Energy study of a habitation using a solar thermal and photovoltaic installation

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ABSTRACT

The integration of renewable energies in the dwellings is a solution to diminish their energy consumption. It also could represent important money savings for the owner, if the design and the control of the devices are correctly set up. Numerical simulation environments are powerful tools, which help to develop such design and control procedure. The software TRNsys 16 was used to study the entire energy consumption during seven months of the model of a dwelling using thermal collectors and photovoltaic panels. The control techniques used for these systems are standard and simple procedures. Both thermal phenomena and electrical phenomena and their interactions were considered. We noted that the solar part of the heat production and the electrical production could be increased. Some solutions, including some new control techniques are proposed in the discussion of this work.

KEYWORDS

Renewable energies, energy autonomy, energy study, thermal loads, building numerical simulation

INTRODUCTION

The buildings represent one of the biggest parts of the world energy consumption. However, reducing their energy consumption became a priority only recently. There are two ways to proceed: the first way consists in improving the architecture of the building, in order to reduce the thermal losses and exploit the extern gains. The second way consists in producing properly the energy of the building. These approaches are not contradictive, but complementary, and successive. Integrating renewable energies in a badly insulated building is a complete mistake.

The integration of renewable energies in a building leads to two problems: the design of the devices and their control. The design is function of the autonomy degree planned for the building. It sets the potential of energy production of the devices. The control optimises the operation of the devices, minimizes the losses and guarantees the comfort of the occupants. This initial study is the first step of the design of new control techniques dealing with both electrical and thermal aspects of the energy behaviour of the dwelling. The final goal is to design some innovative control protocols, using advanced automatic techniques. To achieve it, a reference is necessary to improve these developments and compare their performances. Numeric models represent a powerful tool, which allows testing quickly a large number of devices and controlling systems in many situations. This paper describes the first step of this work: the choice of a dwelling model and its energy systems, and the analysis of its processing using simple control methods. This energy assessment will show how to save more energy and how to get a larger autonomy.

TRNSYS 16 is the software used to simulate the evolution of the building and its components; the study is based it in the city of Lyon, France.

DESCRIPTION OF THE MODEL

Description of the building

The numerical simulation environment used for this work is TRNSYS 16. The building is a single-family house with a surface of 140m², based on two stages. This house does not physically exist, it is a model developed by the International Energy Agency (IEA) [1], for a project called task 26. It is modelled with the type 56 and the TRNBUILD interface.

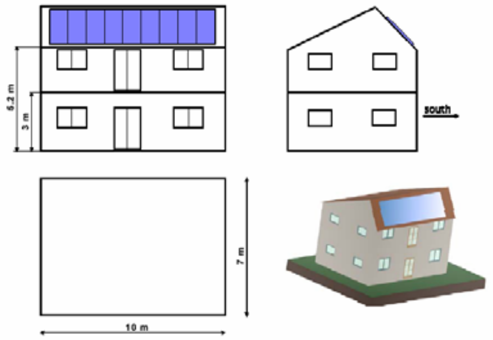

Figure 1: the Task 26 dwelling

It was designed to have an annual space heating consumption of 60 kWh/m² in the location of Zurich. It is a well-insulated building, although it is possible to get better performances.
Windows are double-glazing, modelled with type 2001 from the TRNBUILD library.

Table 1: Windows surface

Wall's orientation	North	South	East	West
Windows surface (m²)	3	12	4	4

Table 2: Walls description

Wall type	Orientation	Surface [m²]	Conductance [W/m²K]
External Wall	North	50	0.342
External Wall	South	50	0.342
External Wall	West	40.5	0.342
External Wall	East	40.5	0.342
Roof	North	61.4	0.227
Roof	South	25	0.227
Ground	Horizontal	70	0.196
Internal Wall		200	2.686

Description of the heat production systems

For the heating space, a solar collector and a wood boiler are integrated in the building. The surface of the collector is 20 m². Its efficiency is modelled by second order quadratic function.
The boiler was in the first design of the IEA a gas boiler but it will be a wood boiler in this case. Its power is 15 kW, its efficiency is 90%.
The solar collector and the boiler are connected to two loops, which supply with hot heating fluid two heat exchangers in a storage tank. This tank is a cylinder tank; it is 1.7 m high with a volume of 0.5 m^3. The solar collector heats the tank in priority. Its pump is activated as soon as the temperature of the fluid exiting the collector is 5°C higher than the tank's bottom's temperature. If the temperature of the tank diminishes lower than 50 °C, the pump of the wood boiler is activated and heats the tank through an heat exchanger with a fluid heated to 80°C, until the temperature of the tank reaches 70°C. The tank also heats domestic heat water.

