EVALUATION AND MINIMIZATION OF THE ENERGY IMPACT OF TYPICAL EUROPEAN BUILDINGS ON THE ELECTRICITY GRID: A SIMULATION CASE STUDY

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ABSTRACT

People spend around 90% of their time in buildings while about 40% of primary energy needs are due to buildings. That is why the present paper deals with a method allowing identifying and assessing the energy impact of a building on the electricity grid. Thanks to the wide range of building models we developed and fuzzy logic contribution, the results we obtained in simulation validate the proposed impact indicator. They highlighted the pertinence of such a tool for optimizing the design of production and storage systems as well as minimizing the amount of energy exchanged by buildings and the grid.

INTRODUCTION

Sustaining human life requires energy. Without energy, everything around us in our daily lives will be interrupted. Moreover, given the growing energy consumption and because the building sector is one of the key sectors in the pursuit of a sustainable society, in numerous countries laws give obligation to reduce buildings energy need and tax assistance has greatly increased sales of renewable energy production systems. Consequently, mainly due to the intermittent nature of the renewable production, one can note a significant increase of both the frequency and the amount of energy exchanged between buildings incorporating such systems and the electricity grid. Developing models for simulation give us information about the way the grid can tolerate the injection of decentralized produced renewable energy and about the increasing energy impact of buildings. Because of the necessity to keep the balance between energy production and energy consumption, high-resolution simulation is required for evaluating the just-mentioned impact. However, quantifying accurately, in real time, the cumulative production of all the decentralized systems is a hard task. In France, this production represents a cumulative power of about 680 MWe and, consequently, has to be taken into account to regulate the working of the grid. Neither quantified nor predictable, a sudden loss in energy resources would lead at best to a sharp increase in energy demand for power industrial plants.

PROPOSED APPROACH

Heating Ventilation and Air-Conditioning (HVAC) systems represent 35% of the overall energy consumption of buildings. Integrated in a building frame, renewable energy production systems can meet a part, or the totality, of both the human and HVAC appliances needs. Renewable energy is a way to reduce fossil energy dependence as well as greenhouse gas emissions (Spiegel and McArthur, 2009). Unfortunately, intermittent resources are an obstacle to the development of such energy (Sovacool, 2009). Moreover, in case of a large deployment of renewable energy production systems, their impact on the electricity grid will be significant (Bradford, 2009). Indeed, one can highlight an increase of both the amount of energy passing through the grid (Paatero and Lund, 2007) and the power demand amplitude, as well as a rapid fluctuation of demand (Peacock and Jenkins, 2008). To minimize the impact of an intermittent production, energy storage systems can be used (Botkin and Perez, 2010), but devices are not enough efficient (Hadjipaschalis et al., 2009). Energy mix could also be a solution for extending production time and the amount of energy produced (Spiegel and McArthur, 2009). Finally, experience shows that a study dealing with human factors, habits and needs as well as availability of energy resources is of paramount interest for the design of facilities (Hammons, 2008, Yilmaz et al., 2008). Taking into account all these parameters is a hard task when designing models and scenarios. That is why expert knowledge about human habits and lifestyle was considered through fuzzy approaches, related to control and modeling. So, the aim of the present work was first to develop pertinent buildings models and to generate simulation data for evaluating their energy impact on the electricity grid (Bahaj et al., 2007). We proposed a criterion dealing with such consideration. Finally, an optimization algorithm dealing with an active-set strategy was used to find the right dimension of energy production and storage systems (Østergaard, 2009) allowing the proposed criterion to be minimized.

ENERGY PERFORMANCE DIAGNOSIS

Quantifying energy efficiency is the goal of the French "Energy Performance Diagnosis" (EPD) (Official Journal, 2002). This diagnosis allows estimating the energy consumed by a building according to HVAC appliances. The UK has nearly the same evaluation system, named "Building Energy Ratings" (BER).

The EPD result is usually expressed on a scale ranging between A and G (i.e. from less than 50 to more than 450 kWh.m^2.year) for low to high-energy consuming buildings. This result can be calculated using several methods, but whatever the method of calculation, the energy performance diagnosis is an information tool only. Calculation is carried out using estimated and mean values, what leads to poor credibility. In addition, a report of the French DGCCRF (Direction Générale de la Concurrence, de la Consommation et de la Répression des Fraudes) (Cerutti, 2006) revealed many problems mainly related to the diagnostician's independence from the building owner. Finally, the EPD gives information about the energy performance of a building over a year only and it does not help in optimizing energy consumption on a fine scale. Indeed, it does not take into account an increase of the net traffic between a building equipped with energy production systems and the electricity grid. This is this kind of information that the "energy impact" criterion highlights, with the aim of reducing the amount of energy exchanged by the building and the grid. Thus, we proposed an approach to classify buildings taking into account both the magnitude of the power demand and the power injected to the electricity grid.

