

A new approach to energy resources management in a grid-connected building equipped with energy production and storage systems: A case study in the south of France

Aurélie Chabaud, Julien Eynard, Stéphane Grieu

▶ **To cite this version:**

Aurélie Chabaud, Julien Eynard, Stéphane Grieu. A new approach to energy resources management in a grid-connected building equipped with energy production and storage systems: A case study in the south of France. Energy and Buildings, 2015, 99, pp.9-31. 10.1016/j.enbuild.2015.04.007 . hal-01259328

HAL Id: hal-01259328
https://hal.science/hal-01259328

Submitted on 20 Jan 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A new approach to energy resources management in a grid-connected building equipped with energy production and storage systems: a case study in the south of France

Aurélie Chabaud[a,b], **Julien Eynard**[a,b], **Stéphane Grieu**[a,b,*]

[a] *PROMES-CNRS, Rambla de la Thermodynamique, Tecnosud, 66100 Perpignan, France*
[b] *University of Perpignan Via Domitia, 52 Avenue Paul Alduy, 66860 Perpignan, France*

Abstract

In the present paper, a new approach to energy resources management in a residential microgrid is proposed and evaluated in simulation, using energy and economic criteria. Its aim is to improve energy efficiency as well as interaction with the electricity grid. So, a grid-connected building located in Perpignan (south of France) and equipped with energy production and storage systems has been modelled using the TRNSYS software. We designed and managed these systems optimally and highlighted configurations that promote self-consumption of energy. In addition, the negative impact on the grid of local power generation (related to both energy injection and extraction) is minimized. The combination of photovoltaic solar panels and a vertical-axis wind turbine as a viable energy mix option for residential buildings in Southern France has also been evaluated. At least, we appraised the way electricity storage impacts on performance as well as the savings one can achieve by shifting some domestic loads from on-peak to off-peak periods.

Keywords: Microgrid, residential building, thermal modelling, decentralized power generation, electricity grid, grid-connected mode, electricity storage, management strategy, demand response mechanisms.

1. Introduction

Climate change due to greenhouse gas emissions as well as an increasing demand in energy, mainly caused by population growth and economic development, are worldwide concerns [1][2]. Consequently, decentralized power generation, one of the keys to energy independance and security, is leading the way to fight global warming and promote energy efficiency (United Nations Framework Convention on Climate Change [1] and Kyoto Protocol [3]).

Let us remind that traditional electricity grids are radial and unidirectional structures built to bring electricity from centralized power plants to end-users (consumers). They were originally designed for regional self-sufficiency whereas interconnections were developed for mutual support between regions [4][5]. Because traditional electricity grids are not equipped with storage facilities, production and demand by end-users must be balanced. The flow of electricity is not monitored in real-time and electrical usage is usually unknown. In addition, power breakdowns, due in particular to overload or unstable power supply, are important issues impacting electricity grids. After all, spikes in energy demand are forcing power companies to invest a lot of money in "peaking facilities" which are rarely used [6].

Because of an increasing penetration of sources of renewable energy, distribution networks are no more passive but active structures. In particular, this penetration impacts on transient and voltage stability, electromagnetic transients, power levelling, energy balancing, and power quality [7][8]. So, decentralized power generation requires dramatic changes in planning practices, and an increased flexibility, because it affects the physical operation of the grids [9]. In Ref. [10], Hammons examined possible solutions to the integration of these new sources of energy into various European distribution networks. He evaluated the "Technology Platform for the Electricity Networks of the Future" proposed in 2005 by the European Commission and highlighted key challenges as well as possible architectures for the grids [11]. The main goal of such a platform is to increase the efficiency, safety and reliability of the European electricity transmission and distribution systems by transforming the traditional grids into an interactive service network. This platform is also about removing obstacles to the large-scale deployment and effective integration of distributed sources of renewable energy. In 2007, Coll-Mayor et al. [12] provided a complete outlook on intelligent power grids, also known as "smart" grids in Europe. The authors highlighted the need for new concepts and architectures, based on distributed intelligence, plug and play, e-trading or power-line communication, and for a regulatory framework dedicated to the control, supervision, and operation of electricity grids [13]. In 2009, Chicco and Mancarella [14] outlined the main possible structures, characteristics, components, energy flows, and interactions for distributed multi-generation systems. As an interesting result, they pointed out that sustainability

*Corresponding author
Email address: stephane.grieu@promes.cnrs.fr (**Stéphane Grieu**)

Nomenclature	
U	Heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
U_{RT2005}	Heat transfer coefficient (French thermal regulation of year 2005) ($\mathrm{W\,m^{-2}\,K^{-1}}$)
T_{sp}	Indoor temperature setpoint (°C)
I	Current (A)
I_L	Light current (A)
I_0	Diode reverse saturation current (A)
R_s	Series resistance (Ω)
R_{sh}	Shunt resistance (Ω)
V	Voltage (V)
a	Modified ideality factor (-)
η_I	Ideality factor (-)
N_s	Number of modules in series in array (-)
k_B	Boltzmann constant ($\mathrm{m^2\,kg\,s^{-2}\,K^{-1}}$)
T_c	PV array temperature (K)
q	Electron charge constant (C)
P	Power output of the wind turbine (kW)
C_p	Power coefficient for a wind turbine (-)
A_R	Rotor area ($\mathrm{m^2}$)
ρ	Air density ($\mathrm{kg\,m^{-3}}$)
U_0	Wind speed ($\mathrm{m\,s^{-1}}$)
k	Time index (-)
T_s	Simulation sampling time (min)
E_{bat}	Amount of energy stored in the batteries (kW h)
E_{bat}^{max}	Maximum (rated) capacity of the batteries (kW h)
E_{bat}^{min}	Minimum capacity of the batteries (kW h)
DoD	Depth of Discharge (%)
E_{ren}^{p}	Amount of energy produced by local systems (kW h)
E_{ren}^{c}	Amount of energy produced and consumed *in situ* (kW h)
E_{sto}	Amount of energy available to be stored in the batteries (kW h)
E_{ext}	Amount of energy extracted from the electricity grid (kW h)
E_{inj}	Amount of energy injected to the electricity grid (kW h)
E_{rel}	Amount of energy released from the batteries (kW h)
E_{hou}	Energy needs of the residential building (kW h)
η_{inv}	Inverter performance (%)
η_{bat}	Charge performance (%)
τ	Hourly self-discharge rate (%)
$\%_{ren}$	Percentage ratio of the renewable energy produced and consumed *in situ* to the total energy consumed (%)
$\%_{sc}$	Percentage ratio of the renewable energy consumed to the renewable energy produced *in situ* (%)
J_{ren}	Renewable energy use (-)
T_{out}	Outdoor temperature (°C)
P_{en}	Electricity price (€ $\mathrm{kW\,h^{-1}}$)
J_{cost}	Economic cost criterion (€)
L_{grid}	Grid load (MW)
$\widetilde{L}_{grid}$	Normalized grid load (-)
J_{grid}	Electricity grid status (-)
T_{grid}	Electricity grid threshold (%)
ΔT_{grid}	Deviation between the grid threshold and the normalized load (-)
I_{inj}	Impact of local production of renewable energy (-)
I_{ext}	Impact of energy extraction (-)
I_{grid}	Overall impact (-)
δ	Difference between the amount of renewable energy produced and instantaneous energy consumption (kW h)
P_{pv}	PV panels peak power (kWp)
P_{wt}	Wind turbine peak power (kWp)

of the distributed multi-generation solutions is guaranteed by a wide range of technical and economic benefits. The same year (2009), Battaglini et al. [15] proposed the concept of "supersmart" grids for a more efficient use of electricity produced from renewables. This concept combines wide area power generation with decentralized power generation. As another interesting work, Nair and Zhang [16] detailed the composition of the power generation system of New Zealand and suggested to follow Europe's platform for its smart grid development. At least, Hledik [17] car-

ried out a simulation of the U.S. power system, which is mainly based on thermal power, and suggested that both conservative and more technologically aggressive possible implementations of a smart grid would produce a significant reduction in CO_2 emissions at the national level.

New concepts and architectures go along with "intelligent" tools and strategies allowing the decentralized power generation to be managed and its impact on the electricity grid operation to be evaluated. In this sense, Fardanesh and Richards highlighted in 1984 that additional coordination and protection considerations are required when sizable cogeneration sources are introduced to the electricity grid in order to maintain a high degree of reliability and service continuity [18]. The same year (1984), Dugan and Rizy considered three potential protection problems associated with the interconnection to the distribution grid of rotating-type, small dispersed storage and energy production systems [19]. In 2006, Pham proposed a new approach based on intentional islanding of power systems in case of a critical situation caused by a massive penetration of renewable energy sources [20]. In 2008, Fontela-Garcia analyzed the robustness of the grid and proposed fault detection algorithms and intentional islanding to limit the impact of electrical failures [21]. In Ref. [22], Courtecuisse addressed both the supervision of multisource power plants equipped with storage systems and the impact of renewable generation on grid stability. He proposed and evaluated several control strategies based in particular on fuzzy logic. In Ref. [23], Alvarez-Hérault proposed a new architecture and a partially-meshed operation for distribution networks. As a result, reliability is preserved, even if the penetration of renewabale energy sources is large. In Ref. [24], Lund and Münster analyzed various energy strategies for Denmark, based on decentralized power generation. In particular, the authors highlighted that the costs of avoiding critical surplus production is much lower than investing in high-voltage transmission lines. Moreover, they concluded that flexibility is of paramount interest in the management of decentralized power generation.

Another key point in energy efficiency and sustainability is the building sector [25]. In 2010, the final residential energy consumption accounted for 26% of the total energy consumption in the European Union of 27 member states [26]. So, automation approaches for smart buildings capable of trimming demand for electricity in response to real-time variations in prices could shave many peaks. They could also help generation and distribution networks reliability to be improved, in particular if penetration of intermittent sources of renewable energy in the power system is high, as well as cost effectiveness. As an interesting concept, a building (or a group of buildings) equipped with (shared) energy production and storage systems can be seen as a "microgrid". So, a (smart) microgrid is a small-scale energy grid that can provide adequate energy supply to cover local demand by integrating decentralized power generation and storage facilities. In such a context, Demand Response (DR) and Demand Side Management

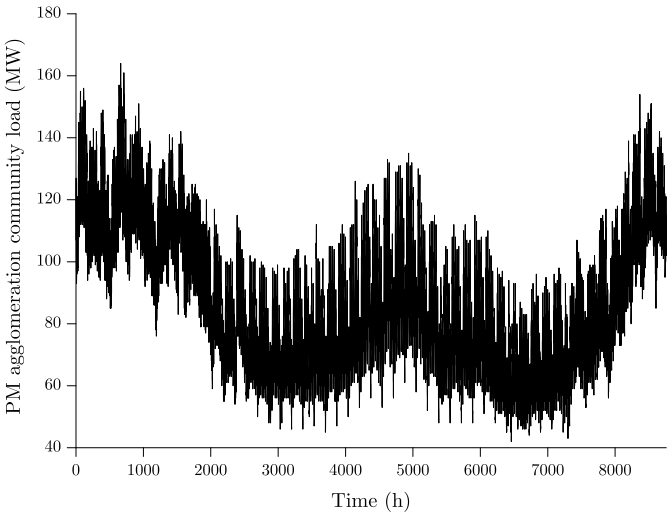


Figure 1: Hourly grid load of the Perpignan-Méditerranée agglomeration community (about 280 000 persons and 655 km^2, Languedoc-Roussillon, France) (MW).

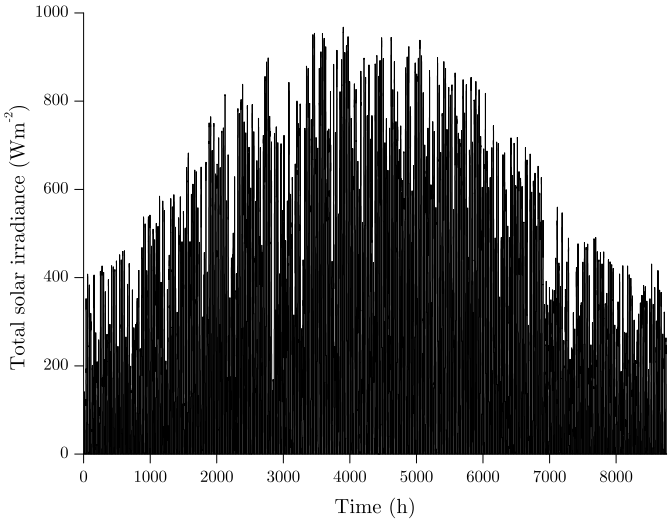


Figure 2: Hourly total solar irradiance in Perpignan, Perpignan-Méditerranée agglomeration community (Languedoc-Roussillon, France) ($W\,m^{-2}$).

(DSM) aim at optimizing the electricity delivery process by taking advantage of consumers' flexibility. According to the Federal Energy Regulatory Commission [27], DR is about "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized". In case of strained electricity supply and demand conditions, DR can reduce peak prices and overall price volatility [28][29]. Moreover, DSM programs encourage end-users to be more energy efficient [30]. Lighting retrofits, building automation upgrades as well as HVAC (Heating, Ventilation and Air-Conditioning) improvements [31][32] can be included in these programs. To summarize, there are three main possible ways in which

end-users can improve energy efficiency: shifting electricity use (household appliances) from on-peak to part-peak or off-peak periods, reducing energy consumption, and consuming locally-produced energy. In 2012, Gelazanskas and Gamage made a review of the demand side management techniques one can find in the literature. In addition, the authors proposed a modern system identification and side load control method based on artificial neural networks [33]. The same year (2012), Kriett and Salani developed a Model Predictive Control (MPC) scheme in order to minimize the operating cost of a residential microgrid which was operated in grid-connected mode [34]. More recently (2013), Kremers et al. proposed an agent-based approach for modelling a smart microgrid [35]. A simple case study allowed the possibilities offered by such an approach to be evaluated. In 2014, Honarmand et al. developed a management approach to power generation and electric vehicles in a microgrid [36]. The authors focused on optimizing the charging and discharging cycles of the batteries.

In the present paper, a new approach to energy resources management in a residential microgrid is proposed and evaluated in simulation, taking the electricity grid status into consideration. So, we used the TRNSYS (Transient System Simulation Tool) software to model a grid-connected building located in Perpignan (south of France) and equipped with energy production and storage systems. Designing and managing these systems optimally was the main goal of the study. Besides, we considered 1980's and RT2005 insulation standards [37] and proposed realistic occupancy (OS_1 and OS_2) and behaviour (BS_1 and BS_2) scenarios. We defined BS_2 by shifting some domestic loads from on-peak to off-peak periods (DR mechanisms). Data collected in the real house allowed the model to be successfully validated (Section 2). Section 3 is about the two strategies one can apply to the residential building. Energy and economic criteria have been defined to evaluate these strategies. In Section 4, configurations that promote self-consumption of energy and allow the negative impact local power generation can have on the grid to be minimized are highlighted. We also appraised the impact of electricity storage (using batteries) on the way the buiding and the electricity grid interact. The paper ends with a conclusion and an outlook to future work (Section 5).

2. Modelling of the residential microgrid

This section of the paper is about the modelling of the considered residential microgrid. So, we modelled the thermal behaviour of a building equipped with energy production and storage systems using the TRNSYS software [38]. The building operates in grid-connected mode. TRNSYS (Transient System Simulation Tool) is a graphically-based software environment used to simulate the behaviour of transient systems.

2.1. Single-storey house

The building we modelled is a 190 m^2 single-storey house located in Perpignan (Perpignan-Méditerranée agglomeration community, Languedoc-Roussillon, France), facing south and inhabited by four persons (two adults and two children) (Figure 1). The city of Perpignan experiences a warm and windy Meditteranean climate, similar to much of southern France. Summers are dry and hot whereas winters are mild (Figures 2, 3 and 4). Rainfall is at its lowest in the summer months and begins to pick up in October. The house is equipped with a zoned HVAC (Heating, Ventilation and Air-Conditioning) system whose maximum power is 1 kW (Figure 5) as well as electrical/electronic appliances, managed using local regulators (TRNSYS model type 56). It is also equipped with a storage tank for Domestic Hot Water (DHW) supply. Each room in the house has a homogenous temperature and radiation heat transfer between the rooms is based on the room area. Heat addition from solar direct and diffuse radiation is calculated

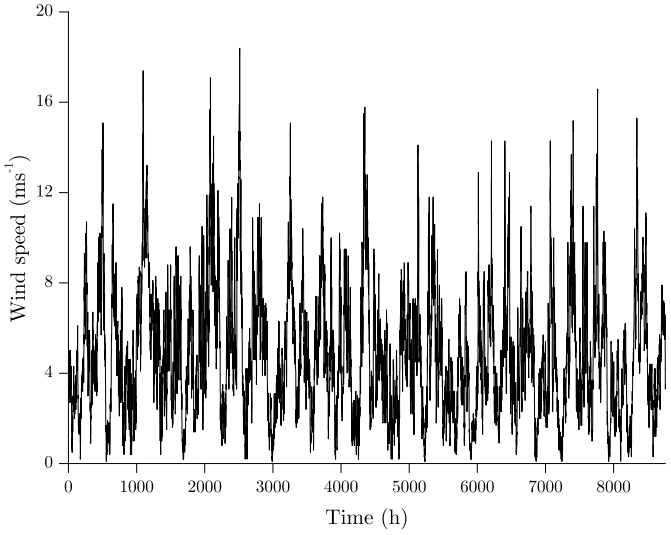


Figure 3: Hourly wind speed in Perpignan, Perpignan-Méditerranée agglomeration community (Languedoc-Roussillon, France) (m s^{-1}).