Table 3: TRNSYS types used for the thermal simulation

System	Type	Details
Solar Collector	Type 1	TRNSYS library
Boiler	Type 700	TESS library
Storage Tank	Type 60	TRNSYS library

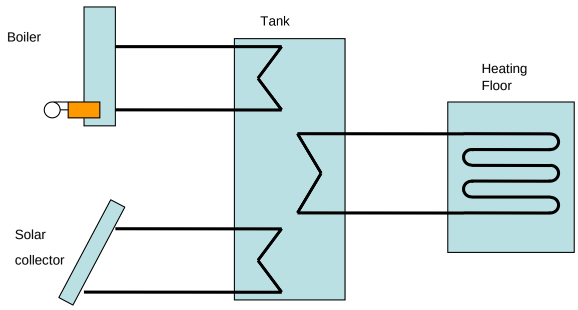

Figure 2: overview of the hydraulic net

Description of the heating floor

The house is heated with a heating floor similar to the floor modelled in the Task 26 [2]. Its surface is 140 m² large; the two stages are supplied with two different loops. It is modelled directly in the definition of the floors of the building. The pipe grid is defined as an active layer of the floor. The pipe spacing from centre to centre is 10 cm, the outside diameter of the pipes is 2 cm. The heating fluid has a 30% glycol fraction with a heat mass capacity of 3.74 kJ/kg. A diverting valve maintains the incoming fluid temperature around 35 °C. The heating fluid is heated in a heat exchanger in the storage tank. The flow rate of the fluid in the floor is 500 kg/h.

Temperature control

A very simple control procedure is used in this case: if the building temperature decreases less than 19.5°C, the pump of the heating floor is turned on until the temperature reaches 20.5°C, then the pump is turned off. No cooling system is used in this study, which is why warmer temperature during spring, autumn and especially summer can be expected.

Description of the electrical loads

Laboratory Ampere has designed a model of the standard electric household appliances. The user chooses which appliances is present in the building, then the model calculates the electricity consumption of all the devices on each time step of the simulation, and also the heat gain released to the building.
For example, the model of a washing machine is calculated with the following data:

- The energetic class of the device.
- The note of the device from the constructor.
- The result of an energetic survey of electrical household appliances consumption [3].

A washing machine cycle is divided in three stages: water heating, washing and drying. Their relative consumption part is function of the temperature of the cycle set up by the user. The most important part of the consumption is due to the heating step. The consumption profile for the three washing cycles is:

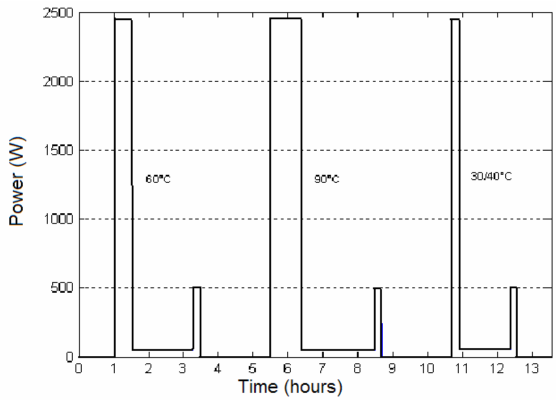

Figure 3: consumption profiles for a washing machine

Furthermore, the energy part released to the building as thermal energy is estimated. This part depends of the device. For the washing machine, since most of the energy is transmitted to the water which is evacuated on the end of the washing cycle, a ratio of 33% has been set.
All the devices chosen in the house are class A ranked, which means they have low energy consumption. The house contains a washing machine, a refrigerator, a dishwasher, freezer and a dryer. These appliances are used by a five member's family that is why the washing machine, the dryer and the dishwasher are being used once a day. It is supposed that the inhabitants are careful with the electric consumption, using only gas for the cooking and using as little lightings as possible. The electric consumption will be certainly underestimated, but it can be considered that the most important electric loads, including the circulation pumps, have been taken into account.