ENERGY IMPACT OF A BUILDING

The energy impact of a building on the grid (E_{imp}) is obtained after calculating its real-time energy impact (E_{impRT}). E_{impRT} is calculated at each simulation time step after carrying out an analysis dealing with energy consumption.

Data acquisition

First, we need data to calculate the real-time energy impact of a building. One can do it as follows:

- By software simulation, for example TRNSYS, which is able to simulate the thermal behaviour of a building, using its previously defined model. Synchronized with MATLAB, one can define occupancy scenarios according to the intended use of the considered building. Meteorological data are required for simulating. Usually, simulation is carried out during one typical year, defined as the mean of two to five years of data. One can also simulate the building behaviour using bought meteorological data.
- Using data from an instrumented building. In this case, the main problem lies in the interpretation of the obtained results. Because it is very hard to identify all the human action and the way they affect electricity consumption, the studied building is considered as a grey box.

Both approaches have limitations. Considering the first one, the use of a building model, which by definition cannot be a perfect depicting of reality, requires approximations, sources of several errors. Considering the second one, the building is deemed to be a grey box: we know devices that equip the building but electric load variations induced by their use are hard to identify. Whatever the approach, the study we carried out highlights needs about final thermal energy for heating, ventilation and air conditioning devices (HVAC appliances) as well as specific energy needs (not considered by the EPD). Next, analysis highlights the most productive renewable energy sources and their adequacy with the building consumption. Finally, one can highlight a passive way to reduce the building's energy impact: improving thermal insulation. This solution will not be directly considered in the present paper.

Real-time energy impact of a building

First, we define, for a building connected to the grid, its real-time energy impact as the balance between its power demand (W_{dem}) and the electric power it produces (W_{prod}) (1). n is the time index:

$$E_{impRT}(n) = W_{dem}(n) - W_{prod}(n) \qquad (1)$$

Energy impact of a building on the grid

Next, the energy impact of a given building on the electricity grid can be expressed as a sum by equations (2a) and (2b), with W_{max} the maximal value of the power demand (or the electric power produced and injected to the grid) during a time interval, $Coef$ a coefficient to be fixed and n_{up} the upper limit of the study interval (time step is 1 minute):

$$E_{imp} = \frac{\sum_{1}^{n_{max}} e^{Coef \times \frac{|E_{impRT}(n)|}{W_{max}}} - 1}{n_{up}} \qquad (2a)$$

$$E_{imp} = \frac{\sum_{1}^{n_{max}} e^{C(n)} - 1}{n_{up}} \; ; \; C(n) = Coef \times \frac{|E_{impRT}(n)|}{W_{max}} \qquad (2b)$$

E_{imp} allows taking into consideration all the electric consumption habits. Usually, the energy impact of a building on the grid is linear. However, it seems judicious to break this feature during the analysis of a building's load curve. That is why we decided to penalize people consuming energy in a bad way. Let us note that for this study, the impact of a building on the electricity grid is considered in the same way the building being a consumer or a producer of energy. That is why we considered the absolute value of E_{impRT}. Because the size of the studied building affects E_{impRT}, it is taken into account. Finally, E_{impRT} is brought back to a value ranging between 0 and 1 dividing it by W_{max}, the maximum value of the power consumed or injected to the electricity grid during a time interval. As a result, 0 is the minimum transfer value allowed by the grid while 1 is the maximum transfer value. As previously mentioned, the result is multiplied by a coefficient (*Coef*) before using the exponential function, as depicted by equation (2), to penalize extreme behaviours. The choice of *Coef* is free and depends on the behaviour you want to penalize. 3 is an interesting value allowing defining penalties at about 70% of the maximum power exchanged between a building and the grid, as shown in Figure 1. In some particular cases, this coefficient can be modified during the simulation process. This preconized value has been chosen after the statistical analysis of the load curves of different buildings from various countries. One can note that below 70% of W_{max}, the power exchanged between the building and the grid can be considered as reasonable. For a higher value, the equipment used is mismanaged (for example, some electrical devices are plugged simultaneously and in a redundant way). Moreover, when looking at a French daily load curve, one can observe that mean consumption values, excluding rush hours, range between 65 and 80% of the power demand during the largest peak of the day.

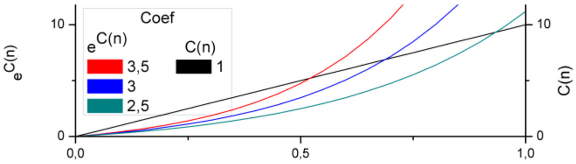

Figure 1 Impact of Coef

In case of negative balance, one can promote energy injection by changing the coefficient allocated to E_{impRT}. One can note that reducing the time step to a value lower than one minute does not provide more information. However if this time step exceeds 10 minutes, the obtained simulation results are not fully representative of the studied behaviour. The final step of the process is an analysis of consumption variations. We considered changes dealing with the building status (from producer to consumer or from consumer to producer) and swift increases of energy consumption per minute. If *Var* crosses over 10% of the total power capacity of the considered building, the *Coef* value is corrected, as presented by Figure 2. With such a correction, one can finally obtain a fully representative E_{imp}.