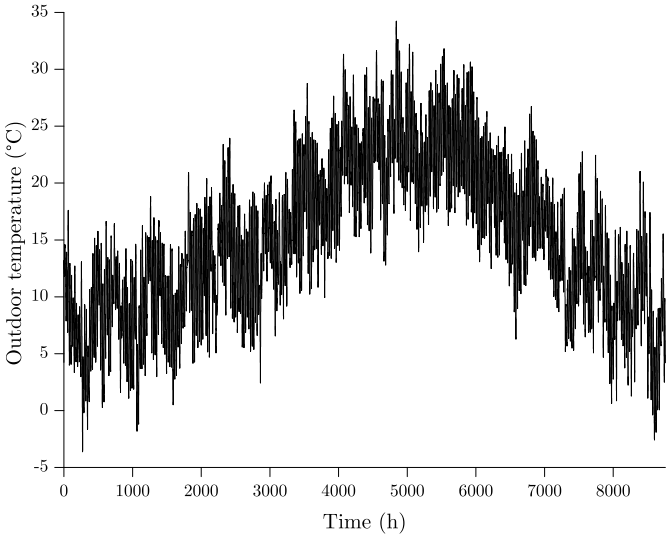


Figure 4: Hourly outdoor temperature in Perpignan, Perpignan-Méditerranée agglomeration community (Languedoc-Roussillon, France) (°C).

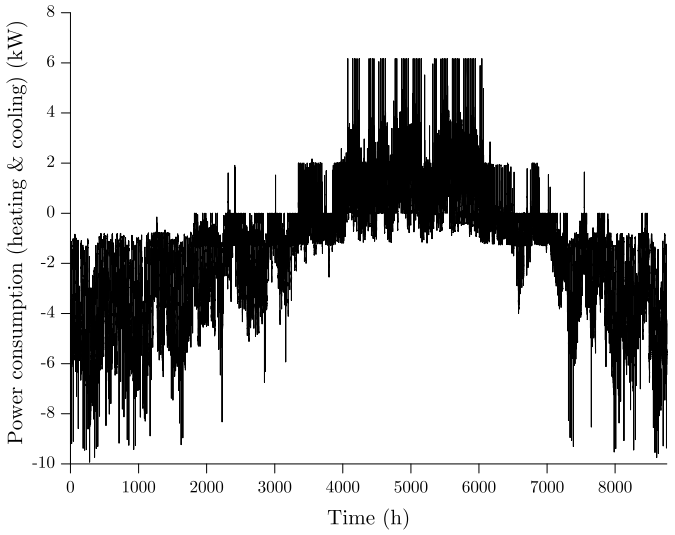


Figure 5: Hourly power consumption for heating and cooling in the single-storey house located in Perpignan (Perpignan-Méditerranée agglomeration community, Languedoc-Roussillon, France) (kW). When power consumption is negative (respectively positive), heating (respectively cooling) mode is on.

for each room, depending on window and heat transfer properties. That house can be equipped with photovoltaic solar panels, a vertical-axis wind turbine, and batteries for electricity storage. Table 1 gives the area of each room in the house as well as the number of windows:

Table 1: Structure of the single-storey house.

Room	Area	Windows
Bathroom	$16\,m^2$	1
Bedroom 1	$19\,m^2$	1
Bedroom 2	$19\,m^2$	1
Bedroom 3	$16\,m^2$	1
Corridor	$17\,m^2$	None
Garage	$38\,m^2$	2
Kitchen	$12\,m^2$	1
Living room	$53\,m^2$	2
Total	$190\,m^2$	9

Tables 2 and 3 list all the materials used in that house as well as their main characteristics. Common materials have been considered and the overall thermal insulation of the structure agrees with relatively new French standards for buildings (RT2005) (Table 2) or with 1980's standards (Table 3). U is the heat transfer coefficient of a material used and U_{RT2005} is the coefficient the French thermal regulation of year 2005 decrees [37]. RT2005 standards apply to new buildings whose planning applications were submitted after September 1st, 2006. However, they do not apply to buildings with a temperature of use which is lower than 12°C, swimming pools, ice rinks, breeding farms, and to buildings having to guarantee specific temperature, hygrometry and air quality conditions. Regulation is based on primary energy consumption and indoor comfort. Both have to be lower than reference values. Because of the climatic disparity of France, RT2005 standards define eight climate zones. Solar protection is indirectly taken into account. These standards also apply if equipment is added or replaced in existing buildings, with the exception of temporary or low-energy consuming buildings. We successfully validated the proposed model using data about energy consumption (for each room and all the identified consuming items) we collected in the real residential building. This house has been equipped with a collecting system and we obtained about one year of data [39]. We also collected detailed information about the inhabitants' way of life so as to propose realistic occupancy (Section 2.2) and behaviour (Section 2.3) scenarios. As a result, the developed model can be regarded as fully representative of the residential building thermal behaviour.

2.2. Occupancy scenarios and temperature regulation

Because of their impact on energy consumption, inhabitants' lifestyle and habits have been first taken into account through occupancy scenarios and indoor temperature setpoints. The first scenario (OS_1) is a conventional RT2005 scenario defined as follows: during working days (*i.e.* from Monday to Friday), the considered house is occupied from 6 p.m. to 10 a.m. During weekends (*i.e.* Saturday and Sunday), it is occupied 24 hours a day. The main drawback of the scenario is that all the rooms in the house have the same occupancy. So, the indoor temperature setpoint is defined in the following way (whatever the room and for both HVAC (Heating, Ventilation and Air-Conditioning) operation modes, *i.e.* heating and cooling):

- HVAC heating mode: T_{sp} = 19 °C during occupancy times and T_{sp} = 16 °C when the single-storey house is not occupied.
- HVAC cooling mode: T_{sp} = 28 °C during occupancy times and T_{sp} = 30 °C when the single-storey house is not occupied.

Due to the limitations of the conventional RT2005 scenario (OS_1), a new scenario has been proposed (OS_2). It allows occupancy to be defined for each of the main rooms in the house (bedrooms 1, 2 and 3, corridor, kitchen, and living room). Let us note that occupancy is unchanged for both the bathroom and garage. Moreover, the temperature setpoint (T_{sp}) remains the same, whatever the HVAC operation mode (*i.e.* heating or cooling):

- Bedroom 1 ($16\,m^2$): 9:00 p.m. to 7:00 a.m. (working days); 9:00 p.m. to 7:00 a.m. (weekends).
- Bedroom 2 ($19\,m^2$): 9:00 p.m. to 7:00 a.m. (working days); 9:00 p.m. to 7:00 a.m. (weekends).
- Bedroom 3 ($19\,m^2$): 9:00 p.m. to 7:00 a.m. (working days); 9:00 p.m. to 7:00 a.m. (weekends).
- Corridor ($17\,m^2$): 6:00 a.m. to 8:30 a.m., 12:00 p.m. to 2 p.m. and 6:00 p.m. to 9:00 p.m. (working days); 9:00 a.m. to 9 p.m. (weekends).

Table 2: Characteristics of the materials used in the residential building (RT2005 insulation standards).

Element	Material	Thickness (m)	U ($\mathrm{W\,m^{-2}\,K^{-1}}$)	U_{RT2005} ($\mathrm{W\,m^{-2}\,K^{-1}}$)
External wall	BA13	0.013	0.602	0.45
	Rockwool	0.06		
	Cinderblock	0.2		
	Surface coating	0.02		
Internal wall	BA13	0.013	0.845	n.a.
	Glass wool	0.04		
	BA13	0.013		
Floor	Tiles	0.022	0.415	0.4
	Mortar	0.05		
	Heavy concrete	0.16		
	Expanded polystyrene	0.08		
Ceiling	BA13	0.013	0.196	0.34
	Glass wool	0.1		
	Air knife	0.5		
	Terracotta	0.01		
Garage ceiling	BA13	0.013	2.37	0.34
	Terracotta	0.2		
Windows	Double glazed	0.2	1.43	2.6

Table 3: Characteristics of the materials used in the residential building (1980's insulation standards).

Element	Material	Thickness (m)	U ($\mathrm{W\,m^{-2}\,K^{-1}}$)
External wall	BA13	0.013	2.172
	Cinderblock	0.2	
	Surface coating	0.02	
Internal wall	BA13	0.013	2.486
	Brick	0.05	
	BA13	0.013	
Floor	Tiles	0.022	2.845
	Mortar	0.05	
	Heavy concrete	0.16	
Ceiling	BA13	0.013	2.37
	Terracotta	0.02	
Windows	Simple glazed	0.0025	0.87

Table 4: Behaviour scenario BS_1. Washing machine, clothes dryer and dishwasher (regular) use.

Home appliance	Nov. 1 to Apr. 30 ("winter/spring" season)	May 1 to Oct. 31 ("summer/autumn" season)
Washing machine	6:00 p.m. to 7:45 p.m.	2:15 p.m. to 4:00 p.m.
Clothes dryer	6:00 p.m. to 8:10 p.m.	2:00 p.m. to 4:10 p.m.
Dishwasher	5:45 p.m. to 7:55 p.m.	2:00 p.m. to 4:15 p.m.

Table 5: Behaviour scenario BS_2. Washing machine, clothes dryer and dishwasher (energy-efficient) use.

Home appliance	Nov. 1 to Apr. 30 ("winter/spring" season)	May 1 to Oct. 31 ("summer/autumn" season)
Washing machine	3:15 a.m. to 5:00 a.m.	3:15 a.m. to 5:00 a.m.
Clothes dryer	3:00 a.m. to 5:10 a.m.	3:00 a.m. to 5:10 a.m.
Dishwasher	3:00 a.m. to 5:15 a.m.	3:00 a.m. to 5:15 a.m.

– Kitchen ($12\,\mathrm{m^2}$): 7:00 a.m. to 8:30 a.m., 12:00 p.m. to 1:30 p.m. and 7:00 p.m. to 8:30 p.m. (working days); 7:00 a.m. to 8:30 a.m., 12:00 p.m. to 1:30 p.m. and 7:00 p.m. to 8:30 p.m. (weekends).

– Living room ($53\,\mathrm{m^2}$): 6:00 a.m. to 7:30 a.m., 12:30 p.m. to 1:30 p.m. and 7:30 p.m. to 9:30 p.m. (working days); 9:00 a.m. to 2:00 p.m. and 7:00 p.m. to 11:00 p.m. (weekends).

2.3. Demand Response (DR) mechanisms

As stated above in the paper (Section 1) and according to the Federal Energy Regulatory Commission, DR is about "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reli-

ability is jeopardized" [27]. So, we defined two behaviour scenarios (BS_1 and BS_2) so as to evaluate the impact of load shifting on energy efficiency as well as the economic savings one can achieve using this technique. Both scenarios allow the operation of all the home appliances (*i.e.* cooking, cleaning, and entertainment appliances) to be scheduled [39]. The first scenario (BS_1) describes a regular (standard) use of these appliances, in accordance with established practice in southern France. It is fully representative of the (real building) inhabitants' behaviour. The second scenario (BS_2) deals with an energy-efficient (economical) use by shifting some of the home appliances from on-peak to off-peak periods, whatever the period of the year. We focused on the washing machine, clothes dryer and dishwasher use (Tables 4 and 5). Taking a look at Table 4 (which is about scenario BS_1), one can clearly observe that the appliances operation is impacted by the period of the year. Indeed, during the "winter/spring" season, the washing machine, clothes dryer and dishwasher are used when the occupants get back home after work or school. However, during the "summer/autumn" season, these appliances are used early in the afternoon, as a result of changes in the building occupancy (due, in particular, to holiday periods). Other home appliances such as HVAC sub-systems, cooking appliances or some consumer electronics cannot be shifted easily, because of thermal comfort and lifestyle constraints.

2.4. Building's energy production systems

Local production of renewable energy has also been modelled. First, we described the photovoltaic solar panels operation using the TRNSYS model type 194. This model is based on both the calculation method presented by DeSoto [40] and the five-parameter (I_L, I_0, R_s, R_{sh}, and a) equivalent circuit proposed by Duffie and Beckman [41]. The main purpose of such a model is to extrapolate performance information provided by the manufacturer at standard rating conditions (1000 $\mathrm{W\,m^{-2}}$, 25 °C, air mass 1.5) to other operating conditions. The current-voltage ($I-V$) relationship is determined, from the above-mentioned parameters, as a function of solar radiation and PV array temperature (1 and 2):

$$I = I_L - I_0 \times [\exp \frac{V + I \cdot R_s}{a}] - \frac{V + I \cdot R_s}{R_{sh}} \quad (1)$$

$$a = \frac{N_s \cdot \eta_I \cdot k_B \cdot T_c}{q} \quad (2)$$

with I_L the light current, I_0 the diode reverse saturation current, R_s the series resistance, R_{sh} the shunt resistance, and a the modified ideality factor. This last parameter is expressed from the number of modules in series in array (N_s), the ideality factor (η_I), the Boltzmann constant (k_B), the PV array temperature (T_c), and the electron charge constant (q). Regarding the vertical-axis wind turbine, it is described using the TRNSYS model type 90. This model comes from the work of Quinlan [42] and allows the power output of a wind energy conversion system based on a power vs. wind speed characteristic to be calculated. The power output of the wind turbine (P) is then evaluated from the power coefficient for a wind turbine (C_p), the rotor area (A_R), air density (ρ), and wind speed (U_0) (3):

$$P = C_p \cdot \rho \cdot A_R \cdot U_0^3 \quad (3)$$

2.5. Batteries for electricity storage

We used the model developed by Bogdan and Salameh [43] to describe the batteries functioning, *i.e.* the charging (4) and discharging (5) processes [44]. At time t, indexed by k, such as $t = k \cdot T_s$ with T_s the simulation sampling time ($T_s = 1\,\mathrm{min}$), the status of the batteries equipping the building is related to both the status at previous time index $k-1$ and the production/consumption of energy at time index k:

$$E_{bat}(k) = (1-\tau) \cdot E_{bat}(k-1) + \left(E^p_{ren}(k) - \frac{E_{sto}(k)}{\eta_{inv}}\right) \cdot \eta_{bat} \quad (4)$$

$$E_{bat}(k) = (1-\tau) \cdot E_{bat}(k-1) + \left(\frac{E_{sto}(k)}{\eta_{inv}} - E^p_{ren}(k)\right) \quad (5)$$

with η_{inv} the inverter performance, η_{bat} the charge performance, E_{sto} the amount of energy available to be stored in the batteries, E_{bat} the amount of energy stored in the batteries, E^p_{ren} the amount of renewable energy produced by the local systems which equip the considered building, after taking the energy losses due to the controller into account, and τ the hourly self-discharge rate (equal to 10^{-4}). Performance is supposed to be constant and equal to 85% in charging mode whereas it is equal to 1 in discharging (release) mode. The amount of energy stored in the batteries is used when the local production is not sufficient to meet the demand in energy. In opposition, energy is stored when the power supplied by the renewable energy systems exceed the house requirements. However, it should be noticed that the amount of energy which can be stored in the batteries equipping the building is related to E^{min}_{bat} and E^{max}_{bat}, as depicted by (6):

$$E^{min}_{bat} \leq E_{bat}(k) \leq E^{max}_{bat} \quad (6)$$

The maximum capacity of the batteries (E^{max}_{bat}) is equal to the rated capacity. On his part, the minimum capacity (E^{min}_{bat}) is evaluated from the Depth of Discharge (DoD), as shown in (7). DoD is used to describe how deeply the batteries are discharged:

$$E^{min}_{bat} = (1 - DoD) \times E^{max}_{bat} \quad (7)$$

According to the various specifications given by the manufacturer, the life of the batteries can be extended if the DoD is between 30% and 50% [41]. So, we considered a depth of discharge of 30%.

Table 6: Energy price model coefficients.

	$i = 0$	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$
$j = 0$	8.11×10^{1}	-4.63×10^{0}	9.14×10^{-2}	1.22×10^{-4}	-3.67×10^{-7}	3.79×10^{-9}
$j = 1$	-1.67×10^{1}	9.06×10^{-1}	-1.58×10^{-2}	1.30×10^{-4}	-4.04×10^{-7}	n/a
$j = 2$	-1.11×10^{-1}	-2.37×10^{-3}	7.01×10^{-5}	5.66×10^{-8}	n/a	n/a
$j = 3$	1.01×10^{-2}	-3.57×10^{-4}	-1.82×10^{-6}	n/a	n/a	n/a
$j = 4$	2.69×10^{-4}	1.29×10^{-5}	n/a	n/a	n/a	n/a
$j = 5$	-1.94×10^{-5}	n/a	n/a	n/a	n/a	n/a

Table 7: Off-peak, part-peak, and on-peak periods.

Period	November 1 to April 30 ("winter/spring" season)	May 1 to October 31 ("summer/autumn" season)
On-peak	10:00 a.m. to 5:00 p.m.	7:00 a.m. to 1:30 p.m. 2:30 p.m. to 4:00 p.m. 5:30 p.m. to 8:30 p.m.
Part-peak	12:00 a.m. to 2:00 a.m. 7:00 a.m. to 10:00 a.m. 5:00 p.m. to 11:00 p.m.	12:00 a.m. to 2:00 a.m. 6:00 a.m. to 7:00 a.m. 1:30 p.m. to 2:30 p.m. 4:00 p.m. to 5:30 p.m. 8:30 p.m. to 11:00 p.m.
Off-peak	2:00 a.m. to 7:00 a.m. 11:00 p.m. to 12:00 a.m.	2:00 a.m. to 6:00 a.m. 11:00 p.m. to 12:00 a.m.

3. Energy management strategies

This section of the paper is about the two strategies we developed and tested in simulation so as to manage the microgrid energy resources efficiently. The first strategy (titled "reference" strategy) deals with managing energy production systems only (photovoltaic solar panels or a combination of photovoltaic solar panels and a vertical-axis wind turbine). With the second strategy (titled "advanced" strategy), one can manage local power generation as well as electricity storage. Demand Response (DR) mechanisms are considered through different behaviour scenarios (Section 2.3), in response to supply conditions. Remember that the first scenario (BS_1) is fully representative of the (real building) inhabitants' behaviour. The second one (BS_2) deals with an energy-efficient use of the home appliances. Various energy and economic criteria are proposed as performance indicators.

