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Methodology for the design of energy production and storage systems in buildings: minimization of the energy impact on the electricity grid

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Abstract: human life requires energy. Moreover, 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 methodology allowing identifying and assessing the energy impact of a building on the electricity grid. Thanks to both the building models we developed and fuzzy logic contribution (used to control ventilation and develop occupancy scenarios related to human habits and lifestyle), the results we obtained in simulation validate the proposed impact indicator. Different insulation levels were considered as well as energy production (solar photovoltaic and thermal panels and a vertical axis windmill) and storage (a domestic hot water tank) systems. These results highlighted the pertinence of such an indicator for optimizing the design of the just-mentioned systems and minimizing the amount of energy exchanged by buildings and the electricity grid. One can promote energy injection or take into account the status of the electricity grid when designing these systems. As a key result, the produced renewable energy is partially self-consumed, what allows for a more efficient and rational use of energy in buildings.

Keywords: buildings, modelling, fuzzy logic, energy production and storage systems, HVAC appliances, energy self-consumption, right sizing.

1. Introduction

Sustaining human life requires energy. Without energy, everything around us will be stopped. 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 France, about 25% of greenhouse gas emissions and 45% of energy consumption are due to buildings), in numerous countries laws give obligation to reduce buildings energy need while tax assistance has greatly increased sales of decentralized renewable energy production systems [1,2]. The concept of decentralized energy is a significant change to the classical approaches dealing with energy production, supply and networks which have been prevalent in France (and in many other countries) during the last decades. An increasing use of decentralized energy (on a long-term basis solar and wind power could represent about 40% of the global electricity production) will mean that both the size and the direction of the power flows in networks will be less predictable than in the centralized model. This leads to the need for more active network management, flexible voltage control as well as sophisticated fault detection and safety procedures [3,4]. Integration issues and grid operation will be key questions for these renewable energy sources. Hammons [5] highlighted that, due to the expected large-scale penetration of dispersed and renewable energy sources, distribution networks will become more active while communication networks have to be established for that purpose. Moreover, the current change of the electricity supply structure towards more and more decentralized power generation requires changes to current safety, control and communication technologies. Known problems include, but are not restricted to, induced harmonics, voltage flicker, system reliability or voltage fluctuation due to a very large deployment of decentralized production systems [6-10]. One of the most critical parameters limiting such a deployment in an already existing grid is overvoltage. This can occur when supply exceeds consumption. This can lead to physical damage [11,12]. As another key point, and although load control is not strictly a decentralized energy issue, the use of more intelligent load control schemes is highly complementary to decentralized energy supply. Indeed, for many appliances the time they run is not critical within limits [13].

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There is a great potential for simple devices to activate these appliances at the appropriate time (in France, Heating Ventilation and Air-Conditioning (HVAC) systems represent about 35% of the overall energy consumption of buildings). Various works showed that a study dealing with human factors, habits and energy needs as well as availability of energy resources is of paramount interest for the design of facilities [5,14,15]. Furthermore, an increasing decentralized production of energy will require changes to the way in which the energy sector is regulated [3]. Of course, renewable energy is a way to reduce fossil energy dependence as well as greenhouse gas emissions [16,17]. As an interesting feature, Sovacool [18] highlighted that, contrary to proclamations stating otherwise, the more the renewable production is deployed, the more stable the system becomes. Indeed, wind- and solar-produced power is very effective when used in large numbers in geographically spaced locations. Moreover, conventional power plants operating on coal, natural gas and uranium suffer variability related to construction costs, short-term supply and demand imbalances, long-term supply and demand fluctuations or volatility in the price of fuels... So, objections to the integration of the renewable energy production may be less about technical limitations and more about tradition, familiarity and arranging social or political order. In case of a large deployment of renewable energy production systems, their impact on the electricity grid will be significant [19]. Indeed, one can highlight an increase of both the amount of energy passing through the grid [20] and the power demand amplitude, as well as a rapid fluctuation of demand [21,22]. To minimize the impact of an intermittent production, energy storage systems can be used [23], but devices are not enough efficient. Hadjipaschalis et al. [24] highlighted that batteries are the dominant technology to be used when continuous energy supply is paramount, while technologies such as flywheel and super capacitors are more suited to power storage applications and where very brief power supply is required. Energy mix could also be a solution for extending production time and the amount of energy produced [16].

Mainly due to the intermittent nature of the renewable production, one can also note a significant increase of both the frequency and the amount of energy exchanged between buildings incorporating such systems and the electricity grid. This is a key point when trying to quantify the impact buildings have on the electricity grid. That is why 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 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 very hard task. In France, such a 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. As a contribution to the necessary development of tools used to manage the decentralized production of renewable energy, the present paper deals with a method allowing identifying and assessing the energy impact of buildings on the electricity grid. So, the aim of the present work was first to develop pertinent building models and to generate simulation data for evaluating the just-mentioned impact [25]. TRNSYS [26] and the SIMBAD toolbox [27] for MATLAB were used to model the thermal behaviour of typical residential buildings, offices and factories one can find across Europe. User profiles were exploited to highlight the way energy is consumed. DAYSIM [28] allowed simulating artificial lighting. Different insulation levels were considered (mainly 80's type and RT2005 insulations) [29] as well as energy production (solar photovoltaic and thermal panels and a vertical axis windmill) and storage (a domestic hot water tank) systems. The design of pertinent models and scenarios is not an easy task. That is why expert knowledge about human habits and lifestyle was considered through fuzzy approaches [30,31]. The results we obtained in simulation validate the proposed impact indicator. Moreover, they highlighted the pertinence of such a tool for optimizing the design of the just-mentioned systems and minimizing the amount of energy exchanged by buildings and the electricity grid. An optimization algorithm, based on an active-set strategy, was used to find the right dimension of energy production and storage systems [32] allowing the proposed criterion to be minimized. One can promote energy injection or take into account the status of the electricity grid when designing these systems. The produced renewable energy is partially self-consumed. Let us remember that, in France, as well as in other countries, these systems are usually designed according to profitability consideration only (one speaks in the present paper of "standard energy production and storage systems"), while the renewable energy produced is fully injected to the electricity grid. Energy self-consumption allows for a more efficient and rational use of energy, as it would imply significant savings in electricity distribution and transport costs and a reduction in the need to invest in new networks.

2. Energy Performance Diagnosis

Quantifying energy efficiency is the goal of the French "Energy Performance Diagnosis" (EPD) [1]. This diagnosis informs about thermal specifications (heating, production of hot water...) and allows estimating the energy consumed by a given building according to HVAC appliances. The UK has nearly the same evaluation system, named "Building Energy Ratings" (BER). In a BER the building is scored based on how much energy it requires for space heating (and cooling), water heating and lighting. Both the EPD and the BER take into account building layouts, construction details for walls, floors and roofs, window and door types as well as heating systems and controllers and ventilation details. The EPD result is given on the following scale for low to high-energy consuming buildings (i.e., from energy-efficient to energy-guzzling housing): A (less than 50 $kWh.m^{-2}.year^{-1}$), B (51 to 90 $kWh.m^{-2}.year^{-1}$), C (91 to 150 $kWh.m^{-2}.year^{-1}$), D (151 to 230 $kWh.m^{-2}.year^{-1}$), E (231 to 330 $kWh.m^{-2}.year^{-1}$), F (331 to 450 $kWh.m^{-2}.year^{-1}$) and G (more than 450 $kWh.m^{-2}.year^{-1}$). 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 very poor credibility. In addition, a new report of the French DGCCRF (Direction Générale de la Concurrence, de la Consommation et de la Répression des Fraudes) [33] revealed many problems 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 management 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 the magnitude of both the power demand and the power injected to the electricity grid.

3. 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 [31].

3.1. Data acquisition

First, we need data to calculate the real-time energy impact of a building. One can do it as follows: (1) By software simulation, for example using TRNSYS [26], which is able to simulate the thermal behaviour of a building, using its previously defined model. Synchronized with MATLAB [34], one can define various 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. (2) 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 French energy performance diagnosis). 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: playing on thermal insulation. Let us note that this solution is always a compromise: in winter, the insulation level has to be sufficient to reduce HVAC needs while the fatal heat produced by occupants as well as electrical devices and equipments needs to be evacuated in summer. This solution is not directly considered in the present paper. However, we studied the impact of different insulation levels on energy performance.

3.2. Real-time energy impact of a building

First, we define, for a building connected to the electricity grid and equipped with energy production and storage systems, 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:

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

3.3. Energy impact of a building on the electricity grid

Next, the energy impact of a given building on the electricity grid can be expressed as a sum by equation (2), with W_{max} the maximal value of the power demand (or the electric power produced and injected to the grid) during a time interval, k a coefficient to be fixed, n_{up} the upper limit of the study interval (time step is set to 1 minute) and P_{status} a corrective term dealing with high fluctuations in load curves and changes in the building status (from producer to consumer or from consumer to producer) (equation (3)):

$$E_{imp} = \frac{\sum_{n=1}^{n_{up}} e^{k \times \frac{\left|E_{impRT}(n)\right|}{W_{\max}}} + P_{status} - 1}{n_{up}} \tag{2}$$

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 (i.e. the power subscribed for the building). 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 (k) before using the exponential function, as depicted by equation (2). The choice of k is free and related to insulation efficiency and the good or bad behaviours about energy use and management in buildings you want to highlight.

Table 1. Values of k_1 related to European electricity grids.