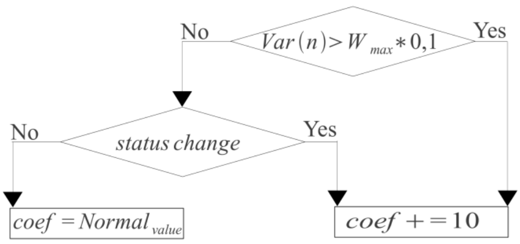

Figure 2 Correction of Coef

Our objective is not to replace the EPD but to provide additional information. In this sense, the load curve of a given building reveals occupants habits the label we propose can highlight. Finally, we used it, taking into consideration renewable energy resources and fatal heat production, for carrying out the design of energy production and storage systems. The right sizing of these systems allows minimizing E_{imp}. As a result, such an optimization will lower the power purchased from the grid, which induces a mechanical reduction of the transported amount of energy. In most of the cases, the right sizing of production and storage devices naturally generates an increase of the self-consumed energy. However, "self-consumption" has to be handled with care. Theoretically, in France, the decentralized production of energy is completely sold to an energy trader. This trader buys energy at a very high price, sometimes subsidized. That is why we talk about a "virtual" trade with the electricity grid, both the injection system and the building consuming energy being always nearly plugged on the same cable, from the same node of the grid.

THE DEVELOPED BUILDING MODELS

After formulating the E_{imp} label, we tested it using simulation data. Because buildings instrumented with acquisition data devices dealing with a time step lower than 10 minutes are rare, we developed building models.

Models features

TRNSYS and the SIMBAD toolbox for MATLAB have been used to model the thermal behavior of typical residential buildings, offices and factories one can find across Europe. User profiles have been exploited to highlight the way energy is consumed. DAYSIM allowed simulating artificial lighting. So, we developped the following building models:

- Industrial building models. Because of economic and confidentiality reasons, industries are sworn to secrecy about factory features. Moreover, one needs to model the behaviour of people working in the buildings and affecting the way energy is consumed. As a consequence, carrying through the modelling process for such buildings is not an easy task. Three building sizes were considered: 250 m^2 for a small factory (3 to 10 staff people), 1000 m^2 for a medium factory (25 to 50 staff people) and, finally, 4000 m^2 for a big factory (more than 200 staff people). Places were reserved to all the office workers (secretaries, bookkeepers, billing agents...). Offices were modelled taking into account supplies (copiers, computers, coffee machines...) generating fatal heat. We made the same thing with production areas where industrial machines take place and generate fatal heat too. Because production areas are not enough insulated for thermal conditioning, thermal regulation policy is only applied to offices. Finally, we considered two kinds of building: current and 80's buildings.
- Models of building facilities. (1) Service building models were defined according to an occupation of about one people for 4 m^2 and energy power needs of about 10 kWh per person and per day. (2) Data centre models were defined according to an occupation of about one people for 100 m^2 and energy power needs of about 500 W per meter square. In both cases, we considered the building to be isolated according to current standards.
- Residential building models: apartments in condominium and private habitations. Private habitations were not hard to model because it was easy to get data dealing with energy consumption and renewable energy production, when the considered house is equipped with such a system. We considered all the habits of the people living

in the buildings. As a result, we obtained high-resolution models, validated using monthly meter readings. Numerous models are now functional with different insulation levels (70's, 80's, RT2005 and RT2012 insulations) and occupancy scenarios (1 to 5 people with restrictions according to the available surface). All the possible combinations are not yet modelled; the objective is to get the maximum number of models, fully representative of the European building park.

Standard building

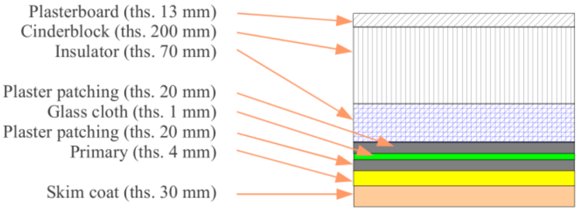

Figure 3 External walls (RT2005 insulation)

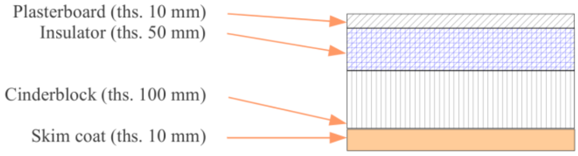

Figure 4 External walls (80's type insulation)

We considered as standard building, a 150 m^2 single storey house, located in Perpignan (south of France), facing south and inhabited by four persons (two adults and two children). This building, built in 2006, is in agreement with the RT2005 documentation (Official Journal, 2006). We considered two variants dealing with a building built in 1986 and a non-insulated building. Lifestyle habits were modelled. Although other structures were considered, the just-mentioned profile is the only one we used during the present study. Indeed, the geometry of a building does not have a significant effect on the phenomena we want to observe. Solar thermal panels, photovoltaic panels and a vertical axis windmill can be integrated to the building. A thermal storage tank for Domestic Hot Water (DHW) was also considered. HVAC control is achieved thanks to a heat pump or a simple electric heater, depending on the building construction (Brumbaugh, 2004). Finally, thermal regulation policy is dependent on the building age. The following building materials were considered:

- RT2005 insulation: windows with double Low-E glass (4x16x4), argon gas with PVC frame for the small ones and aluminium thermal break for the taller ones. External wall layers are described by Figure 3. Insulation is external.
- 80's type insulation: windows with double-glazing (4x8x4) without gas layer for the small ones and an aluminium cold structure for the taller ones. External wall layers are described by Figure 4.