3.1. Performance indicators

3.1.1. Renewable energy coverage rate

The first criterion ($\%_{ren}$) is defined as the percentage ratio of the renewable energy produced and consumed *in situ* to the total energy consumed. The total energy consumed is the sum of the amount of energy produced and consumed *in situ* (E^c_{ren}) and the amount of energy extracted from the electricity grid (E_{ext}). $\%_{ren}$ has to be maximized in order to decrease the dependency on the grid of a building (8):

$$\%_{ren} = 100 \times \frac{E^c_{ren}}{E^c_{ren} + E_{ext}} \tag{8}$$

3.1.2. Self-consumption of energy

$\%_{sc}$ is the percentage ratio of the renewable energy consumed (E^c_{ren}) to the renewable energy produced *in situ* (E^p_{ren}). Maximizing this criterion allows self-consumption of energy to be promoted (9):

$$\%_{sc} = 100 \times \frac{E^c_{ren}}{E^p_{ren}} \tag{9}$$

3.1.3. Renewable energy use

In order to find a reasonable compromise between the renewable energy coverage rate ($\%_{ren}$) and self-consumption of energy ($\%_{sc}$) and, as a result, to avoid the optimization process to lead to non-realistic configurations (*i.e.* highly undersized or oversized energy production and storage systems), both criteria are combined in a single criterion (J_{ren}) defined as follows (10):

$$J_{ren} = \frac{\%_{ren} \times \%_{sc}}{100} \tag{10}$$

3.1.4. Dynamic pricing and economic cost

An economic cost criterion (J_{cost}) has also been defined, not according to the purchase and sale prices currently charged by EDF (*Electricité de France*), the main French electricity supplier, but based on a future application of dynamic pricing in the coming years. Dynamic pricing is already in use in the energy market and consists in adjusting energy prices dynamically, with a short time step. Dynamic pricing reflects variations in electricity production costs as well as daily and seasonally variations in the grid load. So, a polynomial electricity price model (P_{en}) has been identified from both the grid load (L_{grid}) and outdoor temperature (T_{out}) (we used historical data about T_{out} provided by Meteonorm [45]) (11). Meteonorm offers meteorological data (over 30 parameters available) for every place on Earth. Table 6 groups together the coefficiens we identified. Considering data from the European Power Exchange (EPEX SPOT SE) [46], the Mean Square Error

(MSE) observed is about 10%. EPEX SPOT SE operates the power spot markets for short-term (*i.e.* day-ahead and intraday) trading in power in Germany, France, Austria and Switzerland, with Germany and Austria forming one price zone. These five countries account together for about one third of the European power consumption:

$$P_{en}(k) = \sum_{i,j}(a_{i,j} \times L^i_{grid}(k) \times T^j_{out}),\ \forall i,j \in [\![0;5]\!] \quad (11)$$

Economic cost criterion J_{cost} is then calculated as the difference between the cost related to the purchase of energy and the economic gain resulting from the sale of energy. E_{ext} is the amount of energy extracted from the electricity grid, E_{inj} is the amount of energy injected to the grid and P_{en} is the dynamic electricity price. J_{cost} is negative when the amount of energy bought to the grid is more important than the amount of renewable energy produced and sold. It becomes positive when the amount of renewable energy sold to the electricity grid becomes higher than the amount of energy bought to the grid (12):

$$J_{cost} = \sum_{k}(E_{inj}(k) \times P_{en}(k) - E_{ext}(k) \times P_{en}(k)) \quad (12)$$

3.1.5. Electricity grid status

The grid load (L_{grid}) varies in daily (several peaks of electricity consumption) and seasonal (demand in energy is higher in winter than it is in summer) cycles. Taking a look at Figures 3 (May 1 to October 31) and 4 (November 1 to April 30), one can note that electricity consumption is clearly impacted by lifestyle and habits (data are from the electricity grid of the Perpignan-Méditerranée agglomeration community, which is about 280 000 persons and 655 km^2). In addition, daily profiles look similar throughout the year with off-peak periods (*i.e.* low-demand periods) at about 4 a.m. and on-peak periods at about 7 p.m. during the "winter/spring" season (November 1 to April 30) and 3 p.m. during the "summer/autumn" season (May 1 to October 31). So, an analysis allowed us to define on-peak, part-peak and off-peak periods, whatever the season of the year (Table 7). First, so as to characterize the electricity grid status, taking the daily and seasonal variations one can observe in its load into account, a daily normalization ($\widetilde{L}_{grid}$) has been made. d is for a given day of the year (13, 14, and 15):

$$\widetilde{L}_{grid}(h,d) = \frac{L_{grid}(h,d)}{max(L_{grid}(h,d))} \text{ with } h = 1,...,24 \quad (13)$$

$$L_{grid}(h,d) = [L_{grid}(1,d),\ldots,L_{grid}(24,d)] \quad (14)$$

$$\widetilde{L}_{grid}(h,d) = [\widetilde{L}_{grid}(1,d),\ldots,\widetilde{L}_{grid}(24,d)] \quad (15)$$

Then, through the intermediary of a threshold (T_{grid}), we highlighted a limit beyond which injecting to the grid a local production of electricity is not appropriate. From the daily normalized grid load ($\widetilde{L}_{grid}$) and taking the different consumption periods we highlighted in Table 7 into consideration (*i.e.* off-peak, part-peak, and on-peak periods), one can associate peaks in energy consumption to a value of $\widetilde{L}_{grid}$ higher than 0.7 and troughs to a value of $\widetilde{L}_{grid}$ lower than 0.3. So, we proposed two thresholds of 30% and 70% (Figures 6 and 7), respectively, as well as a criterion dealing with the electricity grid status (J_{grid}). This criterion is defined considering part-peak periods either as off-peak or on-peak periods. So, if part-peak periods are considered as off-peak periods, J_{grid} is set as follows, for T_{grid} = 70% (in that case, the electricity grid is in need of energy during peaks of demand only) and d a given day, with $h = 1,...,24$ (16):

$$\begin{aligned} &- J_{grid}(h,d) = 1 \text{ if } \widetilde{L}_{grid}(h,d) \geq T_{grid} \\ &- J_{grid}(h,d) = 0 \text{ if } \widetilde{L}_{grid}(h,d) < T_{grid} \end{aligned} \quad (16)$$

However, if part-peak periods are considered as on-peak periods, J_{grid} is set as follows, for T_{grid} = 30% (in that case, energy can be appropriately injected to the grid most of the time) and d a given day, with $h = 1,...,24$ (17):

$$\begin{aligned} &- J_{grid}(h,d) = 1 \text{ if } \widetilde{L}_{grid}(h,d) \geq T_{grid} \\ &- J_{grid}(h,d) = 0 \text{ if } \widetilde{L}_{grid}(h,d) < T_{grid} \end{aligned} \quad (17)$$

3.1.6. Impact on the electricity grid

In order for the impact of the house equipped with energy production and storage systems on the Perpignan-Méditerranée electricity grid to be estimated, we defined two criteria dealing with local production of renewable energy (I_{inj}) and energy extraction (I_{ext}), respectively. Both criteria (22 and 23) are expressed from ΔT_{grid} (*i.e.* the deviation between the threshold and the grid load). Finally, the overall impact on the grid (I_{grid}) (24) is defined as a combination of I_{inj} and I_{ext}.

Calculation of ΔT_{grid}. The deviation between the threshold and the grid load allows ascertaining if injecting energy to the grid is more or less favourable at time index k. In that case, ΔT_{grid} is normalized between 0 and 1 if $\widetilde{L}_{grid}(k)$ is higher than T_{grid} (18) and between −1 and 0 if $\widetilde{L}_{grid}(k)$ is lower than T_{grid} (19):

$$\Delta T_{grid}(k) = \frac{\widetilde{L}_{grid}(k) - T_{grid}}{1 - T_{grid}} \text{ if } \widetilde{L}_{grid}(k) > T_{grid} \quad (18)$$

$$\Delta T_{grid}(k) = \frac{\widetilde{L}_{grid}(k)}{T_{grid}} - 1 \text{ if } \widetilde{L}_{grid}(k) < T_{grid} \quad (19)$$

As stated above in the paper (Section 3.1.5), a high threshold (a threshold, for example, equal to 70%) is for an electricity grid which is in need of energy during peaks of demand only. In opposition, with a low threshold (a threshold, for example, equal to 30%), energy can be appropriately injected to the grid most of the time.

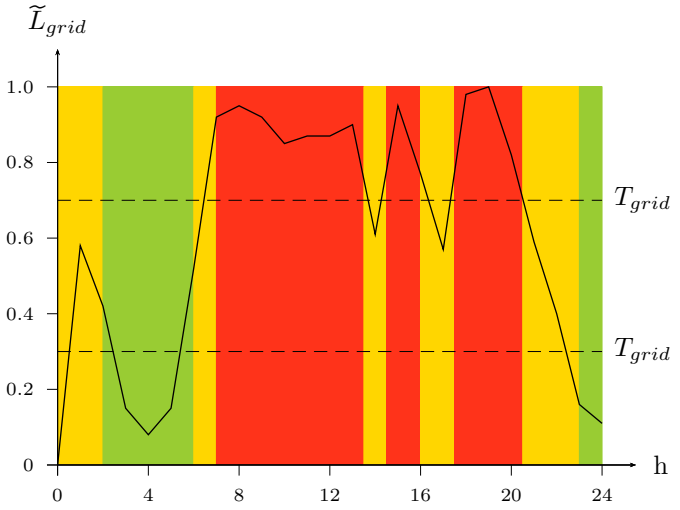


Figure 6: Normalized daily load of the "Perpignan-Méditerranée" agglomeration community ($\widetilde{L}_{grid}$) during the "winter/spring" season (*i.e.* November 1 to April 30). Red, yellow and green colors are for on-peak, part-peak and off-peak periods, respectively. Dashed lines are for the grid thresholds (T_{grid} = 30% and T_{grid} = 70%).

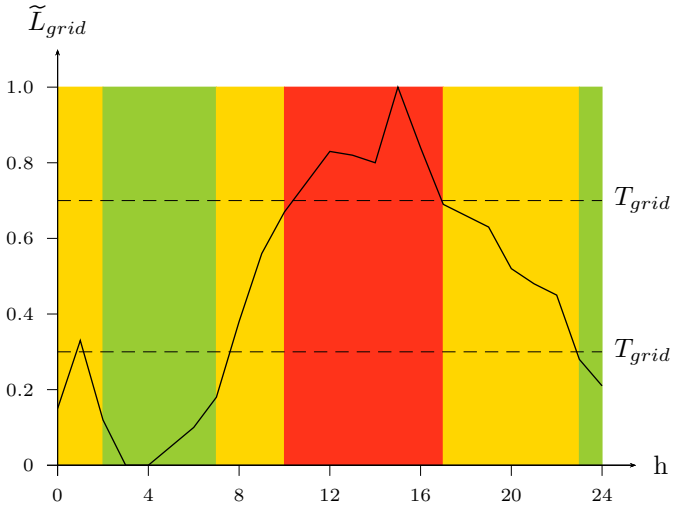


Figure 7: Normalized daily load of the "Perpignan-Méditerranée" agglomeration community ($\widetilde{L}_{grid}$) during the "summer/autumn" season (*i.e.* May 1 to October 31). Red, yellow and green colors are for on-peak, part-peak and off-peak periods, respectively. Dashed lines are for the grid thresholds (T_{grid} = 30% and T_{grid} = 70%).

As for energy injection (18 and 19), the deviation between the threshold and the grid load allows ascertaining if extracting energy from the grid is more or less favourable at time index k. In that case, ΔT_{grid} is normalized between 0 and 1 if $\widetilde{L}_{grid}(k)$ is lower than T_{grid} (20) and between −1 and 0 if $\widetilde{L}_{grid}(k)$ is higher than T_{grid} (21):

$$\Delta T_{grid}(k) = \frac{\widetilde{L}_{grid}(k) - T_{grid}}{1 - T_{grid}} \text{ if } \widetilde{L}_{grid}(k) < T_{grid} \quad (20)$$

$$\Delta T_{grid}(k) = \frac{\widetilde{L}_{grid}(k)}{T_{grid}} - 1 \text{ if } \widetilde{L}_{grid}(k) > T_{grid} \quad (21)$$

Local production of renewable energy. The impact on the grid of the local production of renewable energy (as stated above, the considered house can be equipped with photovoltaic solar panels or with a combination of photovoltaic solar panels and a vertical-axis wind turbine) (I_{inj}) is defined from both the amount of energy injected to the grid (E_{inj}) and ΔT_{grid} (22). k is the time index:

$$I_{inj} = \frac{1}{1000} \times \sum_{k} (E_{inj}(k) \times \Delta T_{grid}(k)) \quad (22)$$

Energy extraction. The impact on the electricity grid of energy extraction (I_{ext}) is defined from both the amount of energy extracted from the grid (E_{ext}) and ΔT_{grid} (23). k remains the time index:

$$I_{ext} = \frac{1}{1000} \times \sum_{k} (E_{ext}(k) \times \Delta T_{grid}(k)) \quad (23)$$

Overall impact. The overall impact criterion (I_{grid}) is defined as the sum of I_{inj} (22) and I_{ext} (23). If it is positive, locally-produced electricity is injected to the grid when demand is high whereas electricity is extracted from the grid when demand is low (24):

$$I_{grid} = I_{inj} + I_{ext} \quad (24)$$

3.2. Management strategy without electricity storage

The first strategy is proposed so as to manage the energy resources of the residential building when it is equipped with production systems only (photovoltaic solar panels or a combination of photovoltaic solar panels and a vertical-axis wind turbine). This strategy is based on three different cases and considered as the "reference" strategy. Performance is of course impacted by the production systems design (sizing) (Figure 8):

- *Overproduction* ($\delta(k) > 0$): The amount of renewable energy produced at time index k ($E^p_{ren}(k)$) is higher than instantaneous energy consumption. As a result, local production covers all the energy needs of the residential building ($E_{hou}(k)$) and no energy is extracted from the grid ($E^c_{ren}(k) = E_{hou}(k)/\eta_{inv}$, with η_{inv} the inverter performance, and $E_{ext}(k) = 0$). The surplus of energy produced *in situ* is injected to the grid ($E_{inj}(k) = \delta(k)$) (case 1).
- *Production and consumption are balanced* ($\delta(k) = 0$): The amount of renewable energy produced at time index k ($E^p_{ren}(k)$) and instantaneous energy consumption are balanced. Therefore, all the energy produced is consumed *in situ* ($E^c_{ren}(k) = E^p_{ren}(k)$) and there is no interaction between the residential building and the electricity grid ($E_{inj}(k) = E_{ext}(k) = 0$) (case 2).
- *Underproduction* ($\delta(k) < 0$): The amount of renewable energy produced at time index k ($E^p_{ren}(k)$) is lower than instantaneous energy consumption. So, all the energy produced is consumed *in situ* ($E^c_{ren}(k) = E^p_{ren}(k)$). In addition, there is no injection of energy

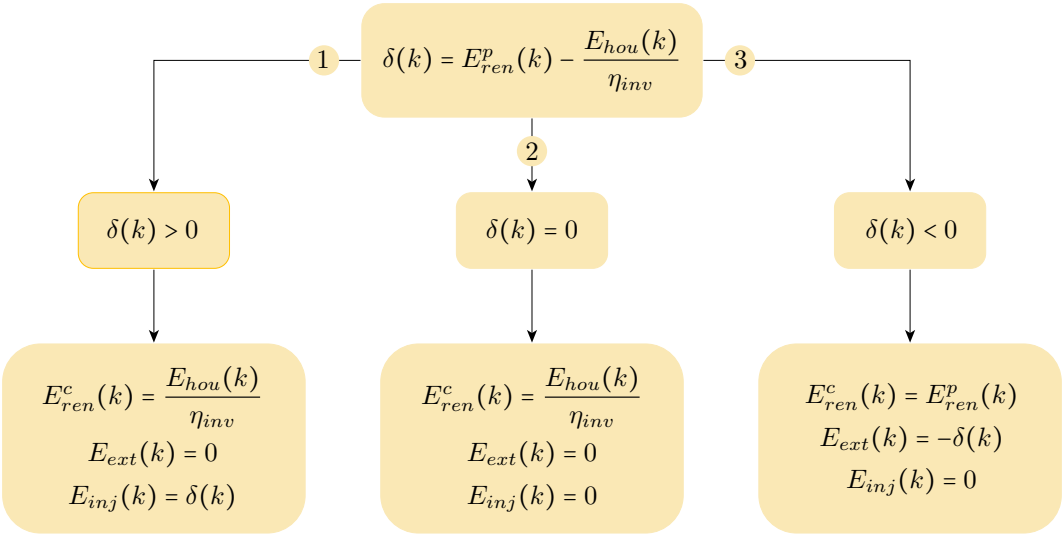


Figure 8: Management strategy without batteries for electricity storage (reference strategy). Case 1 is for overproduction of renewable energy ($\delta(k) > 0$). Case 2 is for local production and energy consumption balanced ($\delta(k) = 0$). Case 3 is for underproduction of renewable energy ($\delta(k) < 0$). See Sections 3.1 and 3.2 for a description of the parameters involved in the strategy.

to the grid ($E_{inj}(k) = 0$). The missing amount of energy related to the needs of the residential building is extracted from the grid ($E_{ext}(k) = -\delta(k)$) (case 3).