Country	*Adequate value of k_1*	*Good behaviour (% of W_{max})*	*Bad behaviour (% of W_{max})*
Poland	*2.7*	*0-87*	*88-100*
France	*3*	*0-78*	*79-100*
Spain	*3.2*	*0-74*	*75-100*
Germany	*3.5*	*0-68*	*69-100*
Switzerland	*4*	*0-59*	*60-100*
Italy	*4.5*	*0-52*	*53-100*

Table 1 summarizes the main values (noted k_1) one can assign to k, according to the electricity grid you want to consider. These values have been chosen based on a statistical analysis of the load curves of different buildings from various countries [35]. When looking at the daily load curves of French buildings, 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. That is why three is an interesting value allowing defining bad behaviours when the power exchanged between a given building (whatever its use and insulation level) and the grid exceeds, during the considered time interval, about 75% of W_{max}. In this case, the equipment used is mismanaged, some electrical devices being for example plugged simultaneously and in a redundant way. As a result, below 75% of W_{max}, the power exchanged between the building and the grid can be considered as reasonable. Figure 1 depicts the way P_{status} can be worked out, depending on both the time index (n) and variations in the considered load curve (Δ_{load}) during a time interval, according to the maximum value of the power consumed or injected to the electricity grid during a time interval (W_{max}). Table 2 shows the appropriate values of both parameters k_2 and k_3, according to n. These values have been empirically tested and validated. As previously mentioned, we considered a time step of 1 minute. This choice impacts the analysis' relevance. Δ_{load} is expressed by equation 3, with E_{impRT} the real-time energy impact of a building connected to the electricity grid:

$$\Delta_{load} = \frac{\left|E_{impRT}(n) - E_{impRT}(n-1)\right|}{W_{max}} \tag{3}$$

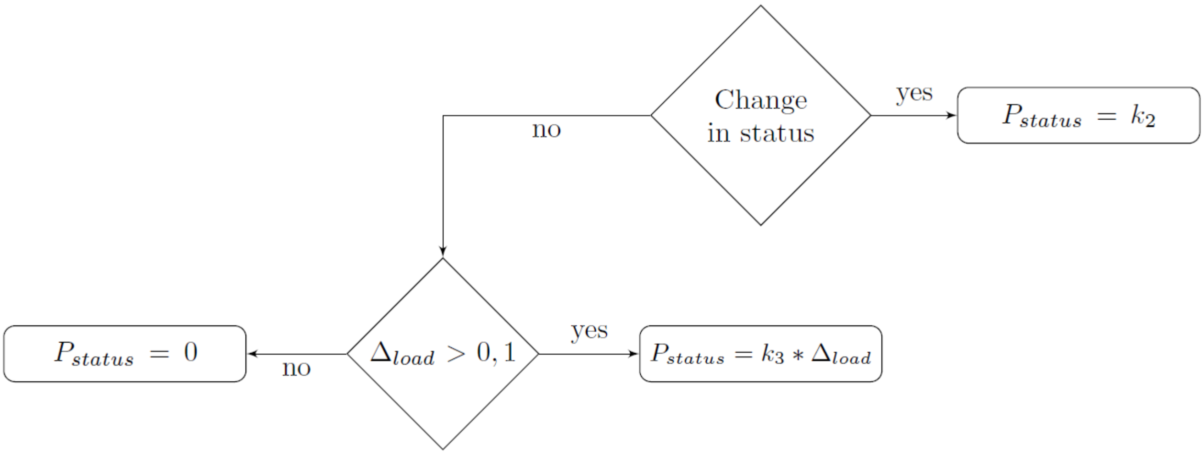

Figure 1. Calculation of P_{status}.

Table 2. Values of k_2 and k_3 related to the time step.

Time step	*Adequate value of k_2*	*Adequate value of k_3*	*Analysis*
1 second	*1*	*20*	*Good*
30 seconds	*5*	*12*	*Excellent*
1 minute	*10*	*10*	*Excellent*
2 minutes	*15*	*9*	*Good*
5 minutes	*17*	*7*	*Right*
10 minutes	*20*	*5*	*Fairly good*
20 minutes	*30*	*2*	*Bad*
30 minutes	*50*	*n.a.*	*Impossible*
60 minutes	*100*	*n.a.*	*Impossible*

As a practical application of the E_{imp} indicator we developed, one can use it to size decentralized production and storage systems while promoting the injection of electricity (option 1, Figure 2) or taking into account the status of the grid (option 2, Figure 3). As a result and whatever the option, the amount of energy exchanged by buildings equipped with such systems and the electricity grid will be minimized. Such options impact on both the calculation of the energy impact of a given building and the design of the just-mentioned systems. Both options are only suitable for such an objective. With option 1, one will pragmatically favour positive-energy buildings. With option 2, one will inject electricity uppermost when the grid needs electricity and the building's needs are met. k_4 (option 1, Table 3), k_5, k_6 and k_7 (option 2) are parameters to be optimized according to energy use and management considerations. k_4 is defined according to the injection amplitude. k_5, k_6 and k_7 are chosen according to the characteristics of the electricity grid you consider (for the French load curves, $k_5 = 0.5$, $k_6 = 3$ and $k_7 = 1$ are adequate values). Finally, Table 4 describes the proposed E_{imp} scale dealing with energy efficiency in buildings and occupants' habits and customs. Let us note that in some particular cases, one can formulate different hypothesis about the just-mentioned considerations. For example when $10 \leq E_{imp} < 15$ (Table 4), such an energy impact on the electricity grid can be the result of an energy efficient building with right-sized energy production and storage systems as well as good occupants' habits and customs or the result of an energy efficient building (energy production and storage systems were not designed with the aim of minimizing the energy impact of the considered building) as well as exemplary and restrictive habits and customs.

Table 3. Values of k_4 related to the injection amplitude.

Value of k_4	*Injection amplitude related to the design of energy production systems (reference: option 1 disabled)*
$0.2 \times k_1$	*Low increase*
$0.3 \times k_1$	*Moderate increase*
$0.5 \times k_1 < k_4 < 0.7 \times k_1$	*Significant increase*
$0.8 \times k_1 < k_4 < k_1$	*Very important increase*

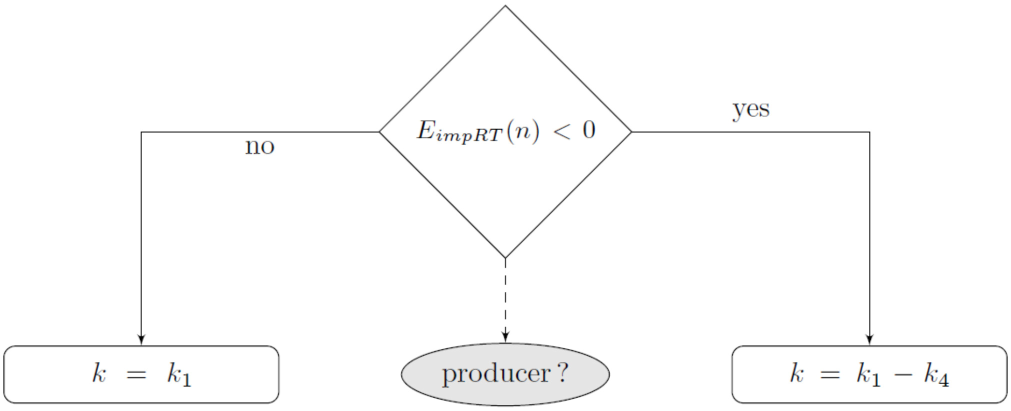

Figure 2. Promoting the injection to the electricity grid (option 1).

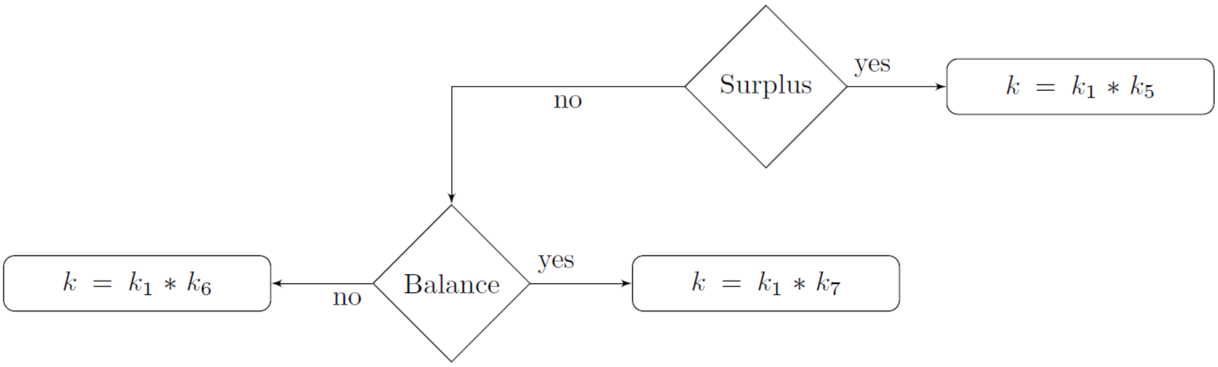

Figure 3. Taking into account the electricity grid status (option 2).

Our objective is not to replace the EPD but to provide additional information. In this sense, the load curve of a building reveals their occupants' habits and customs. The proposed indicator can help to highlight them. 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. Let us note that "self-consumption" has to be handled with care. Theoretically, in France, the decentralized production of energy is completely sold to energy traders. These traders buy 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.

Table 4. Proposed E_{imp} scale.

E_{imp}	Case	Building	Occupants' habits and customs
$E_{imp} < 5$	-	*Energy efficient + Right-sized energy production and storage systems*	*Exemplary and restricitive*
$5 \leq E_{imp} < 10$	-	*Energy efficient + Right-sized energy production and storage systems*	*Exemplary*
$10 \leq E_{imp} < 15$	*Case 1*	*Energy efficient + Right-sized energy production and storage systems*	*Good*
	Case 2	*Energy efficient*	*Exemplary and restrictive*
$15 \leq E_{imp} < 20$	*Case 1*	*Energy efficient + Right-sized energy production and storage systems*	*Bad*
	Case 2	*Good thermal charcateristics*	*Good*
$20 \leq E_{imp} < 50$	-	*Decent thermal characteristics*	*Fairly good*
$50 \leq E_{imp} < 100$	-	*Bad thermal characteristics*	*Bad*
$E_{imp} \geq 100$	-	*Very bad thermal characteristics*	*Fooling*

4. Modelling process

After formulating the E_{imp} indicator, 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. As previously mentioned, TRNSYS [26] and the SIMBAD toolbox [27] for MATLAB were used to model the thermal behaviour of typical residential buildings, offices and factories one can find across Europe. User profiles were exploited to highlight the way energy is consumed. DAYSIM allowed simulating artificial lighting [28]. These tools were connected to each other. DAYSIM used sunshine data and, according to the structure of the considered buildings, simulated artificial lighting needs. As a result, TRNSYS defined the way artificial lighting was used in these buildings. Let us note that we considered real meteorological data with a time step of 1 minute (data come from a meteorological station situated at Perpignan University), what allowed developing specific occupancy scenarios and taking into consideration specific uses of household appliances. Sections 4.1 and 4.2 focus on the models features and the two standard building models we considered for the study. All the models we developed were validated thanks to energy consumption data coming from various private houses and industrial buildings. Moreover, scenarios dealing with occupants' habits and customs as well as industrial activities were developed after collecting information among a panel of representative people. As a result, all these models are representative of what energy use in European buildings is.