Figures 5 and 6 depict the typical daily load curves we obtained using the developed standard building model (RT2005 insulation), the building being equipped (red curve) or not (grey curve) with production systems. Their design is standard and related to profitability. For both configurations, we considered a DHW tank of 300 litres. Let us specify that a positive value means that the balance between consumed energy and injected energy is positive (consumed energy > injected energy) while a negative value means that this balance is negative (consumed energy < injected energy). Figure 5 highlights energy needs related to HVAC appliances (1st case; load curves are given for a cold day) while Figure 6 depicts a hot and sunny day without wind (2nd case; no energy needs related to HVAC appliances). During the cold day (1st case) and whatever the hour of the day, load variations are significant. During the hot day (2nd case), HVAC appliances are not required for two main reasons: a comfortable indoor temperature and renewable energy systems providing enough energy to meet the building thermal energy needs. Because cooking requires energy, one can find on the curves the three daily meal periods. One can also highlight a basic consumption of about 300 W generated by standby equipment (TV, internet box, hi-fi equipment...). Finally, analysing these curves, one can relate human comfort and the building electricity needs.

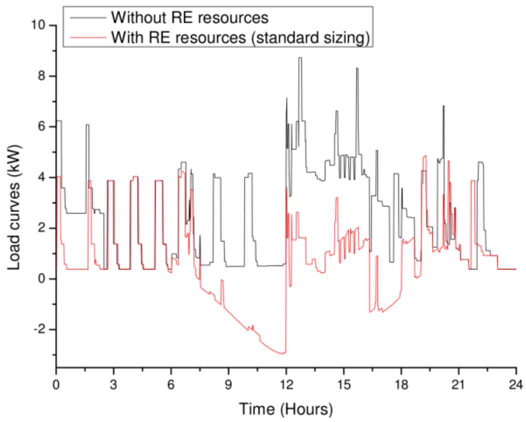

Figure 5 Daily load curves (cold day) (RT2005)

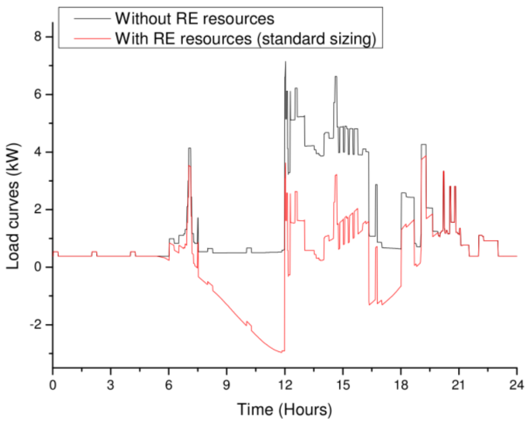

Figure 6 Daily load curves (hot day) (RT2005)

Figures 5 and 6 illustrate why the E_{imp} label is needed and why it has to be minimized. During the first hours of the day, PV cells produced more energy than necessary. So, the surplus of energy is injected to the electricity grid but without being needed by the grid. During the morning, the balance between consumed energy and injected energy becomes negative (with standard renewable energy production systems) despite that PV cells produce energy. Of course, injecting energy to the grid during rush hours (peaks of load) would be welcome. Finally, at the end of the day, PV cells are not able to produce energy while energy is needed.

Human actions modelling

Human actions can only be properly modelled taking into account expert knowledge. However, defining pertinent scenarios dealing with start and stop specifications for devices remains hazardous. As a consequence, these scenarios are usually not fully representative of a real behaviour. Because we wanted to link consumption habits and lifestyle, we needed to design scenarios dealing with the specific energy needs of all the devices of a given building. That is why fuzzy logic controllers and complementary models were developed to improve real-time simulation.