3.3. Management strategy with electricity storage

The second strategy (titled "advanced" strategy) allows the energy resources of the residential building (the single-storey house), when it is equipped with production (photovoltaic solar panels or a a combination of photovoltaic solar panels and a vertical-axis wind turbine) and storage (batteries) systems, to be managed efficiently. This strategy is based on three different cases. Again, performance is clearly impacted by the production and storage systems design (Figures 9, 10 and 11):

- *Overproduction* ($\delta(k) > 0$): the amount of renewable energy produced at time index k ($E^p_{ren}(k)$) is higher than instantaneous energy consumption. As a consequence, local production covers all the energy needs of the considered building ($E_{hou}(k)$) and no energy is extracted from the grid ($E^c_{ren}(k) = E_{hou}(k)/\eta_{inv}$ and $E_{ext}(k) = 0$). The surplus of energy produced *in situ* is managed taking the electricity grid status ($J_{grid}(k)$) into consideration. If the demand in energy is high ($J_{grid}(k) = 1$), the surplus of energy produced is injected to the grid ($E_{inj}(k) = \delta(k)$) and used to maintain the batteries at minimum capacity ($E_{bat}(k) = E^{min}_{bat}$). As stated previously, E^{min}_{bat} is determined from the Depth of Discharge (DoD) (Section 2.5). DoD describes how deeply the batteries are discharged. If the demand in energy is low ($J_{grid}(k) = 0$) and the batteries are not already fully charged, the surplus of energy produced *in situ* is stored in whole ($E_{sto}(k) = \delta(k)$ and $E_{inj}(k) = 0$) or in part ($E_{sto}(k) = E_{bat}(k) - E_{bat}(k-1)$ and $E_{inj}(k) = \delta(k) - E_{sto}(k)$) (Figure 9) (case 1).
- *Production and consumption are balanced* ($\delta(k) = 0$): the amount of renewable energy produced at time index k ($E^p_{ren}(k)$) and instantaneous energy consumption are balanced. As a result, all the energy produced is consumed *in situ* ($E^c_{ren}(k) = E^p_{ren}(k)$) and there is usually no interaction between the building, the electricity grid and the batteries ($E_{inj}(k) = E_{ext}(k) = E_{sto}(k) = 0$). If necessary, energy is extracted from the electricity grid, in that case $E_{ext}(k) = E_{sto}(k)$, so as to maintain the batteries at minimum capacity ($E_{bat}(k) = E^{min}_{bat}$) (Figure 10) (case 2).
- *Underproduction* ($\delta(k) < 0$): the amount of renewable energy produced at time index k ($E^p_{ren}(k)$) is lower than instantaneous energy consumption. As a result, all the energy produced is consumed *in situ* ($E^c_{ren}(k) = E^p_{ren}(k)$) and energy is released from the batteries ($E_{rel}(k) = E_{bat}(k-1) - E_{bat}(k)$), if they are charged. Otherwise, the missing amount of energy necessary to cover all the needs of the building is extracted from the electricity grid ($E_{ext}(k) = -\delta(k) - E_{rel}(k)$). In addition, energy coming from the grid allows the batteries to be maintained at minimum capacity ($E_{bat}(k) = E^{min}_{bat}$). There is no injection of energy to the grid ($E_{inj}(k) = 0$) (Figure 11) (case 3).

3.4. Optimization problem

The optimization problem is formulated as find P_{pv}, P_{wt} and E^{max}_{bat} so that J_{ren} is maximized (25). Let us remember that J_{ren} is defined as a combination of the renewable energy coverage rate ($\%_{ren}$) and the percentage ratio of the renewable energy consumed to the renewable energy produced *in situ* ($\%_{sc}$) (10). P_{pv} is the PV panels peak power (kWp), P_{wt} is the wind turbine peak power (kWp) and E^{max}_{bat} is the rated capacity of the batteries (kW h). We defined the optimization constraints in the following way

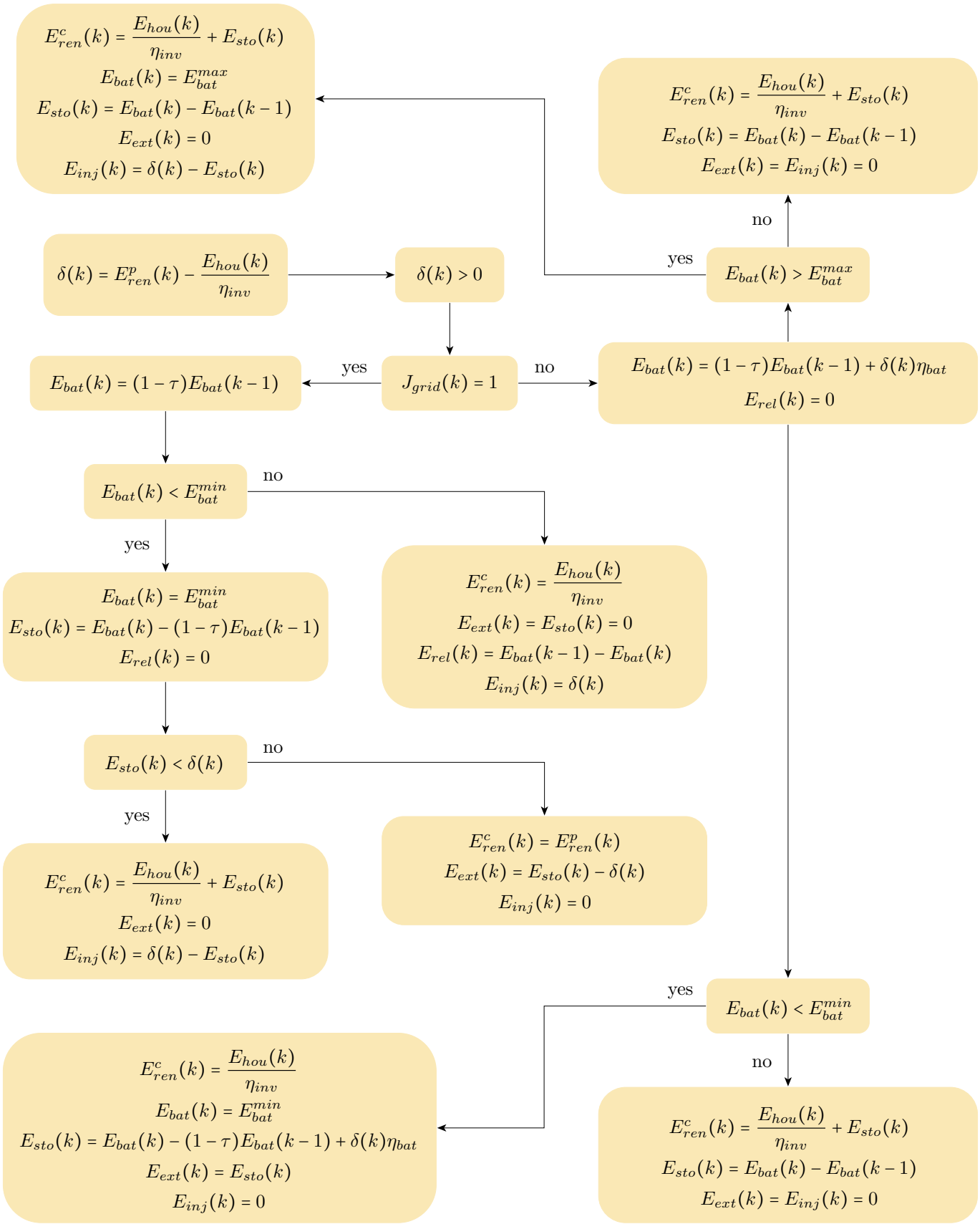


Figure 9: Management strategy with batteries for electricity storage (advanced strategy). Case 1 is for overproduction of renewable energy ($\delta(k) > 0$). See Sections 2.5, 3.1 and 3.2 for a description of the parameters involved in the strategy.

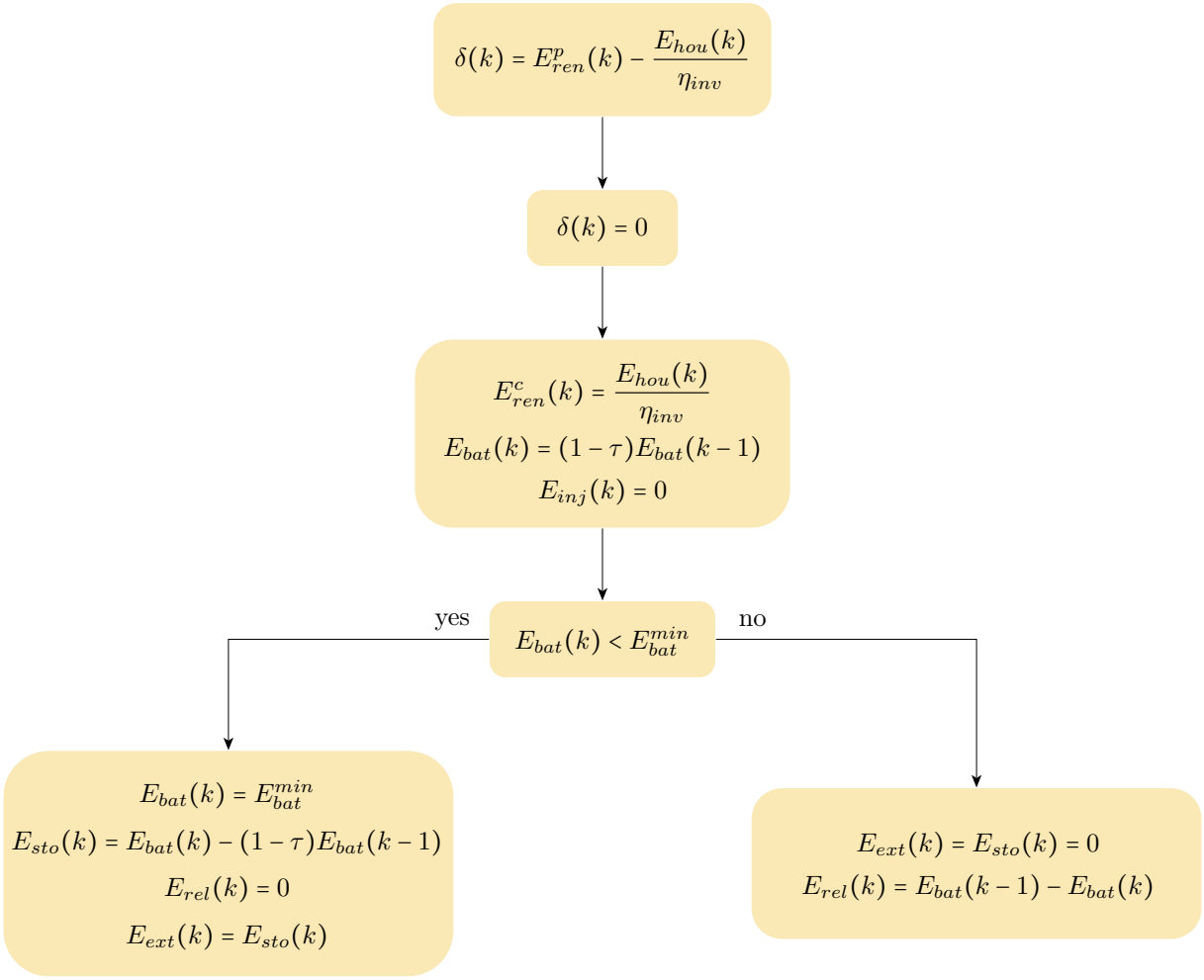


Figure 10: Management strategy with batteries for electricity storage (advanced strategy). Case 2 is for local production and energy consumption balanced ($\delta(k) = 0$). See Sections 2.5, 3.1 and 3.2 for a description of the parameters involved in the strategy.

(26): first, P_{pv} is constrained by the available roof surface area (*i.e.* 80 m^2). So, given that 1 m^2 of photovoltaic solar panels stands for a peak power of 100 Wp [47], the maximum possible value of P_{pv} is 8 kWp. Regarding P_{wt}, its maximum possible value is 20 kWp, according to the vertical-axis wind turbines one can find in the market and install on a residential building roof [47]. Finally, E^{max}_{bat} is constrained by the size of the batteries, and 2 m^3 (what leads to a rated capacity of about 185 kW h) seems to be the maximum volume one can dedicate to electricity storage. So, we decided for $0 \leq E^{max}_{bat} \leq 200$ kW h:

$$\max_{P_{pv}, P_{wt}, E^{max}_{bat}} \left(J_{ren} = \frac{\%_{ren} \times \%_{sc}}{100} \right) \tag{25}$$

$$\text{with} \begin{cases} 0 \leq P_{pv} \leq 8\,\text{kWp} \\ 0 \leq P_{wt} \leq 20\,\text{kWp} \\ 0 \leq E^{max}_{bat} \leq 200\,\text{kW h} \end{cases} \tag{26}$$

In the next section of the paper, noteworthy configurations are highlighted and discussed, for both the "reference" and "advanced" management strategies.

4. Systems design and strategies evaluation

This section of the paper is about designing the energy (photovoltaic solar panels and a vertical-axis wind turbine) and storage (batteries) systems with whom the residential building can be equipped as well as evaluating in simulation the proposed management strategies (Sections 3.2 and 3.3). The section ends with a discussion about the results we obtained and possible improvements. The way both the local production of renewable energy and electricity storage impact on the electricity grid is also studied. Simulation period is one year (meteorological data offered by Meteonorm [45] are used to carry out the process).

4.1. Residential building equipped with energy production systems only (reference strategy)

In this section, we highlight and discuss noteworthy configurations, without electricity storage facilities (*i.e.* batteries) equipping the considered residential building. So, the single-storey house is equipped with photovoltaic solar panels (P_{pv}) only or with photovoltaic solar panels and a vertical-axis wind turbine (P_{wt}). The reference strategy is used to manage these systems (Section 3.2). Tables 8

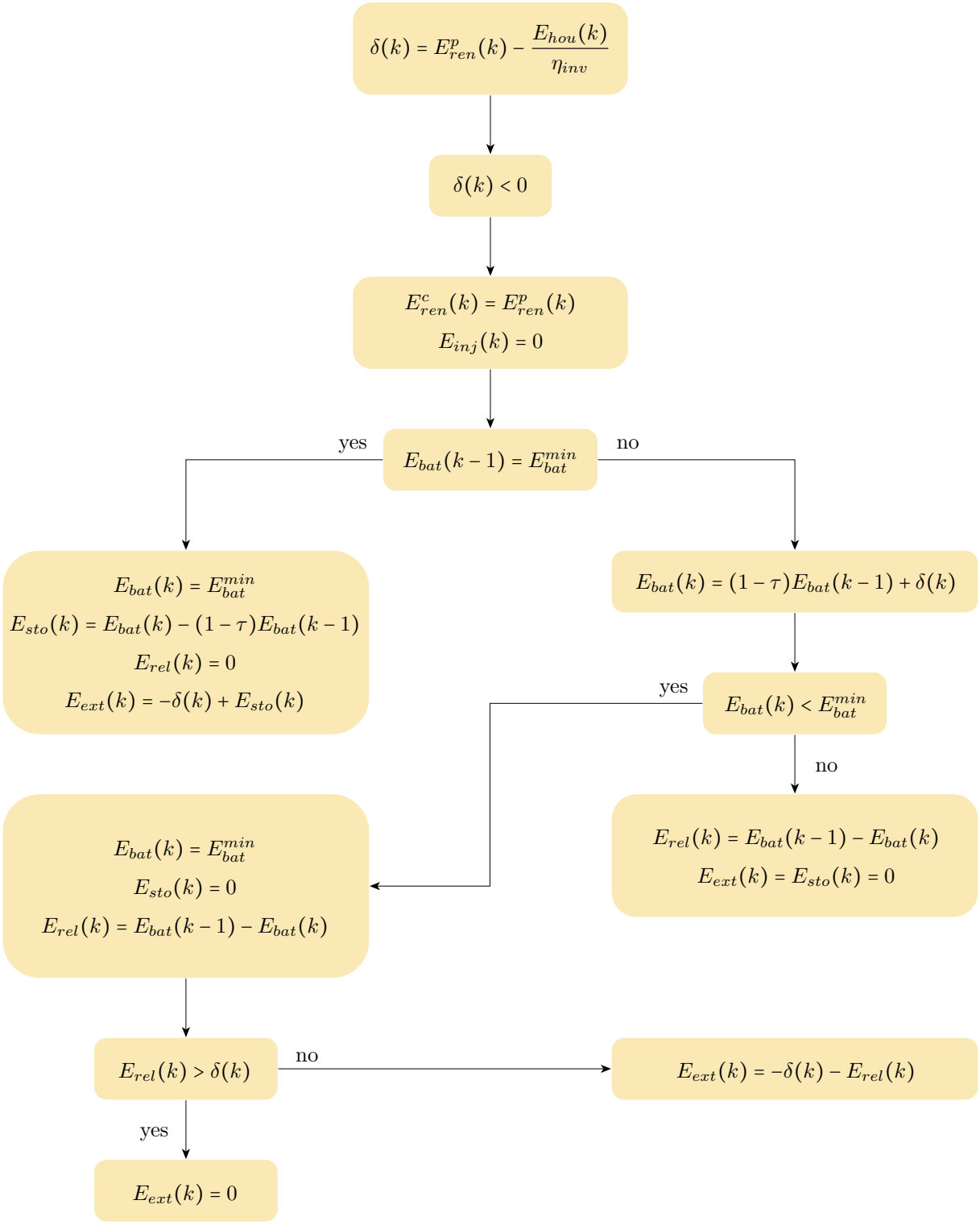


Figure 11: Management strategy with batteries for electricity storage (advanced strategy). Case 3 is for underproduction of renewable energy ($\delta(k) < 0$). See Sections 2.5, 3.1 and 3.2 for a description of the parameters involved in the strategy.

to 11 point out the most insteresting configurations we obtained. For each of the eight combinations of characteristics we considered in the present study (1980's or RT2005 insulation standards, occupancy scenario 1 or 2, behaviour scenario 1 or 2), three configurations are highlighted (see Sections 2.1, 2.2 and 2.3 for details about insulation levels and proposed scenarios). The first configuration is defined on the basis of photovoltaic solar panels of 3 kWp, which is a standard design for such facilities. We obtained the second (in that case, the building is equipped with photovoltaic solar panels only) and third (in that case, the building is equipped with photovoltaic solar panels and a