4.1. The developed building models: overview

- *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 (2010/2011) buildings 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 functional with different insulation levels (mainly 80's type and RT2005 insulations) (Section 4.2) [1] and occupancy scenarios (1 to 5 people with restrictions according to the building's surface). All the possible combinations are not yet modelled; our objective is to develop the maximum number of models, fully representative of the whole European building park.

4.2. French thermal regulation RT2005 [1]

The French RT2005 (thermal regulation 2005) applies to new buildings whose planning applications were submitted after September 1st, 2006. However, it does not apply to buildings with a temperature of use lower than 12°C, to swimming pools, ice rinks, breeding farms, and also to buildings having to guarantee specific temperature, hygrometry and air quality conditions because of their final use requirements. Regulation is based on primary energy consumption and indoor comfort. Both have to be lower than reference values. In addition, some equipments (windows for instance) are designed according to boundary values. Because of the geographical and climatic disparity of France, RT2005 defines eight climate zones while solar protection is indirectly taken into consideration. RT005 also applies when equipments are added or replaced in existing buildings, except for temporary buildings and low-energy consuming buildings. In this case, only new equipments are concerned by the regulation process.

4.3. Standard building models

The present section deals with the two standard buildings models we used to test the pertinence of the proposed impact indicator. The first one describes a dwelling while the second one describes an industrial building whose activity focuses on moulding plastic products. Both are located in Perpignan. As a result, one can take into account occupants' habits and customs as well as industrial activities.

4.3.1. Single storey house

4.3.1.1. Model features

We considered as first 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 (Section 4.2) [1]. We considered two variants dealing with a building built in 1986 and a non-insulated building. Lifestyle habits were modelled. Although other building types and 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 [36]. Finally, thermal regulation policy is dependent on the building age [37]. The following materials were considered, according to the building insulation:

- *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 walls are composed of the following layers: 13 mm of plasterboard, 200 mm of insulator, 70 mm of cinderblock, 20 mm of plaster patching, 1 mm of glass cloth, 20 mm of plaster patching, 4 mm of primary and a skim coat of 30 mm. Insulation is external.

- *80's type insulation (1986)*: windows with double-glazing (4x8x4) without gas layer for the small ones and an aluminium cold structure for the taller ones. External walls are composed of the following layers: 10 mm of plasterboard, 50 mm of insulator, 100 mm of cinderblock and a skim coat of 10 mm [38]. Insulation is external.

4.3.1.2. Daily load curves

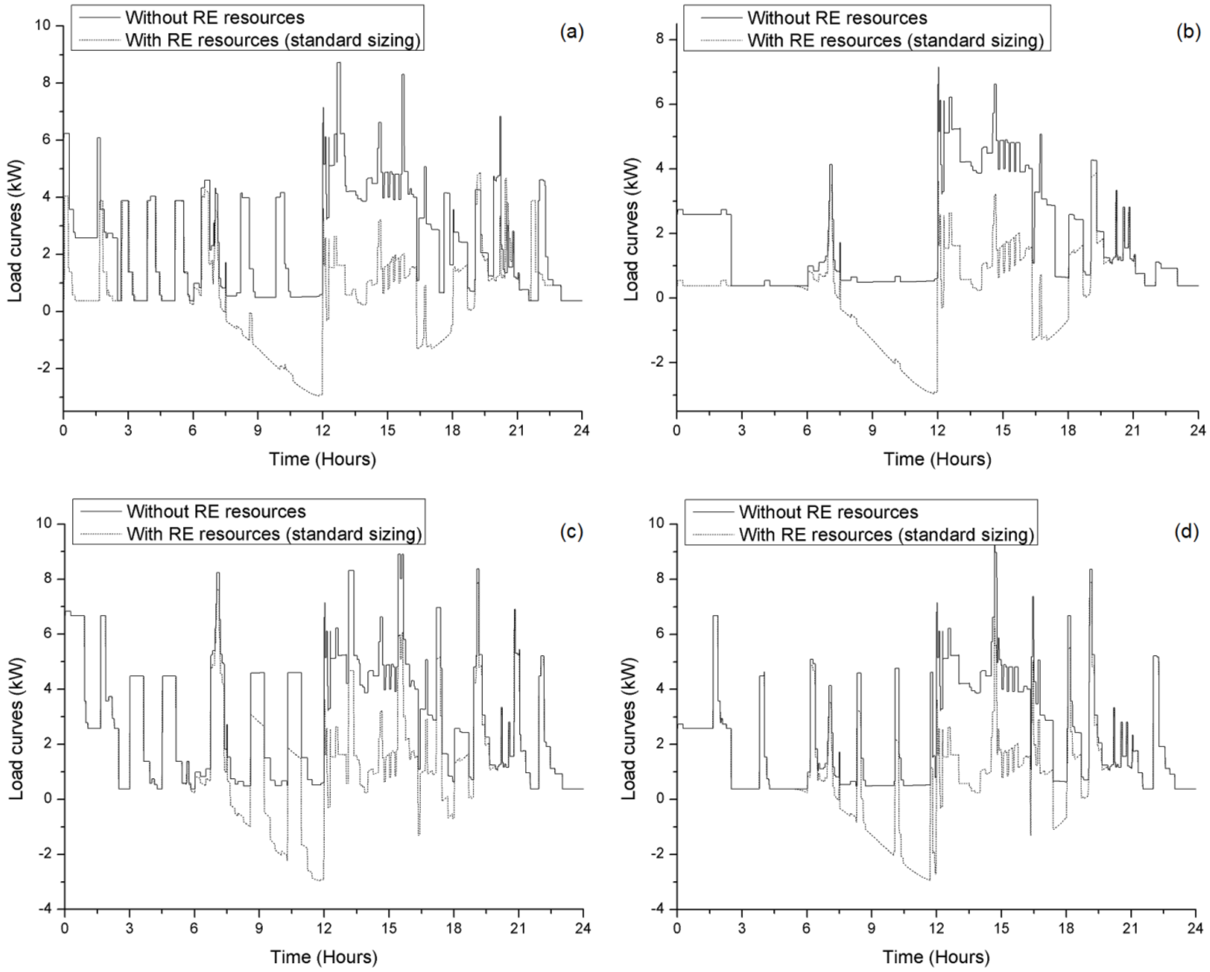

Figure 4. Daily load curves (single storey house).
(a) Cold day and RT2005 insulation. (b) Hot day and RT2005 insulation. (c) Cold day and 80's type insulation. (d) Hot day and 80's type insulation.

Figures 4a and 4b depict the typical daily load curves we obtained using the developed standard building model (RT2005 insulation), the building being equipped (dotted line) or not (solid line) 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 4a highlights energy needs related to HVAC appliances (1st case; load curves are given for a cold day) while Figure 4b 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 very 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, analyzing these curves, one can relate human comfort and the building electricity needs. Figures 4a and 4b illustrate the reason why the E_{imp} indicator is needed and why it has to be minimized. During the first hours of the day, photovoltaic 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 photovoltaic 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, photovoltaic cells are not able to produce energy while energy is clearly needed. Figures 4c and 4d depict the daily load curves we obtained with a 80's type insulation. Again, the building was equipped (dotted line) or not (solid line) with production systems whose design was standard and related to profitability. Similar conclusions can be reached. However, looking at Figures 4c and 4d, one can easily observe that a worst insulation impacts on the variability of the building's load (whatever the considered day). Variability is clearly increased, especially during the first hours of the day, what increases the frequency of changes in the building status (from producer to consumer or from consumer to producer). The amplitude of the peaks is also increased.

4.3.2. Industrial building for the moulding of plastic products

4.3.2.1. Model features

The second standard building we considered is a 3600 m^2 two-level industrial building, located in Perpignan, whose activity deals with the moulding of plastic products. Insulation is standard for such a building. Parts of the building are dedicated to offices (ground floor, 120 m^2) and for stocking raw material (level 1, 120 m^2). Solar thermal panels, photovoltaic panels and a vertical axis windmill can be integrated to the building. Its flat roof in asphalt allows the water to run off freely from a very slight inclination. Glass wool is used as insulation material. Available height is about 4.5 m in the production room, 2.3 m in offices and, finally, 2.2 m in the stocking room. External walls are composed of galvanized steel layers as well as Thermotop panels of about 70 mm and made of high-density extruded polystyrene. The floor is a concrete slab of 160 mm, 80 mm of extruded polyurethane being used as insulation material. Wax is used as coating in both the production and stocking rooms. Offices come equipped with tiled floor.