FUZZY LOGIC CONTRIBUTION

Occupancy scenario

First, fuzzy logic is used to model the multi-energy building occupancy. The scenario we proposed allows managing the fatal heat production as well as electronic devices and household appliance. It is based on inhabitants' presence, meteorological data and traffic. Figure 7 depicts the fuzzification of the inhabitants' presence. Gaussian membership functions were used. Such functions favor quick transitions. The following linguistic labels were associated to the five fuzzy sets: H (Holydays), W (Work), A (Away), J (Journey) and P (Present). "Work" is related to a standard working day while "Journey" means that the considered inhabitant is going from home to office (or school) or from office (or school) to home. Figure 8 shows the fuzzification of weather conditions. Standard triangular membership functions were used. According to outdoor temperature and rain events, the following linguistic labels were associated to the three fuzzy sets: VB (Very Bad), B (Bad) and G (Good). Figure 9 deals with the fuzzification of the Direct Normal Irradiance (DNI). Triangular and trapezoidal membership functions were used. N (Night) and D (Day) were associated to the two fuzzy sets we defined. Let us remember that direct normal irradiance is the amount of solar radiation received per unit area by a surface that is always help perpendicular to the rays that come in a straight line from the direction of the sun at its current position in the sky. We used the DNI only to differentiate day time from night time. Figure 10 depicts the fuzzification of traffic. Triangular membership functions were used. The following linguistic labels were associated to the two fuzzy sets: MF (Moving Freely) and S (Saturated). Knocking-off time is taken into account. Traffic, DNI and weather conditions are only used to determine the away time. Figure 11 deals with the fuzzification of occupancy, for "day-type" (garage, laundry room, kitchen, dining room…) and "night-type" (bedrooms …) rooms. Because we want to reduce so far as we can computation time related to defuzzification (taken into consideration that the proposed tool will be implemented in real buildings to control their behavior in real-time), we used singletons as membership functions. The following linguistic labels were associated to the four fuzzy sets: A (Away), AL (Away Long), AS (Away Short) and P (Present).

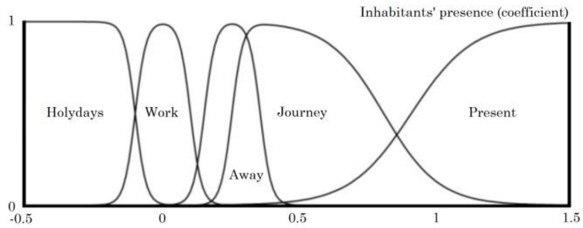

Figure 7 Inhabitants' presence fuzzification

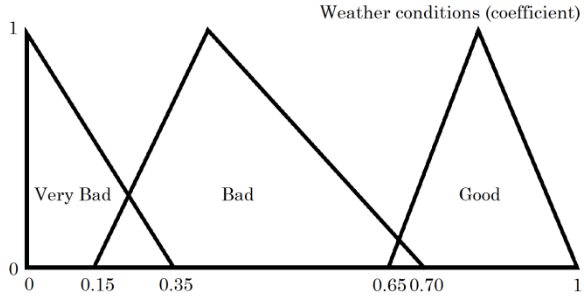

Figure 8 Wheather conditions fuzzification

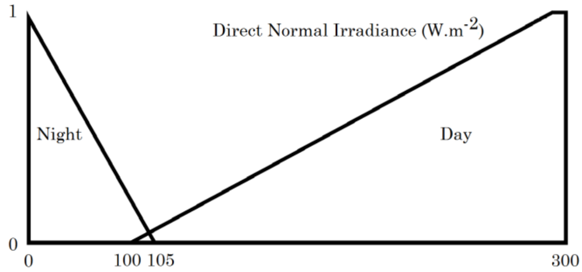

Figure 9 Direct normal irradiance fuzzification

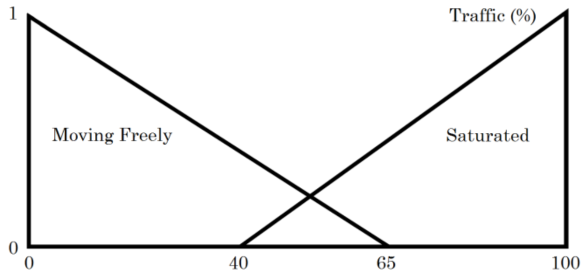

Figure 10 Traffic fuzzification

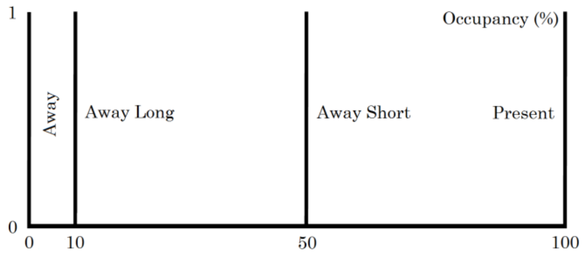

Figure 11 Occupancy fuzzification

Finally, Table 1 depicts the design of the fuzzy rules (for a total of 19 rules). Each rule has two conclusions, the first one for "day" rooms and the second one for "night" rooms ("•" means "whatever the fuzzy set").