Table 8: Noteworthy configurations, with no batteries for electricity storage. P_{pv} and P_{wt} are the PV panels and vertical-axis wind turbine peak powers, E^c_{ren} is the amount of energy produced and consumed *in situ*, E_{inj} is the amount of energy injected to the electricity grid and E_{ext} is the amount of energy extracted from the grid.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	E^c_{ren} (kW h)	E_{inj} (kW h)	E_{ext} (kW h)
1980's insul. standards	1.1	3 & n/a	3520	917	42 241
Occupancy scenario OS_1	1.2	8 & n/a	6803	5029	38 958
Behaviour scenario BS_1	1.3	6.1 & 19	17 786	16 278	27 975
1980's insul. standards	2.1	3 & n/a	3377	1061	42 369
Occupancy scenario OS_1	2.2	8 & n/a	6587	5246	39 159
Behaviour scenario BS_2	2.3	6.2 & 20	17 974	17 556	27 772
1980's insul. standards	3.1	3 & n/a	3559	879	38 577
Occupancy scenario OS_2	3.2	8 & n/a	6900	4933	35 236
Behaviour scenario BS_1	3.3	6.6 & 17	16 836	15 332	25 300
1980's insul. standards	4.1	3 & n/a	3420	1017	38 699
Occupancy scenario OS_2	4.2	8 & n/a	6688	5145	35 432
Behaviour scenario BS_2	4.3	6.6 & 17	16 653	15 514	25 466
RT2005 insul. standards	5.1	3 & n/a	3277	1161	26 098
Occupancy scenario OS_1	5.2	6.5 & n/a	5095	4519	24 280
Behaviour scenario BS_1	5.3	3.7 & 12	11 217	10 071	18 158
RT2005 insul. standards	6.1	3 & n/a	3116	1321	26 214
Occupancy scenario OS_1	6.2	7.1 & n/a	5085	5417	24 245
Behaviour scenario BS_2	6.3	3.5 & 12	10 967	10 026	18 363
RT2005 insul. standards	7.1	3 & n/a	3283	1154	23 848
Occupancy scenario OS_2	7.2	7.2 & n/a	5386	5263	21 744
Behaviour scenario BS_1	7.3	3.9 & 10	10 243	8705	16 888
RT2005 insul. standards	8.1	3 & n/a	3127	1310	23 957
Occupancy scenario OS_2	8.2	7.9 & n/a	5406	6279	21 679
Behaviour scenario BS_2	8.3	3.9 & 11	10 406	9861	16 679

Table 9: Noteworthy configurations, with no batteries for electricity storage. P_{pv} and P_{wt} are the PV panels and vertical-axis wind turbine peak powers, $\%_{sc}$ is the percentage ratio of the renewable energy consumed to the renewable energy produced *in situ*, $\%_{ren}$ is the percentage ratio of the renewable energy produced and consumed *in situ* to the total energy consumed, J_{ren} is about the renewable energy use and J_{cost} is the (annual) economic cost.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	$\%_{sc}$ (%)	$\%_{ren}$ (%)	J_{ren} (%)	J_{cost} (€)
1980's insul. standards	1.1	3 & n/a	79.9	7.7	6.1	-2381.8
Occupancy scenario OS_1	1.2	8 & n/a	57.5	14.9	8.6	-1955.6
Behaviour scenario BS_1	1.3	6.1 & 19	52.2	38.9	20.3	-674.2
1980's insul. standards	2.1	3 & n/a	76.1	7.4	5.6	-2380.9
Occupancy scenario OS_1	2.2	8 & n/a	55.7	14.4	8	-1954.7
Behaviour scenario BS_2	2.3	6.2 & 20	50.6	39.3	19.9	-588.9
1980's insul. standards	3.1	3 & n/a	80.2	8.5	6.8	-2172.9
Occupancy scenario OS_2	3.2	8 & n/a	58.6	16.4	9.6	-1746.6
Behaviour scenario BS_1	3.3	6.6 & 17	52.3	40	20.9	-574.6
1980's insul. standards	4.1	3 & n/a	77.1	8.1	6.3	-2171.9
Occupancy scenario OS_2	4.2	8 & n/a	56.5	15.9	8.9	-1745.6
Behaviour scenario BS_2	4.3	6.6 & 17	51.8	39.5	20.5	-573.6
RT2005 insul. standards	5.1	3 & n/a	73.9	11.2	8.2	-1437.3
Occupancy scenario OS_1	5.2	6.5 & n/a	53	17.3	9.2	-1139
Behaviour scenario BS_1	5.3	3.7 & 12	52.7	38.2	20.1	-466.1
RT2005 insul. standards	6.1	3 & n/a	70.2	10.6	7.5	-1434.7
Occupancy scenario OS_1	6.2	7.1 & n/a	48.4	17.3	8.4	-1085.2
Behaviour scenario BS_2	6.3	3.5 & 12	52.2	37.4	19.5	-480.5
RT2005 insul. standards	7.1	3 & n/a	74	12.1	9	-1308
Occupancy scenario OS_2	7.2	7.2 & n/a	50.6	19.9	10	-949.9
Behaviour scenario BS_1	7.3	3.9 & 10	54.1	37.8	20.4	-471.6
RT2005 insul. standards	8.1	3 & n/a	70.5	11.6	8.1	-1305.3
Occupancy scenario OS_2	8.2	7.9 & n/a	46.3	20	9.2	-887.6
Behaviour scenario BS_2	8.3	3.9 & 11	51.3	38.4	19.7	-395.7

Table 10: Noteworthy configurations, with no batteries for electricity storage. P_{pv} and P_{wt} are the PV panels and vertical-axis wind turbine peak powers, E^c_{ren} is the amount of energy produced and consumed *in situ*, I_{inj} is about the impact on the electricity grid of local production of renewable energy, I_{ext} deals with the impact on the grid of energy extraction and I_{grid} is the overall impact. T_{grid} = 70%.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	I_{inj} (–)	I_{ext} (–)	I_{grid} (–)
1980's insul. standards	1.1	3 & n/a	167	10 146	10 313
Occupancy scenario OS_1	1.2	8 & n/a	777	10 150	10 927
Behaviour scenario BS_1	1.3	6.1 & 19	-1236	6906	5670
1980's insul. standards	2.1	3 & n/a	215	10 630	10 845
Occupancy scenario OS_1	2.2	8 & n/a	843	10 615	11 459
Behaviour scenario BS_2	2.3	6.2 & 20	-1264	7213	5950
1980's insul. standards	3.1	3 & n/a	162	8686	8848
Occupancy scenario OS_2	3.2	8 & n/a	775	8687	9462
Behaviour scenario BS_1	3.3	6.6 & 17	-1090	5885	4795
1980's insul. standards	4.1	3 & n/a	210	9156	9366
Occupancy scenario OS_2	4.2	8 & n/a	840	9139	9980
Behaviour scenario BS_2	4.3	6.6 & 17	-950	6263	5313
RT2005 insul. standards	5.1	3 & n/a	157	6804	6961
Occupancy scenario OS_1	5.2	6.5 & n/a	574	6816	7390
Behaviour scenario BS_1	5.3	3.7 & 12	-820	4694	3874
RT2005 insul. standards	6.1	3 & n/a	209	7032	7241
Occupancy scenario OS_1	6.2	7.1 & n/a	724	7021	7745
Behaviour scenario BS_2	6.3	3.5 & 12	-732	4862	4130
RT2005 insul. standards	7.1	3 & n/a	158	5239	5397
Occupancy scenario OS_2	7.2	7.2 & n/a	672	5240	5912
Behaviour scenario BS_1	7.3	3.9 & 10	-689	3552	2863
RT2005 insul. standards	8.1	3 & n/a	214	5680	5894
Occupancy scenario OS_2	8.2	7.9 & n/a	834	5662	6496
Behaviour scenario BS_2	8.3	3.9 & 11	-748	3844	3096

Table 11: Noteworthy configurations, without batteries for electricity storage. P_{pv} is the PV panels peak power, P_{wt} is the vertical-axis wind turbine peak power, I_{inj} is about the impact on the grid of local production of renewable energy, I_{ext} deals with the impact on the grid of energy extraction and I_{grid} is the overall impact. T_{grid} = 30%.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	I_{inj} (–)	I_{ext} (–)	I_{grid} (–)
1980's insul. standards	1.1	3 & n/a	563	-6231	-5669
Occupancy scenario OS_1	1.2	8 & n/a	2977	-4727	-1751
Behaviour scenario BS_1	1.3	6.1 & 19	5628	-3805	1823
1980's insul. standards	2.1	3 & n/a	663	-5713	-5051
Occupancy scenario OS_1	2.2	8 & n/a	3124	-4256	-1133
Behaviour scenario BS_2	2.3	6.2 & 20	6143	-3357	2786
1980's insul. standards	3.1	3 & n/a	538	-6560	-6023
Occupancy scenario OS_2	3.2	8 & n/a	2927	-5031	-2104
Behaviour scenario BS_1	3.3	6.6 & 17	5336	-4008	1328
1980's insul. standards	4.1	3 & n/a	635	-6053	-5418
Occupancy scenario OS_2	4.2	8 & n/a	3071	-4571	-1500
Behaviour scenario BS_2	4.3	6.6 & 17	5566	-3633	1933
RT2005 insul. standards	5.1	3 & n/a	676	-3261	-2585
Occupancy scenario OS_1	5.2	6.5 & n/a	2589	-2431	157
Behaviour scenario BS_1	5.3	3.7 & 12	3439	-2278	1161
RT2005 insul. standards	6.1	3 & n/a	787	-3005	-2218
Occupancy scenario OS_1	6.2	7.1 & n/a	3122	-2128	994
Behaviour scenario BS_2	6.3	3.5 & 12	3509	-2138	1371
RT2005 insul. standards	7.1	3 & n/a	670	-4189	-3519
Occupancy scenario OS_2	7.2	7.2 & n/a	3012	-3240	-228
Behaviour scenario BS_1	7.3	3.9 & 10	2965	-3114	-149
RT2005 insul. standards	8.1	3 & n/a	780	-3705	-2925
Occupancy scenario OS_2	8.2	7.9 & n/a	3611	-2696	914
Behaviour scenario BS_2	8.3	3.9 & 11	3389	-2678	711

vertical-axis wind turbine) configurations by maximizing J_{ren} (Section 3.4). Table 8 is about the amount of energy produced and consumed *in situ* (E^c_{ren}), the amount of energy injected to the grid (E_{inj}) and the amount of energy extracted from the grid (E_{ext}). Table 9 deals with the percentage ratio of the renewable energy consumed to the renewable energy produced *in situ* ($\%_{sc}$), the percentage ratio of the renewable energy produced and consumed *in situ* to the total energy consumed ($\%_{ren}$), the renewable energy use (J_{ren}) and the economic cost (J_{cost}). Tables 10 and 11 specify the impact on the electricity grid of both the local production of renewable energy (I_{inj}) and energy extraction (I_{ext}) as well as the overall impact (I_{grid}), for T_{grid} = 70% (the electricity grid is in need of energy during peaks of demand only) and T_{grid} = 30% (energy can be appropriately injected to the grid most of the time), respectively.

As a first key point, one can note taking a look at Tables 8 and 9 that Demand Response (DR) (*i.e.* the behaviour scenario, Section 2.3) do not impact theenergy production systems design. Indeed, for identical insulation standards and occupancy scenarios, the optimization process produces the same result, whatever the behaviour scenario (BS_1 or BS_2). For example, when considering a house built using materials which agree with 1980's insulation standards and occupancy scenario OS_2, we obtain photovoltaic solar panels of 6.6 kWp and a vertical-axis wind turbine of 17 kWp (configurations 3.3 and 4.3). One can also note that improving the building insulation level (from 1980's to RT2005 standards) leads to photovoltaic solar panels and a vertical-axis wind turbine of lower power capacities. In addition, the panels power capacity is increased, whereas the wind turbine power capacity is slightly decreased, when considering occupancy scenario OS_1. As an example, P_{pv} = 8 kWp for 1980's insulation standards (configuration 1.2) and P_{pv} = 6.5 kWp for RT2005 standards (configuration 5.2) (with behaviour scenario BS_1). Finally, with the same behaviour scenario and considering a residential building built according to 1980's insulation standards, P_{pv} is increased from 6.1 to 6.6 kWp whereas P_{wt} is decreased from 19 to 17 kWp when switching from OS_1 (configuration 1.3) to OS_2 (configuration 3.3).

From an overall point of view, configurations 2 (the building is equipped with photovoltaic solar panels only) and 3 (the building is equipped with photovoltaic solar panels and a vertical-axis wind turbine) allow a strong increase in the renewable energy coverage rate ($\%_{ren}$) combined with a decrease in the percentage ratio of the renewable energy consumed to the renewable energy produced *in situ* ($\%_{sc}$), whatever the insulation level and the scenarios (the management strategy used is the reference one, Section 3.2). As one can note taking a look at Tables 8 and 9, adding a vertical-axis wind turbine to the building produces a greater flexibility in energy resources management. In particular, the wind turbine allows an increase in the amount of energy produced and consumed *in situ* (E^c_{ren}), even during nighttime, and a decrease in the amount of energy extracted from the grid (E_{ext}). Of course, optimizing the energy production systems design changes the way the considered building and the electricity grid interact. For instance (residential building built on the basis of RT2005 insulation standards; occupancy and behaviour scenarios OS_1 and BS_1), $\%_{ren}$ is increased from 11.2 to 17.3 % (+6.1 pts) whereas $\%_{sc}$ is decreased from 73.9 to 53 % (−20.9 pts) when switching from configuration 5.1 (P_{pv} = 3 kWp) to configuration 5.2 (P_{pv} = 6.5 kWp). Moreover, $\%_{ren}$ is increased from 11.2 to 38.2 % (+27 pts) whereas $\%_{sc}$ is decreased from 73.9 to 52.7 % (−21.2 pts) when switching from configuration 5.1 (P_{pv} = 3 kWp) to configuration 5.3 (P_{pv} = 3.7 kWp and P_{wt} = 12 kWp). With configurations 2 (the building is equipped with photovoltaic solar panels only) and 3 (the building is equipped with photovoltaic solar panels and a vertical-axis wind turbine), the amount of energy produced and consumed *in situ* (E^c_{ren}) increases significantly, what allows the amount of energy extracted from the electricity grid to be reduced (E_{ext}), whatever the building insulation level and the scenarios. In addition, the amount of energy injected to the grid (E_{inj}) is increased, due to a higher total power capacity installed (the management strategy used is the reference one, Section 3.2). As an example (1980's insulation standards, occupancy and behaviour scenarios OS_1 and BS_1), E^c_{ren} and E_{inj} are increased from 3520 to 6803 kW h (+3283 kW h) and 917 to 5029 kW h (+4412 kW h), respectively, whereas E_{ext} is decreased from 42 241 to 38 958 kW h (−3283 kW h) when switching from configuration 1.1 (P_{pv} = 3 kWp) to configuration 1.2 (P_{pv} = 8 kWp). Moreover, E^c_{ren} and E_{inj} are increased from 3520 to 17 786 kW h (+14 266 kW h) and 917 to 16 278 kW h (+15 361 kW h), respectively, whereas E_{ext} is decreased from 42 241 to 27 975 kW h (−14 266 kW h) when switching from configuration 1.1 (P_{pv} = 3 kWp) to configuration 1.3 (P_{pv} = 6.1 kWp and P_{wt} = 19 kWp).

As previously mentioned, Tables 10 (T_{grid} = 70%, what means that the electricity grid is in need of energy during peaks of demand only) and 11 (T_{grid} = 30%, what means that energy can be appropriately injected to the grid most of the time) deal with the impact on the electricity grid of both the local production of renewable energy (I_{inj}) and energy extraction (I_{ext}). The overall impact (I_{grid}) is also evaluated. One can note that optimizing the energy production systems design allows I_{inj}, I_{ext} and I_{grid} to be improved, with the exception of photovoltaic solar panels combined with a vertical-axis wind turbine and T_{grid} = 70%. In that particular case, adding a wind turbine to the building deteriorates I_{inj}, which becomes negative. The overall impact (I_{grid}) is also deteriorated but remains positive, because of I_{inj} being compensated by I_{ext}). As an example (for T_{grid} = 30%), I_{inj}, I_{ext} and I_{grid} are increased from 563 to 2977 (+2414), −6231 to −4727 (+1504) and −5669 to −1751 (+3918), respectively, when switching from configuration 1.1 (P_{pv} = 3 kWp) to configuration 1.2 (P_{pv} = 8 kWp). When switching from configuration 1.1 (P_{pv} = 3 kWp) to configuration 1.3 (P_{pv} = 6.1 kWp and P_{wt} = 19 kWp), I_{inj}, I_{ext} and I_{grid} are increased from

563 to 5628 (+5065), −6231 to −3805 (+2426) and −5669 to 1823 (+7492), respectively. In that case, I_{inj} compensates I_{ext}, what leads to a positive overall impact. As stated above, for T_{grid} = 70%, I_{grid} is deteriorated in case of a building equipped with photovoltaic solar panels and a vertical-axis wind turbine. Indeed, looking at Table 10, one can note that I_{grid} is decreased from 9366 to 5313 (−4053) when switching from configuration 4.1 (P_{pv} = 3 kWp) to configuration 4.3 (P_{pv} = 6.6 kWp and P_{wt} = 17 kWp) and from 5894 to 3096 (−2798) when switching from configuration 8.1 (P_{pv} = 3 kWp) to configuration 8.3 (P_{pv} = 3.9 kWp and P_{wt} = 11 kWp). In both cases, the overall impact of the building on the electricity grid (I_{grid}) remains positive. Finally, by optimizing the production systems design, the (annual) economic cost (J_{cost}) is reduced from 300 to 400 € with no wind turbine equipping the house and from 400 to 1500 € if this residential building is equipped with photovoltaic solar panels and a vertical-axis wind turbine. Reference is the building equipped with panels of 3 kWp.