4.3.2.2. Daily load curves

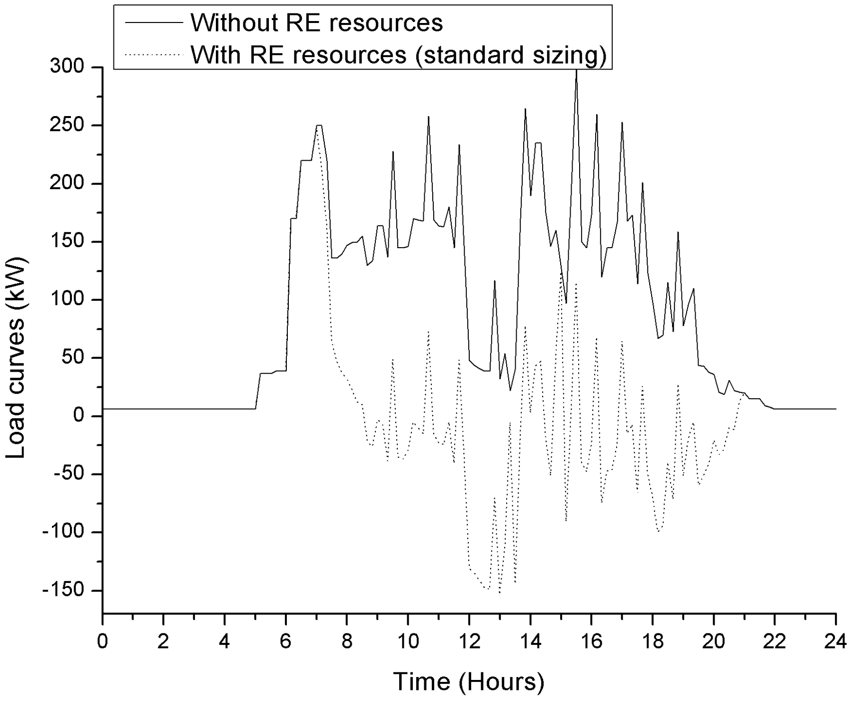

Figure 5. Daily load curves (industrial building with standard insulation, typical day).

As previously mentioned, the industrial activity concerns the moulding of plastic products. Figure 5 depicts the typical daily load curves we obtained (the considered day is a spring day, not too cold or too hot) using the developed industrial building model, the building being equipped (dotted line) or not (solid line) with production systems. In this case, the design of the just-mentioned systems is standard and related to profitability (no windmill; PV and thermal panels on the whole building's roof). We considered a DHW tank of 500 litres. Again, 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). Taking a look at Figure 5, one can explain the load curves we obtained as follows. First, a part of the energy consumed is due to security equipment (security light, signalling devices, fire alarm...). Preheating of pouring systems is carried out between 6 a.m. and 7:30 a.m. Pressurization of pneumatic systems ends 30 minutes before the beginning of the production process. Between 10 a.m. and 12 a.m., as well as between 2 p.m. and 6:30 p.m., one can note some peaks dealing with surfacing phases. At 12 a.m., the production process is suspended. Industrial activity starts again at 2 p.m. and slows down after 5 p.m. The just-mentioned activity is stopped at 6:30 p.m. Office clerks work until 8 p.m. Finally, one can remark that, when the considered building is equipped with standardly-sized energy production systems, the balance between consumed energy and injected energy is at times negative and at times positive while it is always positive without renewable production of energy.

4.4. 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. In some cases, a simple time scale deviation allowed satisfying our precision criterion. For example, the common use of dishwashers was easily modelled. Other complex human actions, such as shutters and windows opening actions, or related to temperature regulation, require considering expert knowledge. In this sense, fuzzy logic was used to develop occupancy scenarios and control ventilation, with the aim of improving real-time simulation and contributing to the minimization of the energy impact of buildings [31,39].

5. Fuzzy logic contribution

Let us just remember that the concept of fuzzy sets deals with the representation of classes whose boundaries are not quite determined. So, fuzzy sets are generally used for representing linguistic labels and can be defined by exemplification, ranking elements according to their typicality with respect to the concept underlying the sets. They preserve a gradual and smooth transition from one category into another and avoid abrupt discontinuities [40]. The specifications thus become more robust and adaptive. Fuzzy sets provide a tool for bridging the gap between the perceived continuity of the world and human discrete cognitive representation. In particular, fuzzy sets help with interfacing numerical data and symbolic labels. Their ability and possibility theory to model, while designing a set of fuzzy rules, gradual properties whose satisfaction is a matter of degree, as well as information pervaded with imprecision and uncertainly, makes them useful in a great variety of applications [41-46]. In particular, fuzzy systems are suitable when mathematical models are difficult to derive.

5.1. Single storey house

5.1.1. Occupancy scenarios

First, fuzzy logic is used to model the multi-energy building occupancy. The scenario we proposed allows managing fatal heat production as well as electronic devices and household appliance. It is based on inhabitants' presence, meteorological data and traffic. Considering the fuzzification of the inhabitants' presence coefficient (its universe of discourse is [-0.5; 1.5]), Gaussian membership functions were used. Such functions favour 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. Considering the fuzzification of weather conditions (its universe of discourse is [0; 1]), 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). Considering the fuzzification of Direct Normal Irradiance (DNI) (its universe of discourse is [0 W.m^{-2}; 300 W.m^{-2}]), 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. Considering the fuzzification of traffic (its universe of discourse is [0%; 100%]), 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. Then, we carried out the fuzzification of occupancy (its universe of discourse is [0%; 100%]), considering "day" (garage, laundry room, kitchen, dining room…) and "night" (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 behaviour 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). Finally, Table 5 depicts the design of the fuzzy rules (for a total of 19 rules). Each rule has two conclusions, the 1st one for "day" rooms and the 2nd one for "night" rooms ("•" means "whatever the fuzzy set").

Table 5. Fuzzy rules for occupancy (single storey house).

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

5.1.2. 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. The universes of discourse of T_{in}, T_{out} and FS are [15°C; 35°C], [0°C; 45°C] and [0 r.min^{-1}; 3000 r.min^{-1}], respectively. 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). 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. Then, we carried out 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, 0 r.min^{-1}), S1 (Speed 1, 1000 r.min^{-1}) and S2 (Speed 2, 3000 r.min^{-1}). Finally, Table 6 depicts the design of the fuzzy rules (for a total of 21 rules) used to control ventilation. This design was the result of a statistical study dealing with activation frequency during simulation time (among all the rules we proposed initially, only rules with a significant activation frequency were kept). The same process was carried out to design the occupancy rules (Table 5). One can note that some situations, dealing with exceptional weather conditions, are not correctly treated with the proposed fuzzy rules. In this case, ventilation is stopped.

Table 6. Fuzzy rules for fan speed (single storey house).

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

5.2. Industrial building for the moulding of plastic products

Here, fuzzy logic is used to control ventilation only. Because of the difficulty in developing occupancy scenarios through inference systems for such an industrial building, we considered standard and generalized procedures. Because of the ambient temperature needed for a smooth functioning of the machines and the necessity of satisfying workers' thermal comfort, ventilation has to be efficiently controlled in industrial buildings. Moreover, ventilation is of paramount interest in case of fatal heat generation, in particular during the summer period. The fuzzy controller we proposed has two inputs, indoor (T_{in}) and outdoor (T_{out}) temperature, and one output, the fan speed (*FS*). The universes of discourse of T_{in}, T_{out} and *FS* are [10°C; 30°C], [0°C; 30°C] and [0 r.min^{-1}; 3000 r.min^{-1}], respectively. We used triangular, trapezoidal as well as singleton membership functions for T_{in} and T_{out} (4 fuzzy sets) as well as the following linguistic labels: Cd (Cold), Co (Cool), P (Pleasant) and H (Hot) for T_{in} and Cd (Cold), Co (Cool), H (Hot) and VH (Very Hot) for T_{out}. Again to reduce computation time, we used singletons as membership functions for *FS*. The following linguistic labels were associated to the three fuzzy sets: S (Stop, 0 r.min^{-1}), S1 (Speed 1, 1000 r.min^{-1}) and S2 (Speed 2, 3000 r.min^{-1}). Finally, Table 7 depicts the design of the fuzzy rules (for a total of 10 rules) used to control ventilation in industrial buildings ("•" means "whatever the fuzzy set"). Again, this design was the result of a statistical study dealing with activation frequency during simulation time.

Table 7. Fuzzy rules for fan speed (industrial building).

Rule	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
T_{in}	*Cd*	*Cd*	*Cd*	*Co*	*Co*	*Co*	*P*	*H*	*H*	*H*
T_{out}	*Cd*	*Co*	*H*	*Cd*	*Co*	*H*	•	*Co*	*H*	*VH*
FS	*S*	*S2*	*S2*	*S*	*S1*	*S1*	*S*	*S2*	*S1*	*S*

6. Right sizing of energy production and storage systems

6.1. Optimization problem

Thanks to the right sizing of energy production and storage systems, one can reduce the energy impact of a given 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. Let us remember that one can design the above-mentioned systems while promoting the injection to the grid of electricity (option 1) or taking into account the status of the grid (option 2) (Section 3.3). 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" or "nonlinear programming". The minimization of the energy impact (E_{imp}) of a building on the electricity grid 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 and related to power. Unit is kW_{peak} for both.
- The power of the vertical axis windmill (W_{wind}), expressed in kW_{peak}.

So, as depicted by equation (4), one can formulate the optimization problem related with the right sizing of energy production and storage systems as follows:

$$\min_{DHW_{tank}, RESol_{ther}, RESol_{PV}, W_{wind}} \left(E_{imp}\right) \tag{4}$$

The following constraints were defined according to the two buildings we considered as well as both technical and legal considerations: $75\ l \leq DHW_{tank} \leq 500\ l$, $0.5\ kW_{peak} \leq RESol_{PV} \leq 6\ kW_{peak}$, $1\ kW_{peak} \leq RESol_{ther} \leq 30\ kW_{peak}$ and $0.2\ kW_{peak} \leq W_{wind} \leq 6\ kW_{peak}$ for the single storey house and $75\ l \leq DHW_{tank} \leq 5000\ l$, $0.5\ kW_{peak} \leq RESol_{PV} \leq 270\ kW_{peak}$, $1\ kW_{peak} \leq RESol_{ther} \leq 80\ kW_{peak}$ and $0.2\ kW_{peak} \leq W_{wind} \leq 100\ kW_{peak}$ for the industrial building.