Table 4: Electrical household appliances used in the building

Appliance	**Power (W)**	**Use condition**
Dryer	2500	Daily use
Washing machine	2100	Daily use
Dishwasher	2100	Daily use
Refrigerator	110	34 cycles per day
Freezer	100	18 cycles per day

Description of the electricity production systems

The electricity used in the dwelling may have three origins. It can be produced by a photovoltaic array. This array is 17.5 m² large. It is the sum of 24 standard panels, each contains 36 silicon cells. The electrical model is based on an equivalent circuit of a one-diode model. The production of the panel is treated by a control system. If there is an energy demand, the electricity is directly converted by the controller's inverter and consumed by the load. The inverter's efficiency is 0.96. If the production is higher than the load's demand, it is stocked in a battery. This lead-acid storage battery contains 15 cells, which each contains 600 Wh. It guarantees 3 days of autonomy. A 0.7 constant value was picked for its charging efficiency, which is an average value.
When the demand is higher than the array's production, energy is restored from the battery and used just like the electricity produced by the array. The discharge limit of the battery is 2%. This means that if the state of charge of the battery decreases under this rate, the photovoltaic production is used in priority to recharge the battery until this limit. This is a use precaution for the inverter and regulator model to avoid that it keeps discharging the battery whereas it is already empty.
If neither the battery nor the array can supply the load, energy is provided from the grid.

Table 5 : TRNSYS types used for the electrical simulation

System	**Type**	**Details**
Inverter	Type 48b	TRNSYS library
Battery	Type 47	TRNSYS library
Electric load profile	Type 155	TRNSYS type calling matlab

Simulation

Since no cooling device is used, the study of the dwelling has not been performed during summer and spring. The simulation begins on September the 1st, and ends on March the 31st. The simulation time step is 0.1 hours.
The study is focused on three phenomena. First, an electric assessment has been realized. The total electrical consumption, the photovoltaic production, the grid contribution, and the battery state of charge were monitored.
The second phenomenon is the evolution of the temperature in the dwelling and the both heat contributions of the electric loads and the heating floor.
The third phenomenon is the evolution of the average temperature of the storage tank and the production of the solar collector and the boiler.

Electric assessment

Global assessment

Table 6: Assessment of the electrical systems

Energy consumption [kWh]	**Photovoltaic production [kWh]**	**Energy from the grid [kWh]**
948	1161	402

During the seven months, 948 kWh have been consumed. The grid provided 402 kWh, which represents 42% of this energy. However, it can be noticed that the photovoltaic array produced 1161 kWh.
A local assessment can explain why 53 % of the photovoltaic production is lost during the simulation.

Local assessments

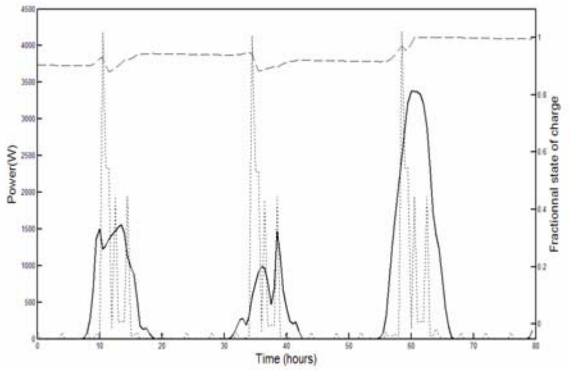

Figure 4: Electrical consumption and production with favourable weather conditions (Electrical consumption, dotted line; Photovoltaic production, solid line; Battery state of charge, Dash-dot line)

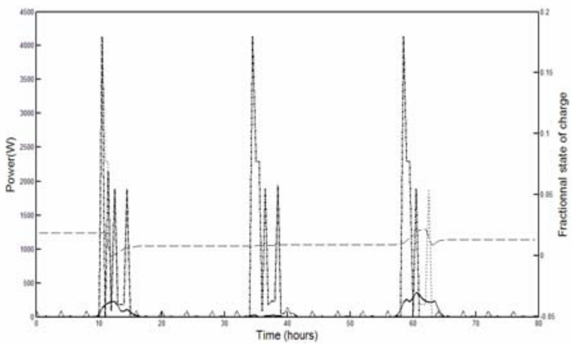

Figure 5: Electrical consumption and production with unfavourable weather conditions (Electrical consumption, dotted line; Photovoltaic production, solid line; Grid contribution, dashed line; Battery state of charge, Dash-dot line)

The evolution of the electrical consumption, the photovoltaic production, the grid contribution and the fractional state of charge were monitored during three days. The figure 4 corresponds to the beginning of September, with high temperatures and high solar radiations. This is a favourable case for the exploitation of photovoltaic electricity. The figure 5 corresponds to the end of November, when solar radiations are much lower. The photovoltaic production is not sufficient to supply the electrical loads and a contribution from the grid is necessary.