4.2. Residential building equipped with energy production and storage systems (advanced strategy)

In this section, we highlight and discuss noteworthy configurations, with electricity storage facilities (*i.e.* batteries) equipping the considered building. The single-storey house is so equipped with photovoltaic solar panels (P_{pv}) and batteries (E_{bat}^{max}) or with photovoltaic solar panels, a vertical-axis wind turbine (P_{wt}) and batteries. Tables 12 to 17 point out the most interesting configurations. For each of the eight combinations of characteristics we considered in the present study (1980's or RT2005 insulation standards, occupancy scenario 1 or 2, behaviour scenario 1 or 2), three configurations are highlighted (see Sections 2.1, 2.2 and 2.3 for details about insulation levels and proposed scenarios). The first one is defined on the basis of photovoltaic solar panels of 8 kWp, which is the peak power for such panels managed by using the "reference" strategy (Section 4.1), and batteries. The third configuration (in that case, the building is equipped with photovoltaic solar panels, a vertical-axis wind turbine and batteries) is given by maximizing J_{ren} (Section 3.4). The second configuration is obtained by removing the batteries from configuration 3 so as to evaluate the impact of electricity storage on performance. Tables 12 and 15 are about the amount of energy produced and consumed *in situ* (E_{ren}^{c}), the amount of energy injected to the grid (E_{inj}), the amount of energy extracted from the grid (E_{ext}) and the amount of energy stored in the batteries (E_{sto}), for T_{grid} = 70% and T_{grid} = 30%, respectively. Tables 13 and 16 deal with the percentage ratio of the renewable energy consumed to the renewable energy produced *in situ* ($\%_{sc}$), the percentage ratio of the renewable energy produced and consumed *in situ* to the total energy consumed ($\%_{ren}$), the renewable energy use (J_{ren}) and the economic cost (J_{cost}), for T_{grid} = 70% and T_{grid} = 30%, respectively. Tables 14 and 17 specify the impact on the electricity grid of both the local production of energy (I_{inj}) and energy extraction (I_{ext}) as well as the overall impact (I_{grid}), for T_{grid} = 70% and T_{grid} = 30%, respectively.

4.2.1. Overall analysis

First, one can observe when taking a look at Tables 12 to 17 that the batteries design is most of the time constrained by $E_{bat}^{max} \leq 200$ kW h, with the exception of a residential building equipped with photovoltaic solar panels only and a grid threshold equal to 70% (configuration 1) (the management strategy used is the advanced one, see Section 3.3). In that case, the capacity of the batteries is set to 100 kW h, whatever the building insulation level and the considered scenarios. One can also note that the total power capacity installed (with or without vertical-axis wind turbine) is higher when equipping the building with batteries than it is with no electricity storage. This is the consequence of an increase in energy consumption due to both the energy losses in the batteries and the need to maintain these batteries at minimum capacity. In addition, one can note that, whatever the behaviour scenario, no impact on the production systems design is noticed. Indeed, shifting some activities from on-peak to off-peak periods (using demand response mechanisms) does not impact this design. In opposition, the building insulation level, when it is improved from 1980's to RT2005 standards, allows the total power capacity to be reduced, as a result of a significant decrease in energy consumption. By switching from OS_1 to OS_2, the total power capacity is increased, with the exception of a building that agrees with 1980's insulation standards and a grid threshold equal to 70%. In that case, the wind turbine peak power is reduced, as a result of an increased energy consumption during daylight hours (in particular during periods of strong sunlight, even if the overall energy consumption is reduced). From an overall point of view, one can observe that the total power capacity is higher for T_{grid} = 70% (the electricity grid is in need of energy during peaks of demand only) than it is for T_{grid} = 30% (energy can be appropriately injected to the grid most of the time).

Finally, whatever the grid threshold T_{grid} (and, consequently, whatever the electricity grid status), one can clearly observe when looking at Figures 12 to 16 (RT2005 insulation standards, occupancy scenario OS_2 and behaviour scenario BS_1) more interaction with the batteries during summer than the rest of the year. Indeed, energy release is clearly correlated with consumption. Moreover, a decrease in the amount of energy injected to the grid is observed during storage times.

4.2.2. Grid threshold set to 70%

In this section of the paper, a complete analysis of the noteworthy configurations we obtained for T_{grid} = 70% is carried out (the advanced management strategy is applied to the building equipped with energy production and storage systems) (Tables 12 to 14), taking as references the configurations we highlighted for the manage-

Table 12: Noteworthy configurations, with batteries. P_{pv} and P_{wt} are the PV panels and vertical-axis wind turbine peak powers, E_{bat}^{max} is the rated capacity of the batteries, E_{ren}^{c} is the amount of energy produced and consumed *in situ*, E_{inj} is the amount of energy injected to the electricity grid, E_{ext} is the amount of energy extracted from the grid and E_{sto} is the amount of energy stored in the batteries. T_{grid} = 70%.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	E_{bat}^{max} (kW h)	E_{ren}^{c} (kW h)	E_{inj} (kW h)	E_{ext} (kW h)	E_{sto} (kW h)
1980's insul. standards	1.1	8 & n/a	100	8584	2934	37 174	1786
Occupancy scenario OS_1	1.2	8 & 18	n/a	18 114	17 442	27 648	n/a
Behaviour scenario BS_1	1.3	8 & 18	200	22 605	12 156	23 161	4497
1980's insul. standards	2.1	8 & n/a	100	8443	3061	37 298	1862
Occupancy scenario OS_1	2.2	8 & 20	n/a	18 591	19 600	27 154	n/a
Behaviour scenario BS_2	2.3	8 & 20	200	23 283	14 079	22 468	4697
1980's insul. standards	3.1	8 & n/a	100	8653	2870	33 480	1758
Occupancy scenario OS_2	3.2	8 & 15	n/a	16 496	14 514	25 640	n/a
Behaviour scenario BS_1	3.3	8 & 15	200	20 873	9980	21 268	4240
1980's insul. standards	4.1	8 & n/a	100	8515	2994	33 600	1833
Occupancy scenario OS_2	4.2	8 & 15	n/a	16 447	15 155	25 672	n/a
Behaviour scenario BS_2	4.3	8 & 15	200	20 754	10 085	21 370	4314
RT2005 insul. standards	5.1	8 & n/a	100	7988	3428	21 381	2361
Occupancy scenario OS_1	5.2	7.4 & 11	n/a	12 009	13 434	17 366	n/a
Behaviour scenario BS_1	5.3	7.4 & 11	200	16 290	8394	13 089	4287
RT2005 insul. standards	6.1	8 & n/a	100	7834	3567	21 490	2448
Occupancy scenario OS_1	6.2	7.9 & 11	n/a	11 923	14 259	17 406	n/a
Behaviour scenario BS_2	6.3	7.9 & 11	200	16 404	8985	12 929	4486
RT2005 insul. standards	7.1	8 & n/a	100	8028	3388	19 097	2359
Occupancy scenario OS_2	7.2	7.8 & 10	n/a	11 468	13 249	15 663	n/a
Behaviour scenario BS_1	7.3	7.8 & 10	200	15 759	8179	11 377	4296
RT2005 insul. standards	8.1	8 & n/a	100	7879	3523	19 200	2444
Occupancy scenario OS_2	8.2	8 & 10	n/a	11 305	13 707	15 779	n/a
Behaviour scenario BS_2	8.3	8 & 10	200	15 727	8501	11 361	4427

Table 13: Noteworthy configurations, with batteries. P_{pv} and P_{wt} are the PV panels and vertical-axis wind turbine peak powers, E_{bat}^{max} is the rated capacity of the batteries, $\%_{sc}$ is the percentage ratio of the renewable energy consumed to the renewable energy produced *in situ*, $\%_{ren}$ is the percentage ratio of the renewable energy produced and consumed *in situ* to the total energy consumed, J_{ren} is about the renewable energy use and J_{cost} is the (annual) economic cost. T_{grid} = 70%.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	E_{bat}^{max} (kW h)	$\%_{sc}$ (%)	$\%_{ren}$ (%)	J_{ren} (%)	J_{cost} (€)
1980's insul. standards	1.1	8 & n/a	100	72.5	18.8	13.6	-1973.5
Occupancy scenario OS_1	1.2	8 & 18	n/a	50.9	39.6	20.2	-524.2
Behaviour scenario BS_1	1.3	8 & 18	200	63.6	49.4	31.4	-634.3
1980's insul. standards	2.1	8 & n/a	100	71.4	18.5	13.2	-1973.4
Occupancy scenario OS_1	2.2	8 & 20	n/a	48.7	40.6	19.8	-435.4
Behaviour scenario BS_2	2.3	8 & 20	200	61.0	50.9	31.0	-483.5
1980's insul. standards	3.1	8 & n/a	100	73.1	20.5	15.0	-1766.3
Occupancy scenario OS_2	3.2	8 & 15	n/a	52.6	39.5	20.8	-607.1
Behaviour scenario BS_1	3.3	8 & 15	200	66.1	49.5	32.7	-651.4
1980's insul. standards	4.1	8 & n/a	100	72.0	20.2	14.6	-1764.1
Occupancy scenario OS_2	4.2	8 & 15	n/a	52.1	39.1	20.3	-606.2
Behaviour scenario BS_2	4.3	8 & 15	200	65.7	49.3	32.4	-650.4
RT2005 insul. standards	5.1	8 & n/a	100	67.5	27.2	18.4	-1034.8
Occupancy scenario OS_1	5.2	7.4 & 11	n/a	47.2	40.9	19.3	-226.6
Behaviour scenario BS_1	5.3	7.4 & 11	200	64.0	55.5	35.5	-270.6
RT2005 insul. standards	6.1	8 & n/a	100	66.2	26.7	17.7	-1033.0
Occupancy scenario OS_1	6.2	7.9 & 11	n/a	45.5	40.7	18.5	-181.4
Behaviour scenario BS_2	6.3	7.9 & 11	200	62.6	55.9	35.0	-227.4
RT2005 insul. standards	7.1	8 & n/a	100	67.8	29.6	20.1	-905.4
Occupancy scenario OS_2	7.2	7.8 & 10	n/a	46.4	42.3	19.6	-139.2
Behaviour scenario BS_1	7.3	7.8 & 10	200	63.8	58.1	37.0	-183.3
RT2005 insul. standards	8.1	8 & n/a	100	66.6	29.1	19.4	-903.6
Occupancy scenario OS_2	8.2	8 & 10	n/a	45.2	41.7	18.9	-119.4
Behaviour scenario BS_2	8.3	8 & 10	200	62.9	58.1	36.5	-164.8

Table 14: Noteworthy configurations, with batteries. P_{pv} and P_{wt} are the PV panels and vertical-axis wind turbine peak powers, E_{bat}^{max} is the rated capacity of the batteries, I_{inj} is about the impact on the electricity grid of local production of renewable energy, I_{ext} deals with the impact on the grid of energy extraction and I_{grid} is the overall impact. T_{grid} = 70%.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	E_{bat}^{max} (kW h)	I_{inj} (–)	I_{ext} (–)	I_{grid} (–)
1980's insul. standards	1.1	8 & n/a	100	1158	9838	10 996
Occupancy scenario OS_1	1.2	8 & 18	n/a	-800	6967	6168
Behaviour scenario BS_1	1.3	8 & 18	200	793	5535	6328
1980's insul. standards	2.1	8 & n/a	100	1233	10 285	11 518
Occupancy scenario OS_1	2.2	8 & 20	n/a	-1021	7192	6171
Behaviour scenario BS_2	2.3	8 & 20	200	633	5630	6264
1980's insul. standards	3.1	8 & n/a	100	1148	8389	9537
Occupancy scenario OS_2	3.2	8 & 15	n/a	-535	6031	5496
Behaviour scenario BS_1	3.3	8 & 15	200	982	4711	5694
1980's insul. standards	4.1	8 & n/a	100	1222	8822	10 044
Occupancy scenario OS_2	4.2	8 & 15	n/a	-404	6418	6014
Behaviour scenario BS_2	4.3	8 & 15	200	1100	5014	6114
RT2005 insul. standards	5.1	8 & n/a	100	1318	6390	7708
Occupancy scenario OS_1	5.2	7.4 & 11	n/a	-172	4764	4592
Behaviour scenario BS_1	5.3	7.4 & 11	200	1298	3543	4841
RT2005 insul. standards	6.1	8 & n/a	100	1401	6562	7963
Occupancy scenario OS_1	6.2	7.9 & 11	n/a	6177	-1624	4552
Behaviour scenario BS_2	6.3	7.9 & 11	200	1487	3585	5072
RT2005 insul. standards	7.1	8 & n/a	100	1323	4807	6130
Occupancy scenario OS_2	7.2	7.8 & 10	n/a	-191	3533	3342
Behaviour scenario BS_1	7.3	7.8 & 10	200	1298	2453	3751
RT2005 insul. standards	8.1	8 & n/a	100	1404	5213	6616
Occupancy scenario OS_2	8.2	8 & 10	n/a	5860	-2202	3657
Behaviour scenario BS_2	8.3	8 & 10	200	1453	2694	4147

Table 15: Noteworthy configurations, with batteries. P_{pv} and P_{wt} are the PV panels and vertical-axis wind turbine peak powers, E_{bat}^{max} is the rated capacity of the batteries, E_{ren}^{c} is the amount of energy produced and consumed *in situ*, E_{inj} is the amount of energy injected to the electricity grid, E_{ext} is the amount of energy extracted from the grid and E_{sto} is the amount of energy stored in the batteries. T_{grid} = 30%.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	E_{bat}^{max} (kW h)	E_{ren}^{c} (kW h)	E_{inj} (kW h)	E_{ext} (kW h)	E_{sto} (kW h)
1980's insul. standards	1.1	8 & n/a	200	6861	4962	38 913	70
Occupancy scenario OS_1	1.2	5.7 & 25	n/a	19 442	21 938	26 320	n/a
Behaviour scenario BS_1	1.3	5.7 & 25	200	21 558	19 447	24 214	2124
1980's insul. standards	2.1	8 & n/a	200	6645	5178	39 114	70
Occupancy scenario OS_1	2.2	5.6 & 25	n/a	19 229	22 003	26 517	n/a
Behaviour scenario BS_2	2.3	5.6 & 25	200	21 302	19 564	24 455	2081
1980's insul. standards	3.1	8 & n/a	200	6955	4869	35 195	67
Occupancy scenario OS_2	3.2	6.1 & 22	n/a	18 334	20 423	23 802	n/a
Behaviour scenario BS_1	3.3	6.1 & 22	200	20 174	17 485	21 972	2033
1980's insul. standards	4.1	8 & n/a	200	6743	5081	35 390	67
Occupancy scenario OS_2	4.2	6.1 & 23	n/a	18 240	21 095	23 879	n/a
Behaviour scenario BS_2	4.3	6.1 & 23	200	20 305	18 665	21 825	2073
RT2005 insul. standards	5.1	7.4 & n/a	200	5520	5410	23 867	102
Occupancy scenario OS_1	5.2	3.5 & 17	n/a	12 591	14 991	16 784	n/a
Behaviour scenario BS_1	5.3	3.5 & 17	200	14 329	12 946	15 058	1745
RT2005 insul. standards	6.1	8 & n/a	200	5496	6319	23 846	116
Occupancy scenario OS_1	6.2	3.4 & 18	n/a	12 632	16 120	16 697	n/a
Behaviour scenario BS_2	6.3	3.4 & 18	200	14 432	14 001	14 908	1807
RT2005 insul. standards	7.1	8 & n/a	200	5777	6038	21 366	114
Occupancy scenario OS_2	7.2	3.8 & 16	n/a	11 935	14 773	15 196	n/a
Behaviour scenario BS_1	7.3	3.8 & 16	200	13 763	12 621	13 378	1835
RT2005 insul. standards	8.1	8 & n/a	200	5543	6272	21 553	115
Occupancy scenario OS_2	8.2	3.6 & 16	n/a	11 694	14 718	15 391	n/a
Behaviour scenario BS_2	8.3	3.6 & 16	200	13 469	12 629	13 626	1782

Table 16: Noteworthy configurations, with batteries. P_{pv} and P_{wt} are the PV panels and vertical-axis wind turbine peak powers, E_{bat}^{max} is the rated capacity of the batteries, $\%_{sc}$ is the percentage ratio of the renewable energy consumed to the renewable energy produced *in situ*, $\%_{ren}$ is the percentage ratio of the renewable energy produced and consumed *in situ* to the total energy consumed, J_{ren} is about the renewable energy use and J_{cost} is the (annual) economic cost. T_{grid} = 30%.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	E_{bat}^{max} (kW h)	$\%_{sc}$ (%)	$\%_{ren}$ (%)	J_{ren} (%)	J_{cost} (€)
1980's insul. standards	1.1	8 & n/a	200	58.0	15.0	8.7	-1956.9
Occupancy scenario OS_1	1.2	5.7 & 25	n/a	47.0	42.5	20.0	-220.0
Behaviour scenario BS_1	1.3	5.7 & 25	200	52.1	47.1	24.5	-274.8
1980's insul. standards	2.1	8 & n/a	200	56.2	14.5	8.2	-1958.2
Occupancy scenario OS_1	2.2	5.6 & 25	n/a	46.6	42.0	19.6	-226.1
Behaviour scenario BS_2	2.3	5.6 & 25	200	51.7	46.6	24.1	-281.9
1980's insul. standards	3.1	8 & n/a	200	58.8	16.5	9.7	-1747.9
Occupancy scenario OS_2	3.2	6.1 & 22	n/a	47.7	43.1	20.6	-237.4
Behaviour scenario BS_1	3.3	6.1 & 22	200	53.1	47.9	25.4	-258.6
1980's insul. standards	4.1	8 & n/a	200	57.0	16.0	9.1	-1747.0
Occupancy scenario OS_2	4.2	6.1 & 23	n/a	46.4	43.3	20.1	-160.5
Behaviour scenario BS_2	4.3	6.1 & 23	200	51.6	48.2	24.9	-182.1
RT2005 insul. standards	5.1	7.4 & n/a	200	50.4	18.8	9.5	-1063.9
Occupancy scenario OS_1	5.2	3.5 & 17	n/a	45.7	42.9	19.6	-103.3
Behaviour scenario BS_1	5.3	3.5 & 17	200	52.0	48.8	25.3	-121.7
RT2005 insul. standards	6.1	8 & n/a	200	46.4	18.7	8.7	-1010.2
Occupancy scenario OS_1	6.2	3.4 & 18	n/a	43.9	43.1	18.9	-33.3
Behaviour scenario BS_2	6.3	3.4 & 18	200	50.2	49.2	24.7	-52.3
RT2005 insul. standards	7.1	8 & n/a	200	48.8	21.3	10.4	-883.5
Occupancy scenario OS_2	7.2	3.8 & 16	n/a	44.7	44.0	19.7	-24.4
Behaviour scenario BS_1	7.3	3.8 & 16	200	51.5	50.7	26.1	-43.6
RT2005 insul. standards	8.1	8 & n/a	200	47.1	43.1	9.6	-880.8
Occupancy scenario OS_2	8.2	3.6 & 16	n/a	44.3	43.2	19.1	-38.8
Behaviour scenario BS_2	8.3	3.6 & 16	200	51.0	49.7	25.4	-57.5

Table 17: Noteworthy configurations, with batteries. P_{pv} and P_{wt} are the PV panels and vertical-axis wind turbine peak powers, E_{bat}^{max} is the rated capacity of the batteries, I_{inj} is about the impact on the electricity grid of local production of renewable energy, I_{ext} deals with the impact on the grid of energy extraction and I_{grid} is the overall impact. T_{grid} = 30%.