6.2. Active set strategy

For solving nonlinear optimization problems, two competing iterative approaches are available: active-set methods and interior-point methods. Although interior-point methods for nonlinear programming have become popular for their ability to efficiently solve large-scale problems with many inequality constraints, active-set methods still constitute an important tool for solving nonlinear optimization problems. Active-set methods are often able to provide more exact solutions and sensitivity information with a clear identification of the active constraint set compared to interior-point methods. Moreover, active-set methods can more effectively make use of a good starting point in a "warm start" procedure (for example, when solving a sequence of closely related problems). In addition, active-set methods are sometimes more stable than interior-point methods as they seem less sensitive to the choice of the initial point and to the scaling of the problem. For these reasons, active-set methods remain popular and there has been a considerable ongoing effort to improve them [47-49]. The traditional Sequential Quadratic Programming (SQP) method [50,51] has proved to be robust and efficient if the number of degrees of freedom in the problem is not too large. However, efficient implementations of contemporary SQP methods require one to form and factorize a reduced Hessian matrix at each outer iteration. Even if the Hessian matrix is sparse, the reduced Hessian will, in general, not be sparse, making this approach often prohibitively expensive for problems with more than a couple thousand degrees of freedom. Active-set algorithms can solve optimization problems with equality and inequality constraints. Method name comes from the classification of constraints, which divides them into active at the current point and inactive ones. The method reduces equality/inequality constrained problem to a sequence of equality-only constrained sub-problems. Active inequality constraints are treated as equality ones while inactive ones are temporarily ignored (although they still be tracked). As a result, this method consists of two nested iterations: inner and outer ones. Outer iterations include two stages: at the first stage of the outer iteration equality-constrained sub-problems (inner iterations) are solved. Some constraints can be activated during the process. This stage is over after inner stopping conditions are met. At the second stage of the outer iteration, constraints can be activated or deactivated. The process can also be stopped at this stage, if outer stopping conditions are met. One can highlight that current point travels through feasible set, "sticking" to or "unsticking" from boundaries. The most important feature of active set algorithms is that this method is easy to implement for problems with linear constraints. Equality-constrained sub-problems can be easily solved by projection onto subspaces spanned by active constraints. In the linear case, the active-set method outperforms its main competitors (penalty, barrier or modified Lagrangian methods). In particular, constraints (both boundary and linear) are satisfied with much higher accuracy [52-54]. In an attempt to overcome some of the bottlenecks of the traditional SQP approach, there has been resurgence in recent years in the so-called "EQP" (Equality Quadratic Programming) form of sequential quadratic programming. Instead of solving quadratic programming sub-problems with inequality constraints, these methods first use some auxiliary mechanism to generate an estimate of the active set, and then solve an equality constrained Quadratic Program (QP) at each iteration, imposing the constraints in the active-set estimate as equalities and temporarily ignoring the other constraints. The Sequential Linear-Quadratic Programming (SLQP) algorithm, first proposed by Fletcher et al.

[55] is one such method. This approach estimates the active set at each iteration by solving a Linear Program (LP) based on a linearization of the nonlinear program at the current iterate.

6.3. Significant results

6.3.1. Single storey house

Table 8 summarizes the results we obtained in simulation (for a 1-year period) using the model of the 150 m^2 single storey house located in Perpignan, facing south and inhabited by four persons. These results are given according to the building insulation (we considered a RT2005 insulation, a 80's type insulation and "no insulation"). Occupants' habits and customs were chosen as "good" (Table 4). First, the proposed impact indicator (Section 3) was used to design energy production and storage systems for the considered house while promoting the injection of energy to the electricity grid (option 1). Whatever the building configuration (NR: no exploitation of renewable resources, Std: standard energy production and storage systems, RS: right-sized energy production and storage systems), the developed ventilation controller and the proposed occupancy scenarios were used [31,39].

Table 8. Results with option 1 (single storey house, k_1 = 3 and k_4 = 0.5).
NR: no exploitation of renewable resources, Std: standard energy production and storage systems,
RS: right-sized energy production and storage systems.

Insulation	*RT2005*			*80's type*			*None*		
Configuration	*NR*	*Std*	*RS*	*NR*	*Std*	*RS*	*NR*	*Std*	*RS*
DHW_{tank} *(l)*	*300*	*300*	*300*	*300*	*300*	*300*	*300*	*500*	*300*
$RESol_{PV}$ *(kW$_{peak}$)*	*0*	*3.5*	*3*	*0*	*3.5*	*6*	*0*	*3*	*6*
$RESol_{ther}$ *(kW$_{peak}$)*	*0*	*8*	*4*	*0*	*18*	*8*	*0*	*30*	*18*
W_{wind} *(kW$_{peak}$)*	*0*	*6*	*2*	*0*	*10*	*3*	*0*	*16*	*2*
EPD (-)	*B*	*B*	*B*	*C*	*C*	*C*	*D*	*D*	*D*
E_{imp} *(-)*	*12*	*17*	*8*	*20*	*19*	*12*	*49*	*50*	*17*
$Ener_{consump}$ *(GWh)*	*13.5*	*13.5*	*13.5*	*22*	*22*	*22*	*31*	*31*	*31*
$Ener_{self\text{-}consump}$ *(GWh)*	*0*	*4.25*	*1.32*	*0*	*7.5*	*5.6*	*0*	*17*	*13*
$Ener_{produc}$ *(GWh)*	*0*	*12.5*	*4*	*0*	*17*	*13.4*	*0*	*32*	*22*
$Ener_{injec}$ *(GWh)*	*0*	*8.25*	*2.68*	*0*	*9.5*	*7.8*	*0*	*15*	*9*
Balance (GWh)	*13.5*	*1*	*9.5*	*22*	*5*	*8.6*	*31*	*-1*	*9*

Figures 6a to 6d (1st case: load curves are given for a cold day; 2nd case: no energy needs related to HVAC appliances) depict the daily load curves we obtained, the building (RT2005 insulation or 80's type insulation) being equipped with standard (dotted line; design is related to profitability) or right-sized (solid line) energy production and storage systems. As expected, the right sizing of the just-mentioned systems (while promoting the injection of energy) 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 insulation), 40% (80's type insulation) and 65% ("no insulation") when these systems as well as the DHW tank are right sized (RT2005 insulation: DHW_{tank} = 300 litres, $RESol_{PV}$ = 3 kW$_{peak}$, $RESol_{ther}$ = 4 kW$_{peak}$, W_{wind} = 2 kW$_{peak}$; 80's type insulation: DHW_{tank} = 300 litres, $RESol_{PV}$ = 6 kW$_{peak}$, $RESol_{ther}$ = 8 kW$_{peak}$, W_{wind} = 3 kW$_{peak}$; "no insulation": DHW_{tank} = 300 litres, $RESol_{PV}$ = 6 kW$_{peak}$, $RESol_{ther}$ = 18 kW$_{peak}$, W_{wind} = 2 kW$_{peak}$). With the same reference, E_{imp} is increased of about 41% (RT2005 insulation) 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 (RT2005 insulation: DHW_{tank} = 300 litres, $RESol_{PV}$ = 3.5 kW$_{peak}$, $RESol_{ther}$ = 8 kW$_{peak}$, W_{wind} = 6 kW$_{peak}$; 80's type insulation: DHW_{tank} = 300 litres, $RESol_{PV}$ = 3.5 kW$_{peak}$, $RESol_{ther}$ = 18 kW$_{peak}$, W_{wind} = 10 kWpeak; "no insulation": DHW_{tank} = 500 litres, $RESol_{PV}$ = 3 kW$_{peak}$, $RESol_{ther}$ = 30 kW$_{peak}$, W_{wind} = 16 kW$_{peak}$). One can remark that the standard design (related to profitability) of energy production systems leads to higher thermal and windmill powers than when these systems are right sized ($RESol_{ther}$: 8 kW$_{peak}$ vs. 4 kW$_{peak}$ with a RT2005 insulation, 18 kW$_{peak}$ vs. 8 kW$_{peak}$ with a 80's type insulation and 30 kW$_{peak}$ vs. 18 kW$_{peak}$ without insulation; W_{wind}: 6 kW$_{peak}$ vs. 2 kW$_{peak}$ with a RT2005 insulation, 10 kW$_{peak}$ vs. 3 kW$_{peak}$ with a 80's type insulation and 16 kW$_{peak}$ vs. 2 kW$_{peak}$ without insulation). 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 (option 1): 17 vs. 8 with a RT2005 insulation, 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 standard or right-sized systems, whatever the insulation type). As expected, a good insulation reduces both the energy impact of a building and the overall consumption of energy. One can highlight, first, that the part of energy produced and consumed *in situ* is globally stable with standard or right-sized energy production and storage systems, whatever the insulation (34% vs. 33% with a RT2005 insulation, 44% vs. 42% with a 80's type insulation and 54% vs. 60% without insulation), and, secondly, that the energy impact indicator and the DPE result are correlated. One can also note that a domestic hot water tank of 300 litres is adapted to almost all the configurations we tested (a higher volume was only necessary with a non-insulated building equipped with standard energy production systems). This highlights the slight impact of the tank volume on system performance. The just-mentioned configuration is the only one leading to a negative overall (annual) balance (-1 GWh; consumed energy < injected energy), this balance being always higher (and positive) with right-sized energy production and storage systems than with standard ones (9.5 GWh vs. 1 GWh with a RT2005 insulation, 8.6 GWh vs. 5 GWh with a 80's type insulation and 9 GWh vs. -1 GWh without insulation).