Table 1
Fuzzy rules for occupancy

Rule	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Presence	*J*	*J*	*J*	*J*	*J*	*J*	*J*
Weather	*VB*	*B*	*B*	*G*	*G*	*VB*	*B*
DNI	*D*	*D*	*D*	*D*	*D*	*N*	*N*
Traffic	•	*S*	*MF*	*S*	*MF*	•	*S*
Occ. (day)	*AL*	*AL*	*P*	*AS*	*P*	*AL*	*AL*
Occ. (night)	*A*	*A*	*AL*	*A*	*P*	*AL*	*AL*
Rule	*8*	*9*	*10*	*11*	*12*	*13*	*14*
Presence	*J*	*J*	*J*	*H*	*W*	*A*	*A*
Weather	*B*	*G*	*G*	•	•	*G*	*G*
DNI	*N*	*N*	*N*	•	•	*D*	*N*
Traffic	*MF*	*S*	*MF*	•	•	•	•
Occ. (day)	*AL*	*AL*	*AS*	*A*	*AL*	*AL*	*AL*
Occ. (night)	*AS*	*AS*	*P*	*A*	*AL*	*AL*	*P*
Rule	*15*	*16*	*17*	*18*	*19*	-	-
Presence	*A*	*A*	*A*	*P*	*P*	-	-
Weather	*B*	*B*	*VB*	•	•	-	-
DNI	*D*	*N*	•	*D*	*N*	-	-
Traffic	•	•	•	•	•	-	-
Occ. (day)	*AS*	*AL*	*AL*	*P*	*AL*	-	-
Occ. (night)	*AL*	*AS*	*AL*	*AL*	*P*	-	-

Ventilation control

Ventilation is a way to reduce energy consumption in buildings. The aim of ventilation is to exchange calories with outside and to favor inhabitants' thermal comfort. The fuzzy controller we proposed has two inputs, indoor (T_{in}) and outdoor (T_{out}) temperature, and one output, the fan speed (FS). Indoor temperature is considered for each of the building rooms. We used triangular and trapezoidal membership functions for T_{in} (6 fuzzy sets) and T_{out} (5 fuzzy sets) as well as the following linguistic labels: Cd (Cold), Co (Cool), P (Pleasant), M (Mild), H (Hot) and VH (Very Hot) (Figures 12 and 13). Let us note that, first, we defined only 3 fuzzy sets for T_{in} and T_{out} but the control results we obtained were disappointing. As a consequence, we increased to 5 the number of fuzzy sets used. This allowed the control strategy to be more subtle and flexible. Chaotic states were eliminated and the search for an optimal thermal comfort was more gradual. As a key point, one can note that we used a trapezoidal membership function for the fuzzy set "Hot" (T_{in}) because a triangular one leaded to instability. With an appropriate design of the fuzzy rules, this was eliminated. However, taking a look at indoor temperatures, we noticed that the temperature the controller was recommending in winter was too low, while, at times, outdoor temperature allows reaching a higher value and reducing energy consumption. That is why, after trying, unsuccessfully, to adapt the design of the fuzzy rules to solve the problem, we increased to 6 the number of fuzzy sets for T_{in}, adding the fuzzy set "Pleasant". A triangular membership function was used.

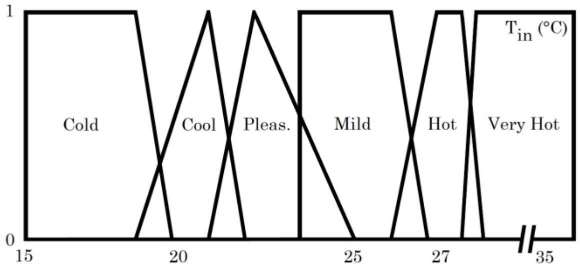

Figure 12 Indoor temperature fuzzification

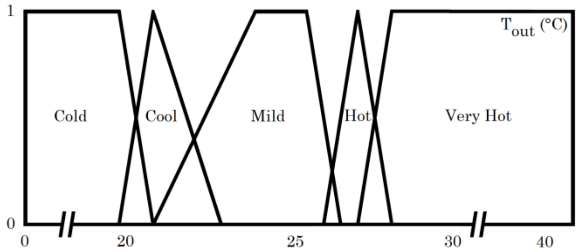

Figure 13 Outdoor temperature fuzzification

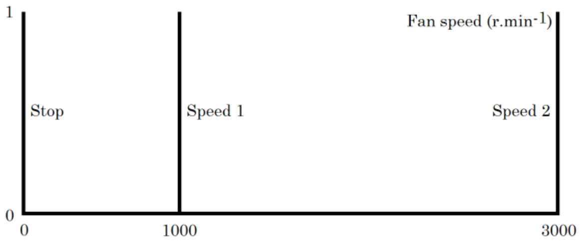

Figure 14 Fan speed fuzzification

Finally, Figure 14 deals with the fuzzification of the fan speed. For the same reasons (related to computation time) as we did for occupancy, we used singletons as membership functions. The following linguistic labels were associated to the three fuzzy sets: S (Stop), S1 (Speed 1) and S2 (Speed 2). Finally, Table 2 depicts the design of the fuzzy rules (for a total of 21 rules) used to control ventilation. As another key point, one can observe that some situations, dealing with exceptional weather conditions, are not correctly treated with the rules we designed. In this case, ventilation is stopped.