Analysis

The global assessment shows us that the photovoltaic is not optimised. It produces during the seven months more than what the electrical load consumes, but the grid still provides 42% of the load energy. This means that only 546 kWh produced by the photovoltaic array was used and 53% is wasted.
There are three explanations for this phenomenon.
The first one is the efficiency of the inverter (0.96) and especially of the charging process of the battery (0.7). When the photovoltaic production is higher than the electric load (figure 4), the exceeding energy is stocked in the battery but 30% of it is lost.
The second explanation is the capacity of the battery: when it reaches its full capacity (figure 4), no more energy can be stocked and all the exceeding energy is completely lost. It is noted that the battery reaches its full capacity during 299 hours in the entire simulation, which represents 12.5 days. It is 6% of the total duration.
The last explanation is the important variation of the solar radiation during the simulation. When the solar radiations are low during a long period, the battery is empty and the grid contribution is necessary. It is the case of figure 4, where the grid contribution is most of the time equal to the load.

Discussion about the electrical systems

The first question is to determine if the dimensioning of the systems is correct. A highest capacity of the battery might have helped wasting less photovoltaic production and decreasing the grid contribution. However, the battery capacity used is already considerable, and requires consequent space and money. Therefore, it will be considered that the battery capacity is correctly set.
The arrays seem in consequence to be probably over dimensioned. Considering the charging efficiency of the battery, which could represent about 30% of the energy loss, it is estimated that at least 20% of the losses provides from overproduction which could not be stocked since the battery was already full. However, the electrical consumption has probably been underestimated. The conditions were the most advantageous, since most of the load's operations were planned during the day, when the arrays were producing electricity. In the reality, many loads are not operating during this moment. The worst case concerns the lighting, which operates when there is no natural light and therefore no solar radiation. The importance of the role of the battery is in reality much bigger, which is why a losses part more important than the conversion rate of the inverter cannot be avoided.
That is why it will be considered that these systems are correctly dimensioned.
The second question is to find how to decrease the grid contribution with the same systems. The best

solution is to concentrate the loads operations during the production of the electricity by the photovoltaic arrays, but as mentioned before, this was almost already the case during the simulation. This could be somehow done more precisely, to avoid such situation as in figure 5: during the first day, the photovoltaic production is higher than the energy load, since the state of charge on the end of the consumption peak is higher than on its beginning. However, it is noted that it sometimes decreases between those two moments, because the instantaneous load is sometimes higher than the instantaneous production (a 4000 W load when the washing machine and the dishwasher are turned on at the same time). This could be avoid by deferring some loads later in order to keep the instantaneous load as much as possible on the same level as the instantaneous production

Study of the heating systems

Global assessment

The evolution of the temperature in the building has been monitored. The temperature always remained higher than 19.5 °C.

Table 7: Repartition of the temperature during the simulation

Temperature interval	**Time spent in the interval (hours)**
19.5°C<T<21.5°C	3660
21.5°C<T<23.5°C	753
23.5°C<T	748

The table shows that 71 % of the time is spent in the lower interval, which is the best comfort interval. The second interval represents 15% of the time. It is a bearable temperature interval. The last interval corresponds to overheat temperatures, where cooling control would be necessary. The overheat periods represent 15% of the time and happened on the beginning of autumn, when the temperature and the solar radiation are still high and the heating floor is mostly turned off.

Considering the contributions of the heating floor and the electrical devices, it was noted that 7.6% of the heat contribution to the building comes from the electric devices.

Table 8: Heating energy assessment

	Total contribution kWh	**Local contribution kWh/m²**
Heating floor	8532	61.2
Electrical devices	702	5.04

The heating contribution for the period of the simulation is 61.2 kWh/m². This is almost the annual contribution since the simulation has not been processed during the hottest seasons where no heating is necessary. The minimal need to maintain the temperature above 20 °C in Lyon during the same period can be evaluated with the simulation. It is 40 kWh/m². The heating floor's contribution is 50% too high. The energy saving potential is 20 kWh. A local assessment will explain how and when these savings cold be realized.

Assessment on two weeks

On assess was realized on the two first weeks of January to understand the causes of the energy waste.