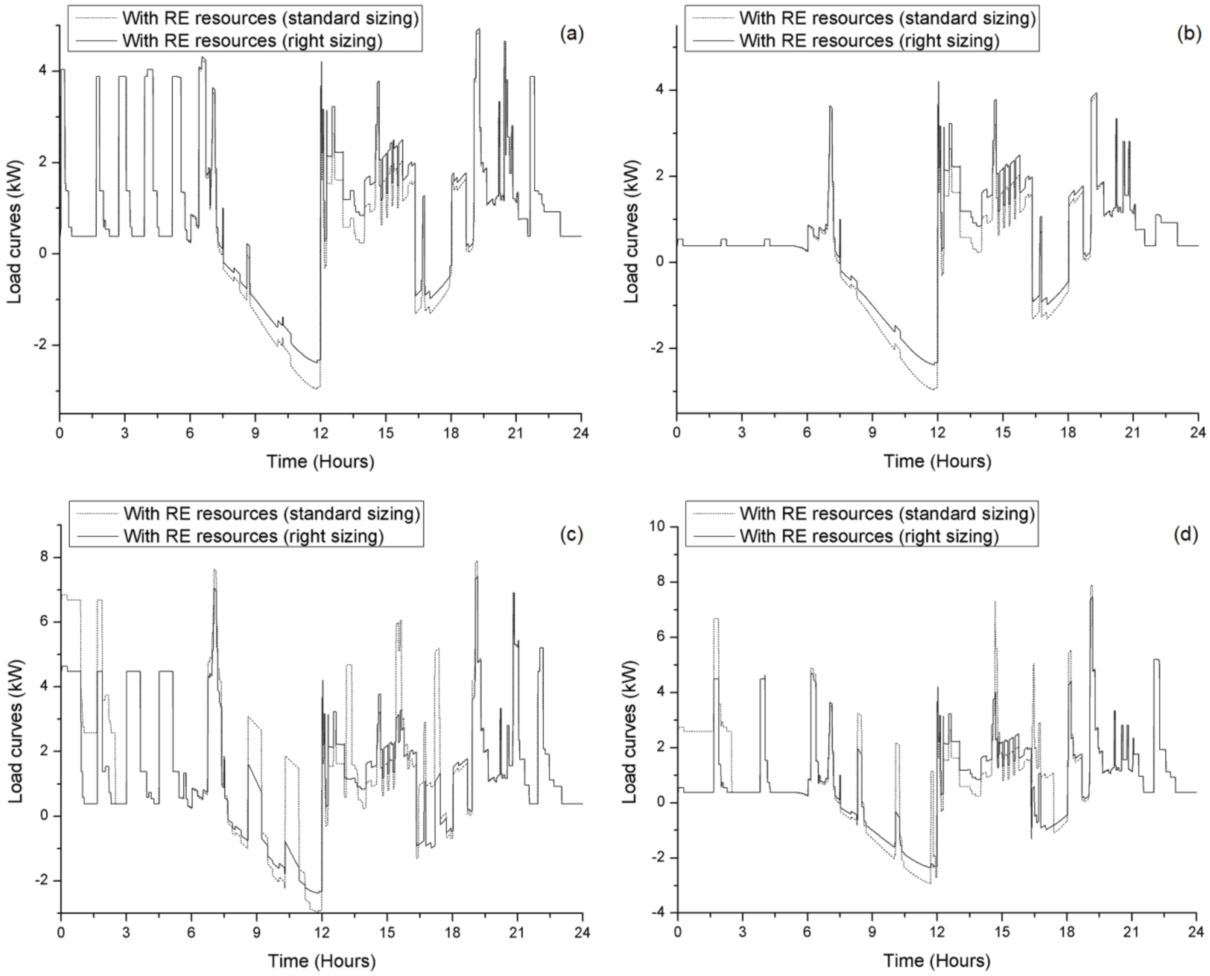

Figure 6. Daily load curves (single storey house).
(a) Cold day and RT2005 insulation. (b) Hot day and RT2005 insulation. (c) Cold day and 80's type insulation. (d) Hot day and 80's type insulation.

Looking at Figures 6a and 6b (RT2005 insulation), one can remark that when the balance is negative (consumed energy < injected energy) amplitudes are reduced thanks to 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 (annual) amount of energy injected to the electricity grid is also significantly reduced (this can be generalized whatever the insulation type). As a key point, one can highlight that the approach we proposed allows better managing of renewable energy resources and overcoming the intermittence of the renewable energy production. Similar conclusions can be reached when looking at Figures 6c and 6d (80's type insulation). However, one can again observe that a worst insulation impacts on the variability of the building's load. With standard energy production and storage systems, variability is increased during some periods of the day, what increases the frequency of changes in the building status (from producer to consumer or from consumer to producer). The amplitude of the peaks is also increased. Finally, Figures 7a to 7d give details about daily power profiles. related to energy consumption (power demand) (Figure 7a) and self-consumption (Figure 7b) as well as related to energy production (Figure 7c) and injection to the electricity grid (Figure 7d) (option 1). These profiles are given for the hot day we considered during the present study and a RT2005 insulation (energy production and storage systems are standard or right-sized). This case is the most significant. Looking at these figures, one can clearly assess the impact of the right sizing of energy production and storage systems (let us remember that the day we considered is not a windy day). Energy is produced and partially self-consumed between 6 a.m. and 8 p.m., approximately. Energy is injected to the grid between 7:30 a.m. and 12 a.m. as well as between 4:30 p.m. and 6 p.m. Injection periods are related to low building's energy needs. As highlighted by overall (annual) values (Table 8), the proposed approach allows better managing of renewable energy resources and overcoming the intermittence of the renewable energy production. Taking as a reference standard energy production and storage systems, the daily energy production is clearly reduced to better meet the building's needs. The respective daily amounts of energy injected to the electricity grid and self-consumed are also significantly reduced. As a result, the energy impact of the building is minimized.

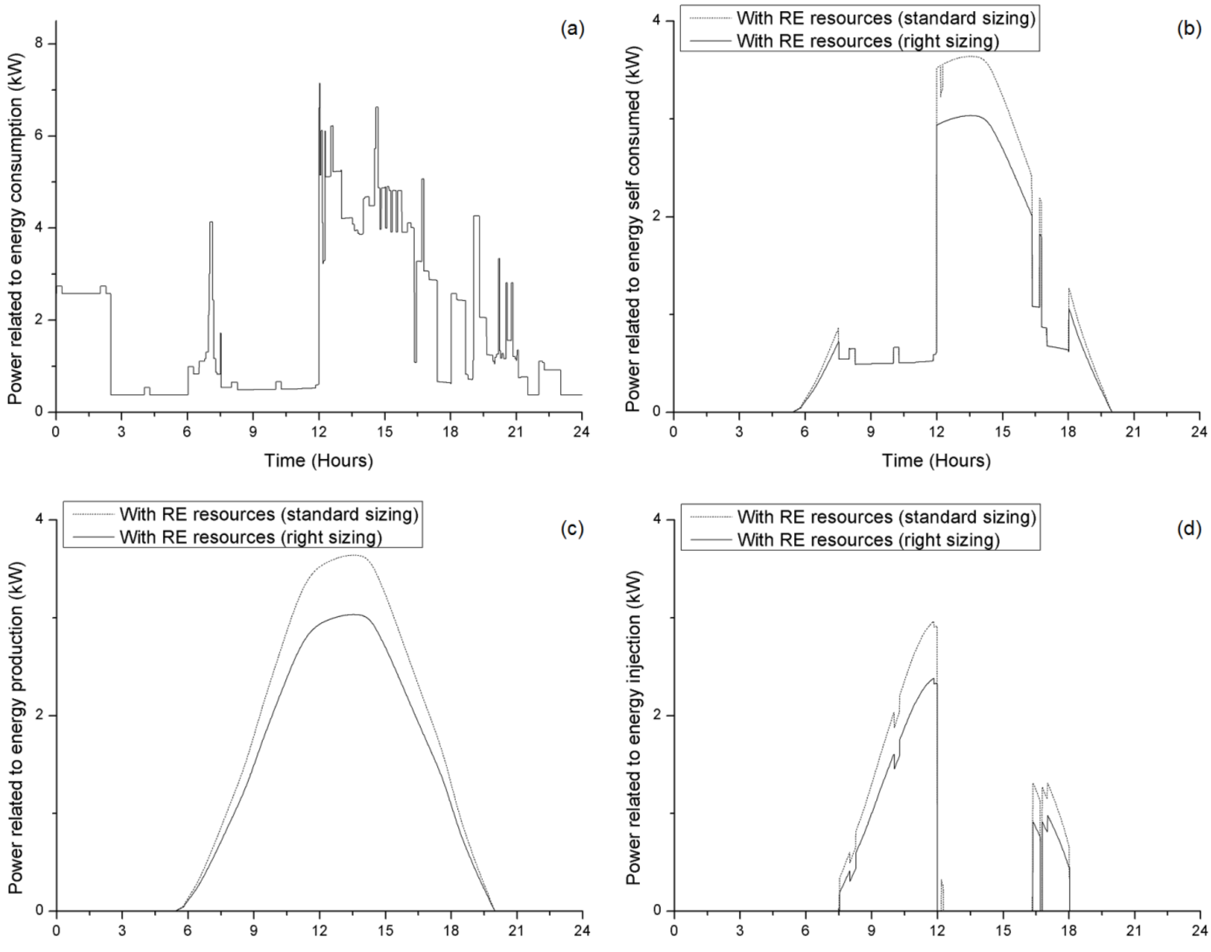

Figure 7. Daily power profiles (single storey house) related to energy consumption (a), energy self-consumption (b), energy production (c) and energy injection (d) (hot day, RT2005 insulation).