Building characteristics	Conf.	P_{pv} & P_{wt} (kWp)	E_{bat}^{max} (kW h)	I_{inj} (–)	I_{ext} (–)	I_{grid} (–)
1980's insul. standards	1.1	8 & n/a	200	2997	-4708	-1711
Occupancy scenario OS_1	1.2	5.7 & 25	n/a	-2464	6498	4034
Behaviour scenario BS_1	1.3	5.7 & 25	200	8198	-3447	4751
1980's insul. standards	2.1	8 & n/a	200	3144	-4237	-1092
Occupancy scenario OS_1	2.2	5.6 & 25	n/a	-2316	6870	4554
Behaviour scenario BS_2	2.3	5.6 & 25	200	8342	-3158	5184
1980's insul. standards	3.1	8 & n/a	200	2945	-5010	-2066
Occupancy scenario OS_2	3.2	6.1 & 22	n/a	-2156	5567	3411
Behaviour scenario BS_1	3.3	6.1 & 22	200	7548	-3630	3918
1980's insul. standards	4.1	8 & n/a	200	3089	-4549	-1460
Occupancy scenario OS_2	4.2	6.1 & 23	n/a	-2203	5869	3665
Behaviour scenario BS_2	4.3	6.1 & 23	200	8024	-3284	4740
RT2005 insul. standards	5.1	7.4 & n/a	200	3187	-2260	927
Occupancy scenario OS_1	5.2	3.5 & 17	n/a	4437	-2101	2336
Behaviour scenario BS_1	5.3	3.5 & 17	200	5670	-1923	3747
RT2005 insul. standards	6.1	8 & n/a	200	3742	-1968	1774
Occupancy scenario OS_1	6.2	3.4 & 18	n/a	981	-2886	-1905
Behaviour scenario BS_2	6.3	3.4 & 18	200	6076	-1780	4296
RT2005 insul. standards	7.1	8 & n/a	200	3557	-3085	472
Occupancy scenario OS_2	7.2	3.8 & 16	n/a	4161	-2790	1371
Behaviour scenario BS_1	7.3	3.8 & 16	200	5485	-2472	3013
RT2005 insul. standards	8.1	8 & n/a	200	3714	-2646	1069
Occupancy scenario OS_2	8.2	3.6 & 16	n/a	4286	-2478	1808
Behaviour scenario BS_2	8.3	3.6 & 16	200	5556	-2228	3328

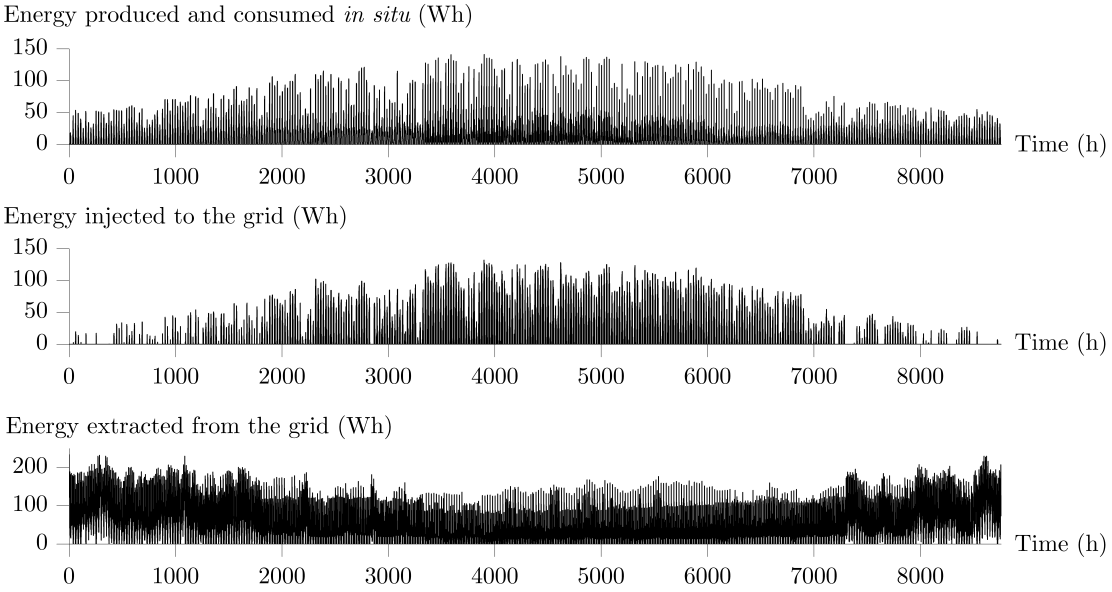


Figure 12: Building energy resources managed using the reference strategy (Section 3.2). RT2005 insulation standards. Occupancy scenario OS_2. Behaviour scenario BS_1. $P_{pv} = 8\,\text{kWp}$.

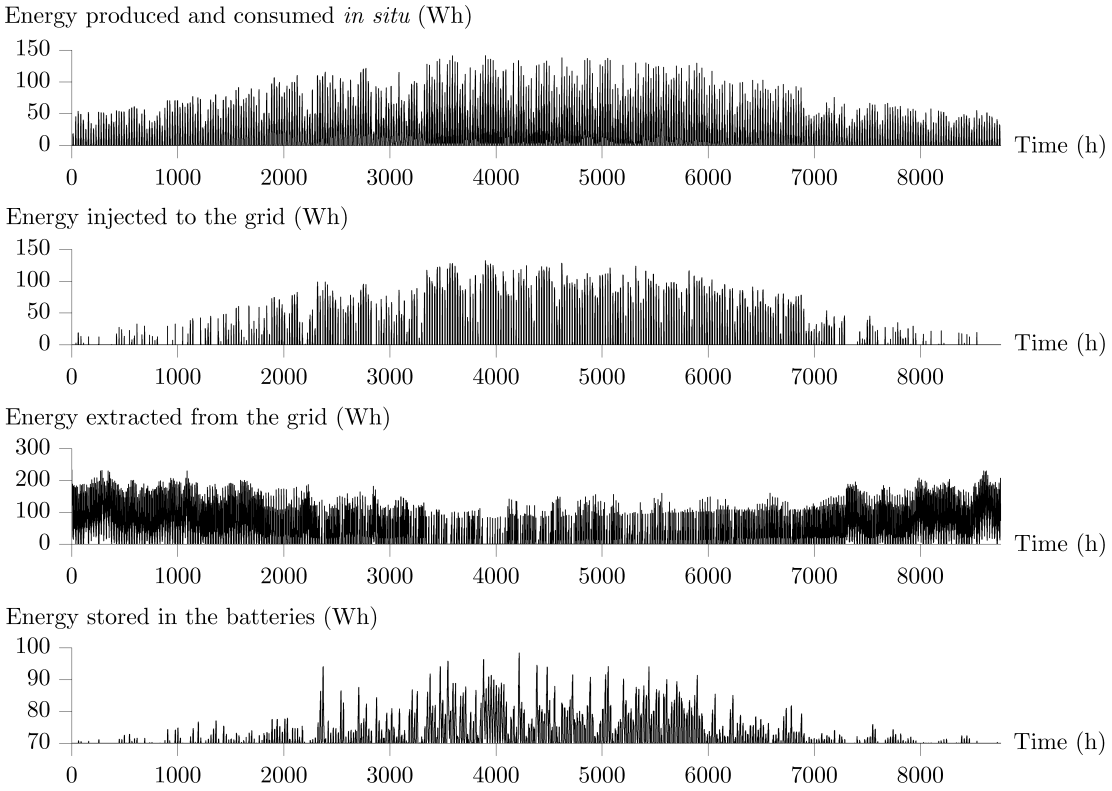


Figure 13: Building energy resources managed using the advanced strategy (Section 3.3). RT2005 insulation standards. Occupancy scenario OS_2. Behaviour scenario BS_1. $T_{grid} = 70\%$. $P_{pv} = 8\,\text{kWp}$. $E_{bat}^{max} = 100\,\text{kW h}$.

ment of the building energy resources when this building is not equipped with batteries for electricity storage (Table 10). First, one can note that, whatever the configuration, P_{pv} (*i.e.* the photovoltaic solar panels peak power) is more or less the same. It is clearly lower for configurations 5.2 and 5.3 only (RT2005 insulation standards, occupancy scenario OS_1, behaviour scenario BS_1), in comparison to the other configurations we highlighted in Tables 12, 13 and 14 (7.4 kWp vs. $\approx 8\,\text{kWp}$). For his part, P_{wt} (*i.e.* the vertical-axis wind turbine peak power) is clearly lower when switching from 1980's to RT2005 insulation standards, whatever the scenarios: as an exam-

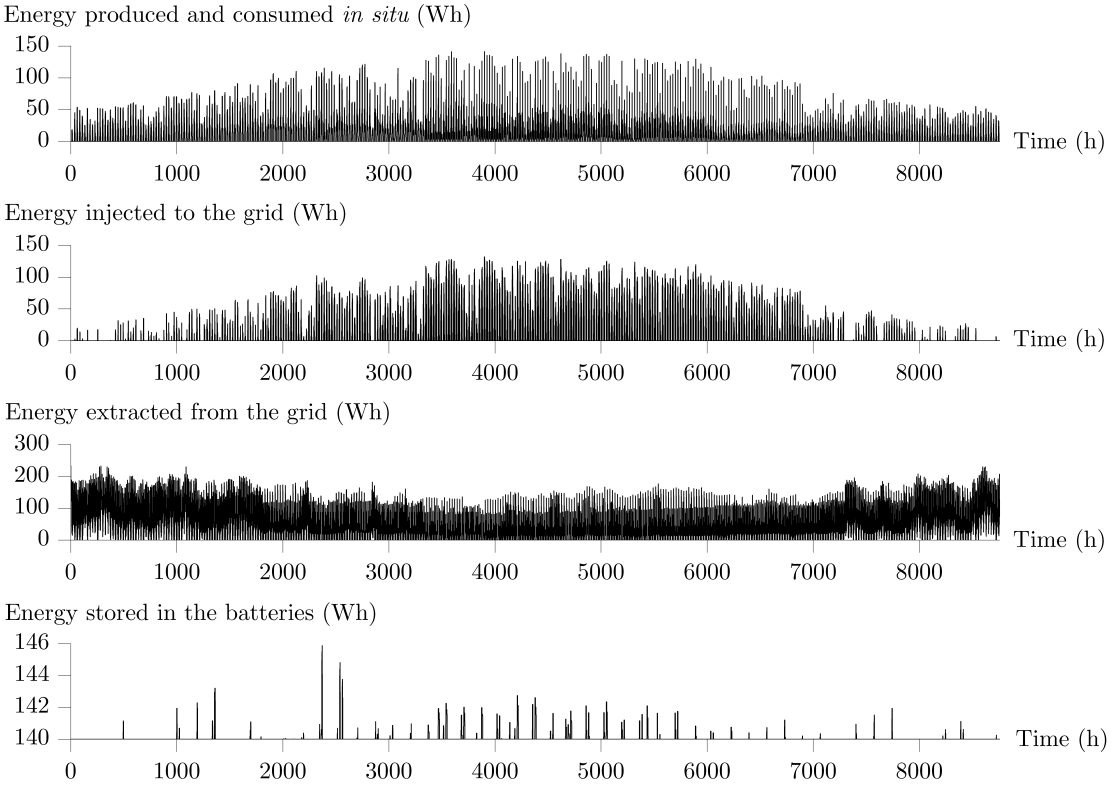


Figure 14: Building energy resources managed using the advanced strategy (Section 3.3). RT2005 insulation standards. Occupancy scenario OS_2. Behaviour scenario BS_1. $T_{grid} = 30\%$. $P_{pv} = 8\,\text{kWp}$. $E_{bat}^{max} = 200\,\text{kW h}$.

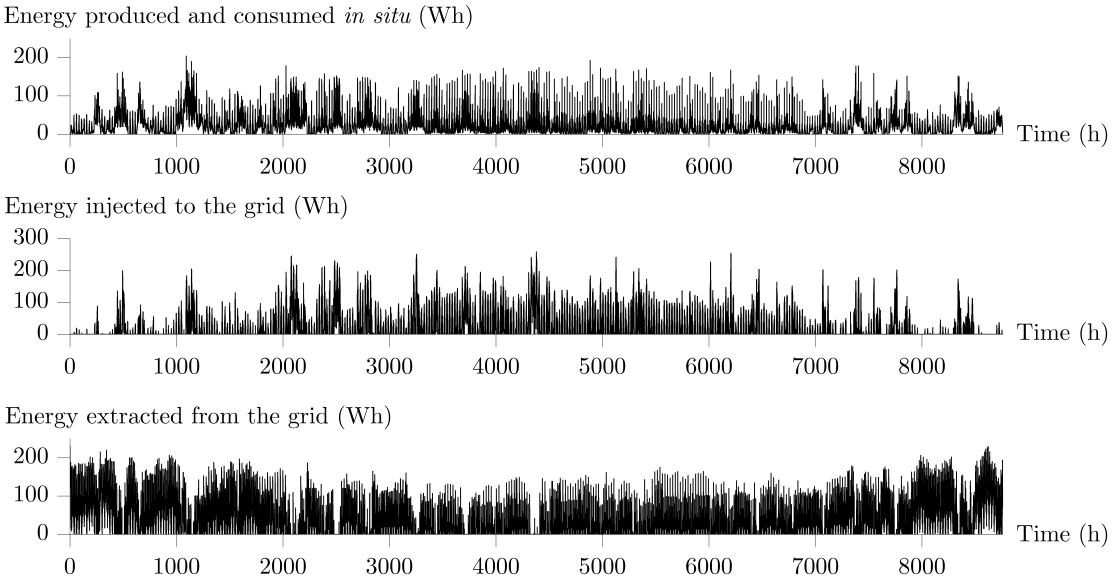


Figure 15: Building energy resources managed using the reference strategy (Section 3.2). RT2005 insulation standards. Occupancy scenario OS_2. Behaviour scenario BS_1. $P_{pv} = 8\,\text{kWp}$. $P_{wt} = 10\,\text{kWp}$.

ple, P_{wt} is decreased from 20 to 10 kWp when switching from configuration 2.3 (1980's insulation standards, occupancy scenario OS_1, behaviour scenario BS_2) to configuration 8.3 (RT2005 insulation standards, occupancy scenario OS_2, behaviour scenario BS_2). One can also note that adding (well-designed) batteries to the building, when it is equipped with a combination of photovoltaic solar panels and a vertical-axis wind turbine, tends to increase the total power capacity, in particular with RT2005 insulation standards. For example, the total power capacity is increased from 15.5 to 18.9 kWp (+3.4 kWp) when adding batteries to the building (RT2005 insulation standards) and con-

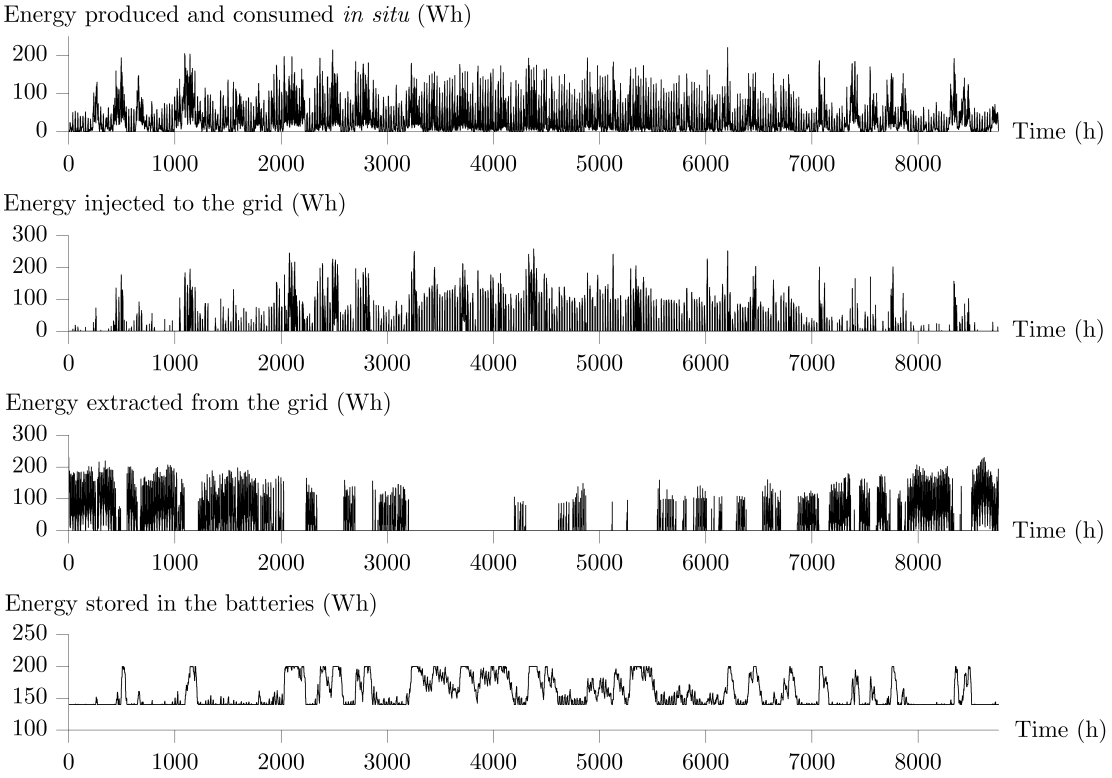


Figure 16: Building energy resources managed using the advanced strategy (Section 3.3). RT2005 insulation standards. Occupancy scenario OS_2. Behaviour scenario BS_1. T_{grid} = 70%. P_{pv} = 8 kWp. P_{wt} = 10 kWp. E_{bat}^{max} = 200 kW h.

