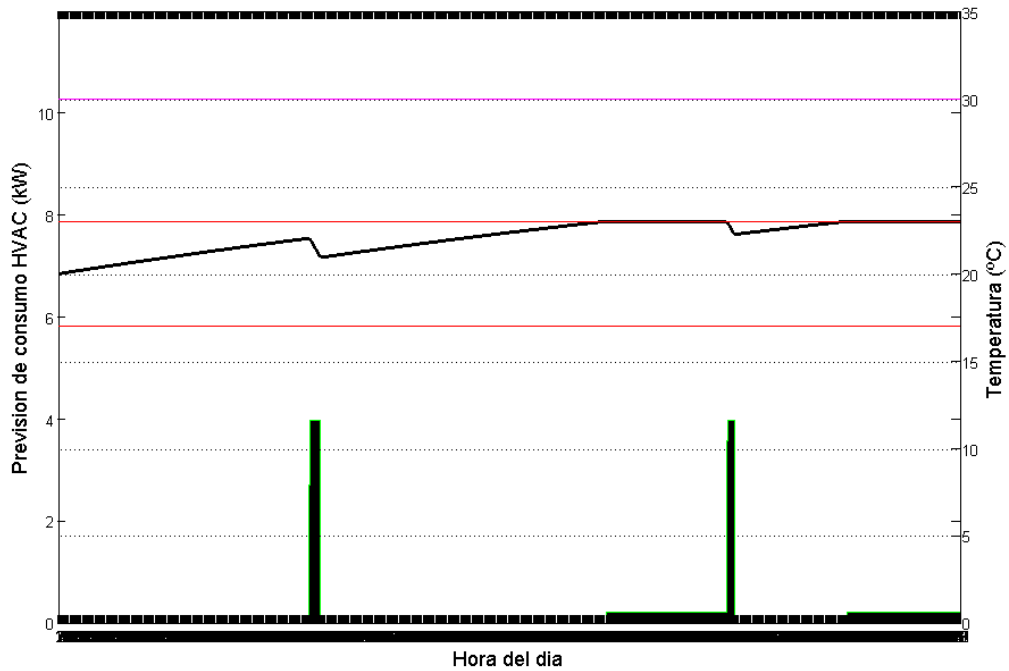


Figure 58: Temperature evolution and consumption of air conditioning

The scheduled consumptions are logical and in line with the restrictions of the algorithm. 3 heating elements of the ceramic top are then switched on, and the results can be seen in Figure 59 and Figure 60.

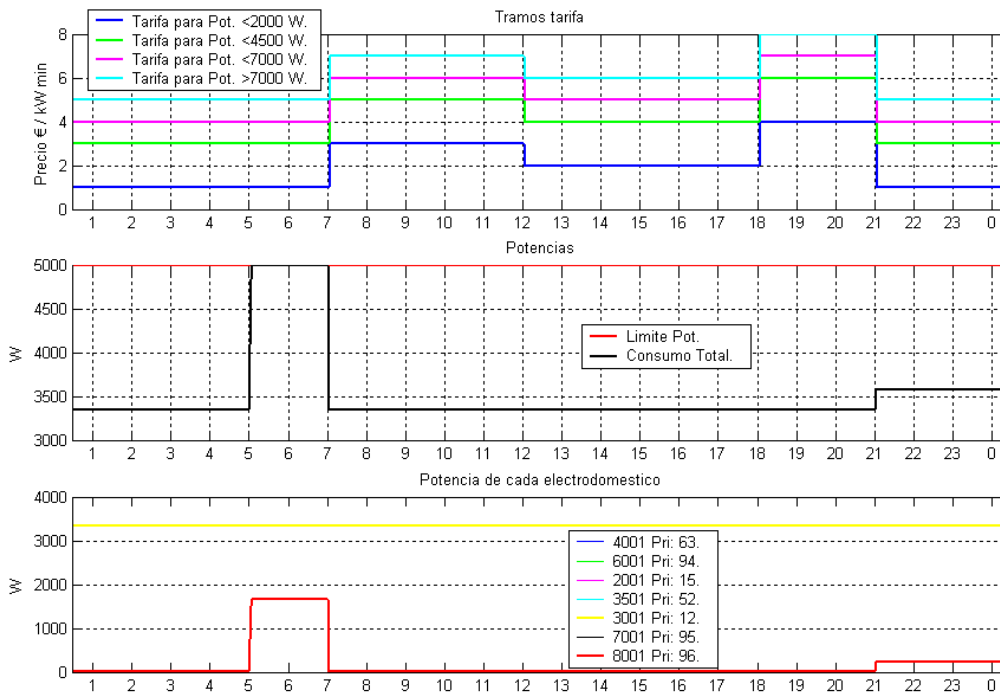


Figure 59: Consumption of the air conditioning and the ceramic top

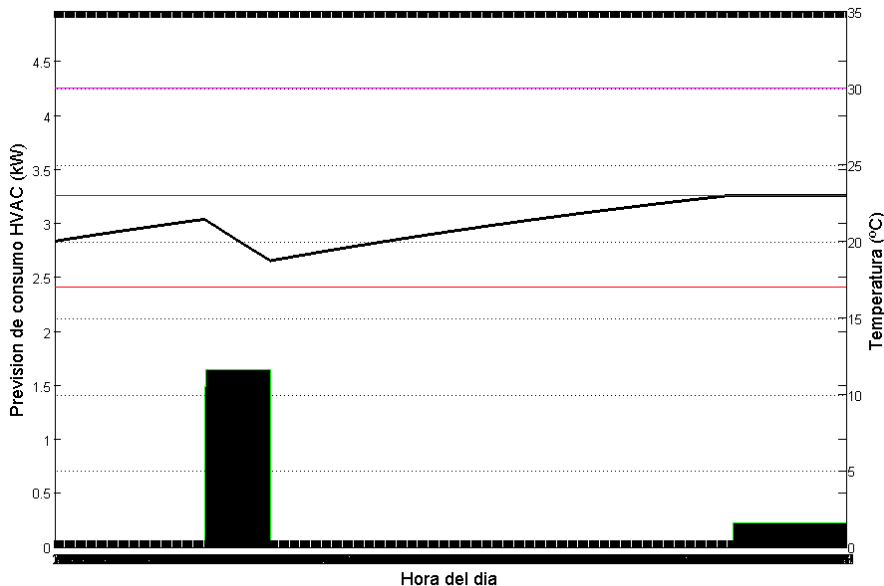


Figure 60: Temperature evolution and consumption of air conditioning

The ceramic top consumes just over 3 kW, so the air conditioning uses the margin of power it has left to maintain the temperature in the house within the desired range without the total consumption in the house exceeding 5 kW at any moment. It can be seen that, as the HVAC has less power available to do its work, it operates for a longer period in order to deliver the same energy as in the first case.

7. Conclusions

This document describes the strategies for energy-management at Cell level. An initial discussion on direct/indirect control approaches has been presented. Then, taking into consideration benefits for the network management, the impact on the comfort perceived by the user, and the system requirements defined on WP1, inputs and outputs of the algorithms are described for the load management algorithms.

Once defined the algorithms for the load management, the different simulation models are presented, being finally included the results of these simulations for several scenarios.

The main outcome of this Deliverable is the load management algorithm to be integrated in the CDC. This algorithm uses the information about the features of the domestic appliances, the priorities and preferences established by the user, and the prices and consumption limits laid down by the contracts.

Obtained simulation results should be subsequently contrasted with the demonstrators to be carried out in WP7 and WP8, in order to check the energy saving and monitoring technologies.

Acknowledgements

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