Table 9 summarizes the results we obtained taking into account the status of the electricity grid when designing energy production and storage systems for the 150 m^2 single storey house located in Perpignan (option 2). Taking again as a reference the building not equipped with energy production systems, one can note that E_{imp} is reduced of about 50% (RT2005 insulation and 80's type insulation) and 73% ("no insulation") when these systems as well as the DHW tank are right sized (RT2005 insulation: DHW_{tank} = 500 litres, $RESol_{PV}$ = 4 kW$_{peak}$, $RESol_{ther}$ = 6 kW$_{peak}$, W_{wind} = 3 kW$_{peak}$; 80's type insulation: DHW_{tank} = 500 litres, $RESol_{PV}$ = 7 kW$_{peak}$, $RESol_{ther}$ = 16 kW$_{peak}$, W_{wind} = 1 kW$_{peak}$; "no insulation": DHW_{tank} = 500 litres, $RESol_{PV}$ = 9 kW$_{peak}$, $RESol_{ther}$ = 20 kW$_{peak}$, W_{wind} = 1 kW$_{peak}$). With the same reference, E_{imp} is increased of about 11% (RT2005 insulation) and 7% ("no insulation") while it remains unchanged (80's type insulation) when both the energy production and storage systems are standardly sized (RT2005 insulation: DHW_{tank} = 300 litres, $RESol_{PV}$ = 3.5 kW$_{peak}$, $RESol_{ther}$ = 8 kW$_{peak}$, W_{wind} = 6 kW$_{peak}$; 80's type insulation: DHW_{tank} = 300 litres, $RESol_{PV}$ = 3.5 kW$_{peak}$, $RESol_{ther}$ = 18 kW$_{peak}$, W_{wind} = 10 kWpeak; "no insulation": DHW_{tank} = 500 litres, $RESol_{PV}$ = 3 kW$_{peak}$, $RESol_{ther}$ = 30 kW$_{peak}$, W_{wind} = 16 kW$_{peak}$). Again, one can remark that the standard design (related to profitability) of energy production systems leads to higher thermal and windmill powers than when these systems are right-sized ($RESol_{ther}$: 8 kW$_{peak}$ vs. 6 kW$_{peak}$ with a RT2005 insulation, 18 kW$_{peak}$ vs. 16 kW$_{peak}$ with a 80's type insulation and 30 kW$_{peak}$ vs. 20 kW$_{peak}$ without insulation; W_{wind}: 6 kW$_{peak}$ vs. 3 kW$_{peak}$ with a RT2005 insulation, 10 kW$_{peak}$ vs. 1 kW$_{peak}$ with a 80's type insulation and 16 kW$_{peak}$ vs. 1 kW$_{peak}$ without insulation). Moreover, 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 (option 2): 20 vs. 9 with a RT2005 insulation, 30 vs. 14 with a 80's type insulation and 55 vs. 15 without insulation. Again, the amount of energy injected to the grid increases while the amount of energy purchased from the grid decreases with standard or right-sized systems, whatever the insulation level. A good insulation reduces both the energy impact of a building and the overall consumption of energy. As previously highlighted, the energy impact and the DPE result are correlated. One can remark that minimizing the energy impact of the considered building when insulation is in agreement with RT2005 standards, while taking into account the status of the electricity grid, leads to a domestic hot water of 500 litres (instead of 300 litres with option 1). Here the impact of the volume of the tank on system performance is more significant than it is when designing energy production and storage systems while promoting electricity injection.

Table 9. Results with option 2 (single storey house, $k_1 = 3$, $k_5 = 0.5$, $k_6 = 3$ and $k_7 = 1$).
NR: no exploitation of renewable resources, Std: standard energy production and storage systems, RS: right-sized energy production and storage systems.

Insulation	*RT2005*			*80's type*			*None*		
Configuration	*NR*	*Std*	*RS*	*NR*	*Std*	*RS*	*NR*	*Std*	*RS*
DHW_{tank} *(l)*	*300*	*300*	*500*	*300*	*300*	*500*	*300*	*500*	*500*
$RESol_{PV}$ *(kW$_{peak}$)*	*0*	*3.5*	*4*	*0*	*3.5*	*7*	*0*	*3*	*9*
$RESol_{ther}$ *(kW$_{peak}$)*	*0*	*8*	*6*	*0*	*18*	*16*	*0*	*30*	*20*
W_{wind} *(kW$_{peak}$)*	*0*	*6*	*3*	*0*	*10*	*1*	*0*	*16*	*1*
EPD (-)	*B*	*B*	*B*	*C*	*C*	*C*	*D*	*D*	*D*
E_{imp} *(-)*	*18*	*20*	*9*	*28*	*30*	*14*	*55*	*55*	*15*
$Ener_{consump}$ *(GWh)*	*13.5*	*13.5*	*13.5*	*22*	*22*	*22*	*31*	*31*	*31*
$Ener_{self\text{-}consump}$ *(GWh)*	*0*	*4.25*	*4.9*	*0*	*7.5*	*9.6*	*0*	*17*	*16*
$Ener_{produc}$ *(GWh)*	*0*	*12.5*	*7.15*	*0*	*17*	*16.1*	*0*	*32*	*21*
$Ener_{injec}$ *(GWh)*	*0*	*8.25*	*2.25*	*0*	*9.5*	*6.5*	*0*	*15*	*5*
Balance (GWh)	*13.5*	*1*	*6.35*	*22*	*5*	*5.9*	*31*	*-1*	*10*

When taking a look at Tables 8 and 9, one can remark that, in most cases, $RESol_{PV}$, $RESol_{ther}$ and W_{wind} are higher when one takes into account the status of the grid (option 2) than when one promotes energy injection (option 1), whatever the insulation level of the building. Indeed, with a RT2005 insulation, $RESol_{PV}$, $RESol_{ther}$ and W_{wind} increase from 3 to 4 kW$_{peak}$, from 4 to 6 kW$_{peak}$ and from 2 to 3 kW$_{peak}$, respectively. Considering a 80's type insulation, $RESol_{PV}$ and $RESol_{ther}$ increase from 6 to 7 kW$_{peak}$ and from 8 to 16 kW$_{peak}$, respectively. In opposition, W_{wind} decreases from 3 to 1 kW$_{peak}$. Finally, without insulation, $RESol_{PV}$ and $RESol_{ther}$ increase from 6 to 9 kW$_{peak}$ and from 18 to 20 kW$_{peak}$, respectively, while W_{wind} decreases from 2 to 1 kW$_{peak}$. Such a result is the consequence of a better match between grid load levels and the building load curve. With option 2, the right sizing of energy production and storage systems allows, in some cases, satisfying the grid energy demand. As expected, and whatever the insulation level of the building, the amount of energy injected to the grid is higher when the just-mentioned systems are designed while promoting energy injection (option 1) than when taking into account the status of the grid (option 2) (RT2005 insulation: 2.68 GWh vs. 2.25 GWh; 80’s type insulation: 7.8 GWh vs. 6.5 GWh; "no insulation": 9 GWh vs. 5 GWh). In opposition, energy self-consumption is notably higher when these systems are designed with option 2 (RT2005 insulation: 4.9 GWh vs. 1.32 GWh; 80’s type insulation: 9.6 GWh vs. 5.6 GWh; "no insulation": 16 GWh vs. 13 GWh). Whatever the chosen option, the right sizing of energy production and storage systems is always a compromise between minimizing the energy impact of a given building and satisfying, when it is possible, a part of the electricity grid needs. As a key point, one can again highlight that the proposed approach allows better managing of renewable energy resources and overcoming the intermittence of the renewable energy production.

6.3.2. Industrial building

Table 10 summarizes the results we obtained in simulation (again for a 1-year period) using the model of the industrial building located in Perpignan and whose activity deals with the moulding of plastic products. Occupants’ habits and customs were chosen as "good" (Table 4). Insulation is standard for such a building (Section 4.3.2). Whatever its configuration (NR: no exploitation of renewable resources, Std: standard energy production and storage systems, RS: right-sized energy production and storage systems), the developed ventilation controller is used. As previously mentioned, standard and generalized procedures were considered for occupancy. One can note that an energy performance diagnosis can’t be carried out for industrial buildings. Moreover, let us remember that the standard sizing of energy production and storage systems is related to the surface available on the building’s roof (the whole roof is slated with PV and thermal panels). In this case, the considered building is not equipped with a vertical axis windmill. Again, energy production and storage systems can be designed while promoting the injection of electricity (option 1) or taking into account the status of the grid (option 2).

Table 10. Results (industrial building, $k_1 = 3$, $k_4 = 0.5$, $k_5 = 0.5$, $k_6 = 3$ and $k_7 = 1$). NR: no exploitation of renewable resources, Std: standard energy production and storage systems, RS: right-sized energy production and storage systems, n.a.: not applicable.

Activated option	*Option 1*			*Option 2*		
Configuration	*NR*	*Std*	*RS*	*NR*	*Std*	*RS*
DHW_{tank} (l)	500	500	1000	500	500	2000
$RESol_{PV}$ (kW_{peak})	0	250	200	0	250	170
$RESol_{ther}$ (kW_{peak})	0	6	10	0	6	14
W_{wind} (kW_{peak})	0	0	0	0	0	40
EPD (-)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
E_{imp} (-)	37	41	30	49	50	20
$Ener_{consump}$ (GWh)	570.57	570.57	570.57	570.57	570.57	570.57
$Ener_{self\text{-}consump}$ (GWh)	0	385.86	343.67	0	385.86	388.36
$Ener_{produc}$ (GWh)	0	500.93	400.74	0	500.93	426.1
$Ener_{injec}$ (GWh)	0	115.07	57.07	0	115.07	37.74
Balance (GWh)	570.57	69.64	169.83	570.57	69.64	144.47

As previously noted with the single storey house (Tables 8 and 9), the right sizing of energy production and storage systems allows minimizing the energy impact on the electricity grid (while promoting the injection of energy to the grid or taking into account the status of the grid) of the considered industrial building. As expected, the energy impact of such an insulated building is over-all higher than it is for the single storey house (RT2005 and 80’s insulation levels). Taking as a reference the building not equipped with energy production systems, one can note that E_{imp} is reduced of about 19% (option 1) and 59% (option 2) when these systems as well as the DHW tank are right sized (option 1: DHW_{tank} = 1000 litres, $RESol_{PV}$ = 200 kW_{peak}, $RESol_{ther}$ = 10 kW_{peak}, W_{wind} = 0 kW_{peak}; option 2: DHW_{tank} = 2000 litres, $RESol_{PV}$ = 170 kW_{peak}, $RESol_{ther}$ = 14 kW_{peak}, W_{wind} = 40 kW_{peak}). With the same reference, E_{imp} is increased of about 11% (option 1) and 2%

(option 2) when both the energy production and storage systems are standardly sized (DHW_{tank} = 500 litres, $RESol_{PV}$ = 250 kW$_{peak}$, $RESol_{ther}$ = 6 kW$_{peak}$, W_{wind} = 0 kW$_{peak}$). 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: 41 vs. 30 with option 1 and 50 and 20 vs. 17 with option 2. With right-sized energy production and storage systems, one can remark that the amount of energy produced is slightly lower when promoting energy injection (option 1) than when taking into account the status of the grid (option 2) (400.74 GWh vs. 426.1 GWh). Moreover, energy self-consumption is higher with option 2 (388.86 GWh vs. 343.67 GWh) while energy injection is higher with option 1 (57.07 GWh vs. 37.74 GWh). In addition, the DHW tank volume impacts on system performance in a more significant way for such an industrial building than for the single storey house: DHW_{tank} = 1000 litres when promoting energy injection and DHW_{tank} = 2000 litres when taking into account the status of the electricity grid (DHW_{tank} = 500 litres when energy production and storage systems are standardly sized).