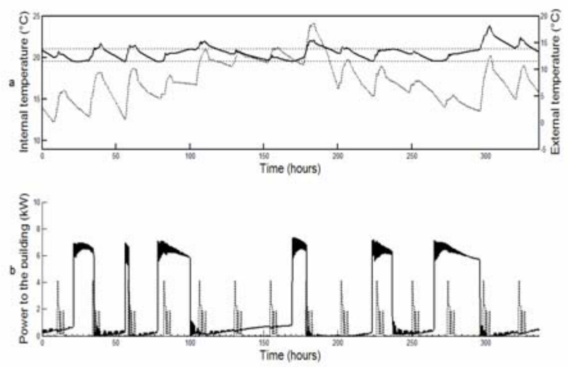

Figure 6 a: Evolution of the temperature in the building (Internal temperature, solid line; External temperature, dotted line)
b: Evolution of the power in the building (Heating floor, solid line; Electrical appliances, dotted line)

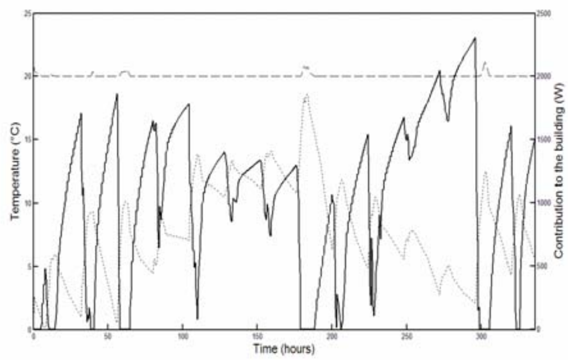

Figure 7: Evolution of the minimal heating need (Internal temperature, dashed line; External temperature, dotted line, heating power, solid line)

These are two typical winter weeks, with low temperatures around -5°C, and also warmer temperature around 15°C. This is the external temperature variation rather than the low or high temperature level, which is hard to compensate in the building. The minimal heat energy need calculated for these two weeks is 352 kWh. In the simulation, the heat energy provided is a 670 kWh amount, almost the double.

Analysis

The control procedure of the building temperature is the reason of the energy waste. It turns the heating floor on as soon as the temperature decreases less than 19.5°C and turns it off when it reaches 21°C. Although the temperature decreases slower that it increases, heating the building until 20°C is excessive, all the more that it is sometimes responsible of overheats. The problem remains in the fact that the control only monitors the internal temperature without taking into account the other phenomena impacting on it. The daily contribution of the electric appliances is small but it has an impact on the internal temperature evolution. The most important disturbance is the solar contribution, which is as efficient as the heating floor. A bad coincidence between this contribution and the heating control is the source of the energy waste and of the overheat periods. This could be seen on figure 5, on the time 75 h. The heating floor was turned on and the temperature reaches 21°C just on the middle of the morning. A high solar contribution begins then and elevates the temperature until 24°C.

Discussion about the heating system

The main defect of the systems is the control procedure. It provides an almost constant heating power of 6 kW (figure 6). It can be noted on the ideal control in figure 6 that at most 2.5 kW are needed to maintain the temperature. An improved control procedure should take into account each external gain to calculate the heating energy the heating floor should provide to the building. To do so, the controller should first measure or estimate the external contributions and then evaluate their impact on the building. The controller will then finally deduce the heating power needed. These calculations could be realized with the use of methods from the control theory.

Heat production assessment

Global assessment

Table 9: Thermal assessment

Solar collector [kWh]	**Boiler [kWh]**		**Thermal load [kWh]**	
Contribution to the tank [kWh]	Wood consumption	Contribution to the tank	Heating floor	DHW
1405	11831	9873	8263	3033

This assessment is focused on the contribution of the boiler, of the solar collector to the tank, and of the thermal load which is the sum of the energy removed by the heating floor and the energy removed by the domestic hot water consumption.
It is noted that the solar collector provides the tank with the half of the energy it needs to produce the domestic hot water for the building. The boiler provides the rest of the energy production.

Assessments on one week

Three weeks were picked to highlight the different cases of operation of the thermal systems.