Table 2
Fuzzy rules for fan speed

Rule	*1*	*2*	*3*	*4*	*5*	*6*	*7*
T_{in}	*Cd*	*Cd*	*Co*	*Co*	*Co*	*Co*	*Co*
T_{out}	*Co*	*M*	*Cd*	*Co*	*M*	*H*	*VH*
FS	*S*	*S2*	*S*	*S*	*S2*	*S1*	*S*
Rule	*8*	*9*	*10*	*11*	*12*	*13*	*14*
T_{in}	*P*	*P*	*P*	*P*	*M*	*M*	*M*
T_{out}	*Co*	*M*	*H*	*VH*	*Cd*	*Co*	*M*
FS	*S*	*S2*	*S1*	*S*	*S*	*S1*	*S2*
Rule	*15*	*16*	*17*	*18*	*19*	*20*	*21*
T_{in}	*M*	*H*	*H*	*H*	*VH*	*VH*	*VH*
T_{out}	*H*	*Co*	*M*	*H*	*Co*	*M*	*H*
FS	*S*	*S2*	*S1*	*S*	*S2*	*S2*	*S*

ENERGY IMPACT MINIMIZATION

Thanks to the right sizing of energy production and storage systems, one can reduce the real-time energy impact of a building. This allows reducing the amount of energy exchanged by the building and the electricity grid (i.e., the net balance). Moreover, this favours self-consumption and reduces the risk related to energy transport. This optimization problem was solved using an active-set strategy. With such a method, one attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate. This is usually referred to as "constrained nonlinear optimization". The minimization of E_{imp} is based on optimizing the following criteria:

- The capability of the DHW tank (DHW_{tank}) to maximize the part of solar DHW, expressed in litres per unit. The space allocated to the device should not be too large and has to be in agreement with the estimated building DHW needs.
- The respective solar PV ($RESol_{PV}$) and thermal panels ($RESol_{ther}$) surfaces. These two surfaces are dependent on each other. Unit is kW_{peak} for both.
- The power of the vertical axis windmill (W_{wind}), expressed in kW_{peak}.

So, as depicted by equation (3), one can formulate the optimization problem in the following way:

$$\min_{DHW_{tank}, RESol_{ther}, RESol_{PV}, W_{wind}} (E_{imp}) \quad (3)$$
$$75l < DHW_{tank} < 500l$$
$$1\ kW_{peak} < RESol_{ther} < 30\ kW_{peak}$$
$$0.5\ kW_{peak} < RESol_{PV} < 6\ kW_{peak}$$
$$0.2\ kW_{peak} < W_{wind} < 6\ kW_{peak}$$

Table 3 summarizes the results we obtained during a 1-year simulation using the model of the 150 m^2 standard building located in Perpignan, facing south and inhabited by 4 persons. These results are given according to the building insulation (RT2005, 80's type insulation and "no insulation"). Whatever the building's configuration (NR: no exploitation of renewable resources, Std: standard energy production and storage systems, RS: right-sized energy production and storage systems), the ventilation controller and occupancy scenarios were used. Figures 15 (1st case; daily load curves are given for a cold day) and 16 (2nd case; no energy needs related to HVAC appliances) depict the load curves we obtained, the building (RT2005 insulation) being equipped with standard (red curve; design is related to profitability) or right-sized (blue curve) energy production and storage systems. As expected, the right sizing of energy production and storage systems allows minimizing the energy impact of the considered building on the electricity grid. Taking as a reference the building not equipped with energy production systems, one can note that E_{imp} is reduced of about 33% (RT2005), 40% (80's type insulation) and 65% ("no insulation") when these systems as well as the DHW tank are right sized. With the same reference, E_{imp} is increased of about 41% (RT2005) and 2% ("no insulation") while it is reduced of about 5% (80's type insulation) when both the energy production and storage systems are standardly sized. The standard design of energy production and storage systems related to profitability leads to a worse energy impact than when these systems are right sized (17 vs. 8 with RT2005, 19 vs. 12 with a 80's type insulation and 50 vs. 17 without insulation). Taking again as a reference the building not equipped with energy production systems, and as a result of energy production, the amount of energy injected to the grid increases while the amount of energy purchased from the grid decreases (with standardly or right-sized systems, whatever the insulation type). As expected, a good insulation reduces both the energy impact and the overall consumption of energy. One can also remark, first, that the part of the production consumed *in situ* is globally stable with standardly or right-sized energy production and storage systems, whatever the insulation (34% vs. 33% with RT2005, 44% vs. 42% with a 80's type insulation and 54% vs. 60% without insulation) and, secondly, that the energy impact and the DPE result are correlated. One can note that the load curves variability is reduced.