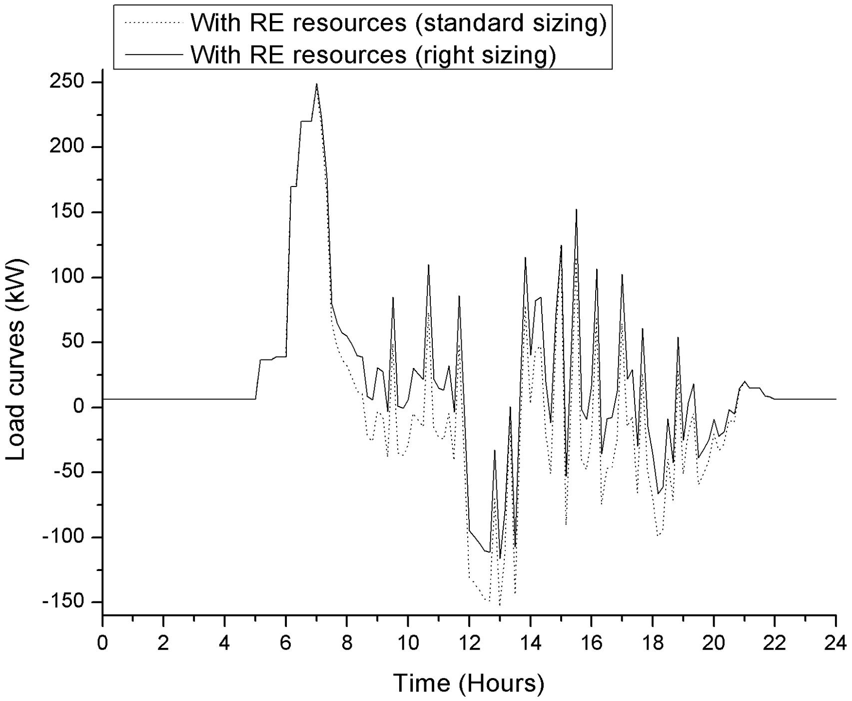

Figure 8. Daily load curves (industrial building with standard insulation, typical day).

Figure 8 depicts the daily load curves we obtained for a typical day, the considered industrial building being equipped with standard (dotted line; design is related to profitability) or right-sized (solid line) energy production and storage systems. These systems were designed while promoting energy injection (option 1). When the balance is negative (consumed energy < injected energy) the right sizing allows reducing amplitudes. As previously highlighted for the single storey house, the proposed approach allows better managing of renewable energy resources and overcoming the intermittence of the renewable production. Again, energy production is clearly reduced (taking as a reference standardly-sized systems) to better meet the industrial building's energy needs. The overall (annual) amount of energy injected to the electricity grid is also significantly reduced (this can be generalized whatever the option one wants to consider when designing energy production and storage systems). Finally, Figures 9a to 9d give details about daily power profiles related to energy consumption (power demand) (Figure 9a) and self-consumption (Figure 9b) as well as related to energy production (Figure 9c) and injection to the electricity grid (Figure 9d) (option 1). These profiles are given for the typical day we considered for such an industrial building and a standard insulation level (energy production and storage systems are standard or right-sized). Looking at these figures, one can clearly assess the impact of the right sizing of the systems. Energy is produced and self-consumed between 7:30 a.m. and 9 p.m. Because of fluctuating building's energy needs (related to activity), energy is injected to the grid in an intermittent way between 8:30 a.m. and 9 p.m. Looking at Table 10 and both Figures 8 and 9, one can understand the way energy is used and managed in the considered industrial building. One can also quantify the impact of an industrial activity on the electricity grid.

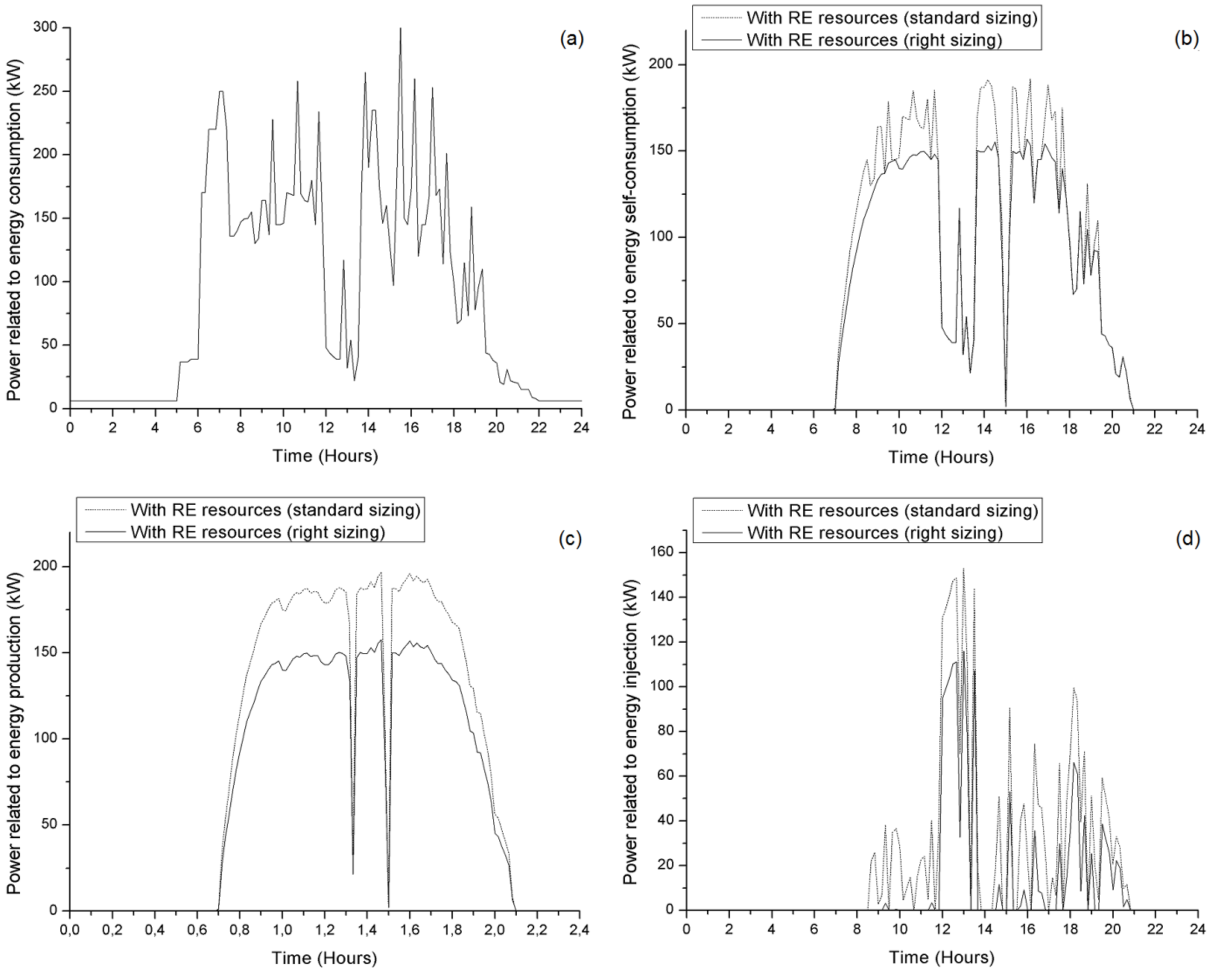

Figure 9. Daily power profiles (industrial building) related to energy consumption (a), energy self-consumption (b), energy production (c) and energy injection (d) (typical day, standard insulation).

7. Conclusion

The present paper focuses on a methodology allowing evaluating the energy impact of buildings equipped with energy production and storage systems on the electricity grid. The proposed impact indicator is used to design the just-mentioned systems while promoting the injection of energy or taking into account the status of the grid. With the aim of validating the proposed approach in simulation, we developed and validated several building models. In the present paper, we focused on a 150 m^2 single storey house and an industrial building whose activity deals with the moulding of plastic products. Both are located in the city of Perpignan (south of France). We considered the single storey house to be in agreement with 2005 or 80's insulation standards. The lack of insulation was also considered. Lifestyle habits were modelled. A standard insulation level was considered for the industrial building. Solar thermal panels, photovoltaic panels and a vertical axis windmill could be integrated to the buildings. A thermal storage tank was used for domestic hot water. 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 minimize the energy impact of the considered buildings thanks to the right sizing of the production and storage systems. Whatever the building, the results we obtained highlight the proposed approach relevance: thanks to the right sizing of such systems (in France, as well in other countries, these systems are usually designed according to profitability considerations only), the power purchased from the grid is reduced while the produced energy is partially self-consumed. Energy self-consumption allows for a more efficient and rational use of energy, as it would imply significant savings in electricity distribution and transport costs and a reduction in the need to invest in new networks. Future work will now focus, first, on trying to improve the developed models (in terms of envelop and systems, in order to be appropriate for the short time step of sampling, and inhabitants' behavior using a stochastic approach) 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 will be used in instrumented real buildings.

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