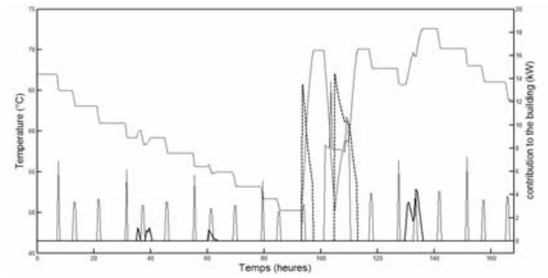

Figure 8: Thermal state of the storage tank during a week of September (Average tank temperature, dotted line; Collector contribution, bolded solid line; Boiler contribution, dashed line; Thermal load, thin solid line)

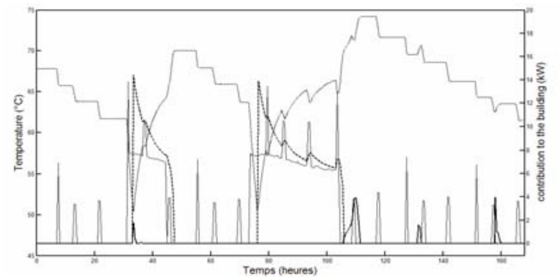

Figure 9: Energetic state of the storage tank during a week of October (Average tank temperature, dotted line; Collector contribution, bolded solid line; Boiler contribution, dashed line; Thermal load, thin solid line)

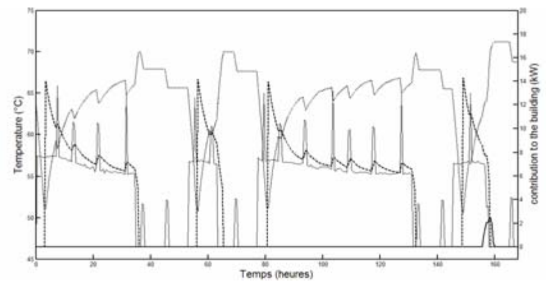

Figure 10: Energetic state of the storage tank during a week of January (Average tank temperature, dotted line; Collector contribution, bolded solid line; Boiler contribution, dashed line; Thermal load, thin solid line)

Analysis

It can be noted on the figure 7 the capacity of the storage tank: when it is heated until 70°C, it contains enough energy to provide the building with domestic hot water. It is also noted that it takes about four hours for the boiler to recharge the storage tank.
It can be noted on figure 8 that an energy need from the heating floor is much more important than the domestic hot water needs. In consequence, it takes only a few hours to discharge the tank when the heating floor is turned on.
In winter, like in figure 9, when the heating need is the highest, the heating floor is almost always turned on, as the boiler is. The solar contribution is then minimal. However, even in September, when the weather is warm and the solar radiations are high, the solar contribution remains low. The reason of this is probably the control procedure of the boiler. It is programmed to maintain a high average temperature in the tank. But the energy, which the boiler and the collector can give to the tank, depends of the temperature difference between the tank and the fluid heated by the device. The boiler can easily heat the fluid to a high temperature but it is harder for the collector to do the same.

Discussion about the thermal systems

Despite a large collector surface, the solar part of the thermal energy used in the building is low (12%). This part could be increased by lowering the high set point of the recharge procedure of the tank by the boiler. It would even be interesting to keep the temperature of the tank as low as possible before the moments when the collector will start producing thermal energy. This could be done by evaluating the solar radiation of the day and the daily production potential of the array. The same method could be used as proposed previously for the heating control. In the case of a high production potential, the use of domestic hot water could be concentrated before the peak, for example by using it in electrical household appliances. Turning on the heating floor would not be a good idea since these high productions are due to high solar radiation, which will already strongly heat the building. This procedure would then lead to high overheat that must be avoided.
Another solution is the increase of the volume of the tank. This will probably be done in future studies.

CONCLUSION

The demonstration was made that there is a huge energy saving potential in this building. Many leads were suggested to increase the part of photovoltaic electricity and solar thermal energy in the building.
The photovoltaic part of the electricity production could be increased by the dynamic management of the planning of the loads in function of the photovoltaic production.
The solar part of the thermal energy production could be increased by the use of a better control of the temperature. A bigger storage tank could also help to maximize the solar production.
The next step of this work will be focused on the thermal aspect and the improvement of the temperature control in the dwelling. Then a method to maximize the solar part of the thermal energy will be designed. The work on the electric side will be improved by the addition of more detailed loads. In the same time, an artificial intelligence method called multi-agent systems is being designed to deal with the electric loads deferring.
On each step of this work, each development will be tested by comparing it to the model presented here.

AKNOWLEDGMENT

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