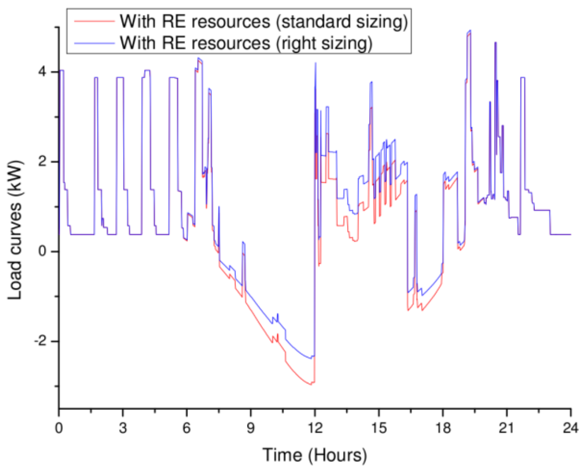

Figure 15 Daily load curves (cold day) (RT2005)

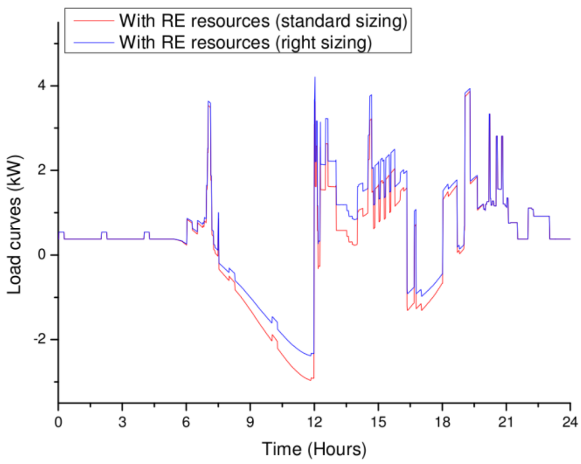

Figure 16 Daily load curves (hot day) (RT2005)

Looking at Figures 15 and 16, one can remark that when the balance is negative (consumed energy < injected energy) amplitudes are reduced. As a result of the right sizing of energy production and storage systems, energy production is clearly reduced (taking as a reference standardly-sized systems) to better meet the building's energy needs. The overall (anual) amount of energy injected to the electricity grid is also significantly reduced (this can be generalized whatever the insulation type). One can highlight that the approach we proposed allows better managing of renewable energy resources and overcoming the intermittence of the renewable energy production.

Table 3
Results (1-year simulation)

Insulation	*RT2005*			*80's type*		
Configuration	*NR*	*Std*	*RS*	*NR*	*Std*	*RS*
DHW_{tank} (l)	300	300	300	300	300	300
$RESol_{PV}$ (kW_{peak})	0	3.5	3	0	3.5	3
$RESol_{ther}$ (kW_{peak})	0	8	4	0	18	8
W_{wind} (kW_{peak})	0	6	2	0	10	3
EPD (-)	B	B	B	C	C	C
E_{imp} (-)	12	17	8	20	19	12
$Ener_{consump}$ (GWh)	13.5	13.5	13.5	22	22	22
$Ener_{self\text{-}consump}$ (GWh)	0	4.25	1.32	0	7.5	5.6
$Ener_{produc}$ (GWh)	0	12.5	4	0	17	13.4
$Ener_{injec}$ (GWh)	0	8.25	2.68	0	9.5	7.8
Balance (GWh)	13.5	1	9.5	22	5	8.6

Insulation	*None*		
Configuration	*NR*	*Std*	*RS*
DHW_{tank} (l)	300	500	300
$RESol_{PV}$ (kW_{peak})	0	3	6
$RESol_{ther}$ (kW_{peak})	0	30	18
W_{wind} (kW_{peak})	0	16	2
EPD (-)	D	D	D
E_{imp} (-)	49	50	17
$Ener_{consump}$ (GWh)	31	31	31
$Ener_{self\text{-}consump}$ (GWh)	0	17	13
$Ener_{produc}$ (GWh)	0	32	22
$Ener_{injec}$ (GWh)	0	15	9
Balance (GWh)	31	-1	9

CONCLUSION

The present paper deals with evaluating and minimizing the energy impact of buildings on the electricity grid. Thus, we proposed a method to define this impact and we developed several building models (including energy production and storage systems) to validate the proposed approach in simulation. Moreover, fuzzy logic allowed taking into account expert knowledge with the aim of defining occupancy scenarios and a ventilation controller. Finally, an active-set strategy was used to find the right dimension of the production and storage systems allowing the energy impact to be clearly minimized. The results we obtained highlight the proposed approach relevance: thanks to the right sizing of production and storage systems (in France these systems are usually designed according to profitability), the power purchased from the grid is reduced while the produced energy is partially self-consumed. Future work will now focus, first, on carrying out the same study considering industrial buildings (with the aim of quantifying the influence of business activities) and, secondly, on aggregating all the building models we developed to quantify the energy impact of a district on the electricity grid. Moreover, the proposed approach, dealing with the reduction of the energy impact of buildings thanks to the right sizing of energy production and storage systems, will be tested in instrumented real buildings.

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