sidering occupancy scenario OS_1 and behaviour scenario BS_2. It is increased from 14.9 to 18 kWp (+3.1 kWp) when adding batteries to the building (RT2005 insulation standards) and considering occupancy scenario OS_2 and behaviour scenario BS_2. In addition, adding (well-designed) batteries allows J_{ren} (which is about the renewable enegy use, see Section 3.1.3) to be improved, as a result of an increased renewable energy coverage rate ($\%_{ren}$) and a better percentage ratio of the renewable energy consumed to the renewable energy produced *in situ* ($\%_{sc}$). As an example, J_{ren} is increased from 20.2 to 31.4% (+11.2 pts) when switching from configuration 1.2 (P_{pv} = 8 kWp and P_{wt} = 18 kWp) to configuration 1.3 (batteries of a rated capacity of 200 kW h are added to the building) (1980's insulation standards, occupancy scenario OS_1, behaviour scenario BS_1). As another example, J_{ren} is increased from 19.6 to 37% (+17.4 pts) when switching from configuration 7.2 (P_{pv} = 7.8 kWp and P_{wt} = 10 kWp) to configuration 7.3 (batteries of a rated capacity of 200 kW h are added to the building) (RT2005 insulation standards, occupancy scenario OS_2, behaviour scenario BS_1). In addition, electricity storage allows the amount of energy injected to the grid (E_{inj}) as well as the amount of energy extracted from the grid (E_{ext}) to be reduced. When switching from configuration 2.2 to configuration 2.3 (1980's insulation standards, occupancy scenario OS_1, behaviour scenario BS_2), E_{inj} is reduced from 19 600 to 14 079 kW h (−5521 kW h) whereas E_{ext} is reduced from 27 154 to 22 468 kW h (−4686 kW h). E_{inj} is reduced from 14 259 to 8985 kW h (−5274 kW h) and E_{ext} is reduced from 17 406 to 12 929 kW h (−4477 kW h) when switching from configuration 6.2 to configuration 6.3 (RT2005 insulation standards, occupancy scenario OS_1, behaviour scenario BS_2).

When the electricity grid is in need of energy during peaks of demand only (what leads to T_{grid} = 70%), adding (well-designed) batteries to the considered house and managing the energy production and storage systems using the proposed advanced strategy (see Section 3.3) change the way this residential building and the grid interact. In particular, one can remark that, for most of the configurations, I_{ext} (which is about the impact on the grid of energy extraction) decreases whereas I_{inj} (which is about the impact on the grid of local production of renewale energy) increases. The overall impact criterion (I_{grid}) is improved (Table 14). As a first example, I_{ext} is decreased from 6031 to 4711 (−1320) whereas I_{inj} is increased from −535 to 982 (+1571) when switching from configuration 3.2 (P_{pv} = 8 kWp and P_{wt} = 15 kWp) to configuration 3.3 (batteries of a rated capacity of 200 kW h are added to the building) (1980's insulation standards, occupancy scenario OS_2, behaviour scenario BS_1). As another example, I_{ext} is decreased from 4764 to 3543 (−1221) whereas I_{inj} is increased from −172 to 1298 (+1470) when switching from configuration 5.2 (P_{pv} = 7.4 kWp and P_{wt} = 11 kWp) to configuration 5.3 (batteries of a rated capacity of 200 kW h are added to the building) (RT2005 insulation standards, occupancy scenario OS_1, behaviour scenario BS_1). Finally, batteries for electricity storage allow the (annual)

economic cost (J_{cost}) to be reduced up to 110 €, depending on the configuration (*i.e.* the building insulation level and scenarios) (T_{grid} = 70%). Electricity storage (using batteries), even though technologies have to be perfected, is an interesting option for overcoming renewable energy's intermittency. Indeed, it contributes to fill the gap between local production and demand in energy.

4.2.3. Grid threshold set to 30%

As for an electricity grid which is in need of energy during peaks of demand only (T_{grid} = 70%), a complete analysis of the noteworthy configurations we obtained for T_{grid} = 30% is carried out in this section (the advanced management strategy is applied to the building equipped with energy production and storage systems) (Tables 15 to 17). We took as references the configurations we highlighted for the management of the building energy resources when the building is not equipped with batteries for electricity storage (Table 11). First, one can note that P_{pv} (the photovoltaic solar panels peak power) and P_{wt} (the vertical-axis wind turbine peak power) are both clearly impacted when changing the building insulation level and/or the scenarios. As one can see in Table 15, P_{pv} and P_{wt} are decreased when improving the insulation level (from 1980's to RT2005 standards) and adding (well-designed) batteries to the building, whatever the considered scenarios. For example, P_{pv} and P_{wt} are reduced from 5.7 to 3.5 kWp (−2.2 kWp) and from 25 to 17 kWp (−8 kWp), respectively, when switching from configuration 1.3 to configuration 5.3 (E_{bat}^{max} = 200 kW h). As another example, P_{pv} and P_{wt} are reduced from 6.1 to 3.6 kWp (−2.5 kWp) and from 23 to 16 kWp (−7 kWp), respectively, when switching from configuration 4.3 to configuration 8.3 (E_{bat}^{max} = 200 kW h). As for T_{grid} = 70%, one can note that adding (well-designed) batteries to the building, when it is equipped with a combination of photovoltaic solar panels and a vertical-axis wind turbine, tends to increase the total power capacity, wathever the building insulation level. For example, the total power capacity is increased from 25.1 to 30.7 kWp (+5.6 kWp) in case of adding batteries to the building (1980's insulation standards) and considering occupancy scenario OS_1 and behaviour scenario BS_1. It is increased from 13.9 to 19.8 kWp (+5.9 kWp) when resorting to electricity storage and considering occupancy scenario OS_2 and behaviour scenario BS_1 (RT2005 insulation standards). One can also remark that, when adding batteries to the building, the total power capacity installed is higher for T_{grid} = 30% (energy can be appropriately injected to the grid most of the time) than it is for T_{grid} = 70% (the electricity grid is in need of energy during peaks of demand only). In addition, electricity storage allows J_{ren} to be improved, as a result of an increased renewable energy coverage rate ($\%_{ren}$) and a better percentage ratio of the renewable energy consumed to the renewable energy produced *in situ* ($\%_{sc}$). As an example, J_{ren} is increased from 20 to 24.5% (+4.5 pts) when switching from configuration 1.2 (P_{pv} = 5.7 kWp and P_{wt} = 25 kWp) to configuration 1.3 (batteries of a rated capacity of 200 kWh are added to the building) (1980's insulation standards, occupancy scenario OS_1, behaviour scenario BS_1). As another example, J_{ren} is increased from 19.7 to 26.1% (+6.4 pts) when switching from configuration 7.2 (P_{pv} = 3.8 kWp and P_{wt} = 16 kWp) to configuration 7.3 (batteries of a rated capacity of 200 kW h are added to the building) (RT2005 insulation standards, occupancy scenario OS_2, behaviour scenario BS_1). In addition, taking a look at Tables 13 and 16, one can remark that J_{ren} is lower for T_{grid} = 30% than it is for T_{grid} = 70%, when the building is equipped with batteries and a combination of photovoltaic solar panels and a vertical-axis wind turbine. Otherwise, electricity storage allows both the amount of energy injected to the grid (E_{inj}) and the amount of energy extracted from the grid (E_{ext}) to be reduced. When switching from configuration 2.2 to configuration 2.3 (1980's insulation standards, occupancy scenario OS_1, behaviour scenario BS_2), E_{inj} is reduced from 22 003 to 19 564 kW h (−2439 kW h) whereas E_{ext} is reduced from 26 517 to 24 455 kW h (−2062 kW h). E_{inj} is reduced from 16 120 to 14 001 kW h (−2119 kW h) and E_{ext} is reduced from 16 697 to 14 908 kW h (−1789 kW h) when switching from configuration 6.2 to configuration 6.3 (RT2005 insulation standards, occupancy scenario OS_1, behaviour scenario BS_2). For T_{grid} = 30% (energy can be appropriately injected to the grid most of the time), the decrease due to electricity storage one can observe in both the amount of energy injected to the grid (E_{inj}) and the amount of energy extracted from the grid (E_{ext}) is lower than it is for T_{grid} = 70% (the electricity grid is in need of energy during peaks of demand only).

As for an electricity grid which is in need of energy during peaks of demand only (T_{grid} = 70%), equipping the considered house with (well-designed) batteries and managing the energy production and storage systems using the proposed advanced strategy (see Section 3.3) change the way this residential building and the grid interact. I_{ext} (which is about the impact on the grid of energy extraction) decreases if the building insulation level agrees with 1980's standards whereas it increases if this level agrees with RT2005 standards. The overall impact criterion (I_{grid}) is improved and always positive (Table 17). As a first example, which is about 1980's insulation standards, I_{ext} is decreased from 5567 to −3630 (−9197) whereas I_{inj} is increased from −2156 to 7548 (+9704) when switching from configuration 3.2 (P_{pv} = 6.1 kWp and P_{wt} = 22 kWp) to configuration 3.3 (batteries of a rated capacity of 200 kW h are added to the building, occupancy scenario is OS_2 and behaviour scenario is BS_1). As another example, which is about RT2005 insulation standards, I_{ext} and I_{inj} are both increased from 4437 to 5670 (+1233) and −2101 to −1923 (+178), respectively, when switching from configuration 5.2 (P_{pv} = 3.5 kWp and P_{wt} = 17 kWp) to configuration 5.3 (batteries of a rated capacity of 200 kW h are added to the building, occupancy scenario is OS_1 and behaviour scenario is BS_1).

Finally, batteries for electricity storage allow the (annual) economic cost (J_{cost}) to be reduced up to 60 €, depending on the configuration (*i.e.* the building insulation level and scenarios) (T_{grid} = 30%). As for T_{grid} = 70%, electricity storage, even though technologies have to be perfected, is an interesting option for overcoming renewable energy's intermittency and contributes to fill the gap between local production and demand in energy.

5. Conclusion and outlook

Decentralized power generation, as a result of both an increasing demand in energy and the exhaustion of fossil fuels, is leading the way to fight global warming and promote energy efficiency. However, because a massive penetration of renewable energy sources affects the physical operation of a grid, dramatic changes in planning practices as well as an increased flexibility are required. So, a new approach to energy resources management is proposed for residential microgrids. In this sense, the thermal behaviour of a grid-connected building equipped with energy production and storage systems has been modelled using the TRNSYS (Transient System Simulation Tool) software. The house faces south and is inhabited by four persons (two adults and two children).Besides, we considered 1980's and RT2005 insulation standards and proposed realistic occupancy (OS_1 and OS_2) and behaviour (BS_1 and BS_2) scenarios. We defined BS_2 by shifting some domestic loads from on-peak to off-peak periods. The data about energy consumption (for each room and all the identified consuming items) we collected in the real residential building located in Perpignan (Perpignan-Méditerranée agglomeration community, Languedoc-Roussillon region, south of France) allowed the model to be successfully validated. Consequently, the model can be regarded as fully representative of the building thermal behaviour.

We developed two strategies one can apply to the considered residential building so as to manage its energy resources optimally. The first one (titled "reference" strategy) deals with managing energy production systems only (photovoltaic solar panels or a combination of photovoltaic solar panels and a vertical-axis wind turbine). With the second one (titled "advanced" strategy), one can manage both the renewable energy production and the batteries used for electricity storage. Energy and economic criteria have been defined in order to evaluate the proposed approach. Whatever the strategy used, the electricity grid status is taken into consideration and we highlighted interesting configurations that promote self-consumption of energy and allow the negative impact decentralized power generation can have on the grid to be minimized.

As interesting simulation results, we highlighed the combination of photovoltaic solar panels and a vertical-axis wind turbine as a viable energy mix option for residential buildings located in the south of France as well as the savings one can achieve by shifting some domestic loads from on-peak to off-peak periods. Clearly, adding a wind turbine to the building produces a greater flexibility in energy resources management. In particular, it enables an increase in the amount of energy produced and consumed *in situ*, even during nighttime. Without electricity storage (in that case, the "reference" management strategy is used), the wind turbine allows I_{inj} (which is about the impact on the grid of local production of renewale energy), I_{ext} (which is about the impact on the grid of energy extraction) and I_{grid} (the overall impact) to be increased in case of peaks in energy demand. Note that these three criteria are reduced during low-demand periods. One can highlight the following configurations in terms of maximizing J_{ren} (defined as a combination of the renewable energy coverage rate and the percentage ratio of the renewable energy consumed to the renewable energy produced *in situ*) (OS_2 and BS_1): P_{pv} = 6.6 kWp and P_{wt} = 17 kWp in case of a building insulation that agrees with 1980's standards (J_{ren} = 20.9%), whereas P_{pv} = 3.9 kWp and P_{wt} = 10 kWp if RT2005 standards are considered (J_{ren} = 20.4%).

One can also note that electricity storage, even though technologies (batteries) have to be perfected, is an interesting option for overcoming renewable energy's intermittency. It contributes to fill the gap between local production and demand in energy. In addition, batteries allow the amount of energy injected to the electricity grid to be reduced, what improves I_{inj}. Both I_{ext}, even if the amount of energy extracted from the grid is reduced, and I_{grid} increase. As a key point, batteries help to extract energy from the grid at favorable times. However, the economic impact of electricity storage remains low. One can highlight the following configurations in terms of maximizing J_{ren} (OS_2 and BS_1): for a grid threshold T_{grid} equal to 30% (energy can be appropriately injected to the grid most of the time), P_{pv} = 6.1 kWp, P_{wt} = 22 kWp and E_{bat}^{max} = 200 kW h in case of a building insulation that agrees with 1980's standards (J_{ren} = 25.4%), whereas P_{pv} = 3.8 kWp, P_{wt} = 16 kWp and E_{bat}^{max} = 200 kW h if RT2005 standards are considered (J_{ren} = 26.1%); for a grid threshold T_{grid} equal to 70% (the electricity grid is in need of energy during peaks of demand only), P_{pv} = 8 kWp, P_{wt} = 15 kWp and E_{bat}^{max} = 200 kW h if 1980's insulation standards are considered (J_{ren} = 32.7%), whereas P_{pv} = 7.8 kWp, P_{wt} = 10 kWp and E_{bat}^{max} = 200 kW h in case of a building insulation that agrees with RT2005 standards (J_{ren} = 37.0%).

Future work will first focus on developing and testing in simulation a predictive strategy so as to refine, in particular, the batteries management. With such a strategy, energy resources availability (total solar irrandiance and wind speed), changes in energy demand, as well as the electricity grid status will be anticipated. Therefore, an *in situ* validation of all the proposed strategies will be launched. Finally, we will evaluate the impact on energy resources management and performance of geographical factors (to this end, we will consider various possible locations for the considered building, in particular windy and/or sunny locations as well as locations with no significant wind and sun resources), different heating systems (an all-electric

system, a heat pump system, a geothermal system with radiant floors, a solar system...) and Domestic Hot Water (DHW) production.

References

[1] United Nations framework convention on climate change, Climate change: impacts, vulnerabilities and adaptation in developing countries (2007).

[2] Technical Support Unit Working Group III, Postdam Institute for Climate Impact Research, Renewable Energy Sources and Climate Change Mitigation, Special Report of the Intergovernmental Panel on Climate Change (2012).

[3] United Nations framework convention on climate change, Kyoto protocol (1998).

[4] A. von Meier, Electric power systems: A conceptual introduction, Wiley-IEEE Press, 2006.

[5] T. A. Short, Electric power distribution handbook, Second edition, CRC Press, 2014.

[6] G. M. Masters, Renewable and efficient electric power systems, John Wiley and Sons, 2004.

[7] S. Ruester, S. Schwenen, C. Battle, I. Pérez-Arriaga, From distribution networks to smart distribution systems: Rethinking the regulation of european electricity DSOs, Utilities Policy 31 (2014) 229–237.

[8] T. J. Hammons, Impact of electric power generation on green house gas emissions in europe: Russia, Greece, Italy and views of the eu power plant supply industry a critical analysis, International Journal of Electrical Power and Energy Systems 28 (8) (2006) 548–564.

[9] X. Fang, S. Misra, G. Xue, D. Yang, Smart grid - The new and improved power grid: A survey, IEEE Communications Surveys and Tutorials 14 (4) (2012) 944–980.

[10] T. J. Hammons, Integrating renewable energy sources into european grids, International Journal of Electrical Power and Energy Systems 30 (8) (2008) 462–475.

[11] European Union, Technology platform for the electricity networks of the future (2005).

[12] D. Coll-Mayor, M. Paget, E. Lightner, Future intelligent power grids: Analysis of the vision of the european union and the united states, Energy Policy 35 (4) (2007) 2453–2465.

[13] P. J. Agrell, P. Bogetoft, M. Mikkers, Smart-grid investments, regulation and organization, Energy Policy 52 (1) (2013) 656–666.

[14] G. Chicco, P. Mancarella, Distributed multi-genaration: A comprehensive view, Renewable and Sustainable Energy Reviews 13 (3) (2009) 535–551.

[15] A. Battaglini, J. Lilliestam, A. Haas, A. Patt, Development of supersmart grids for a more efficient utilisation of electricity from renewable sources, Journal of Cleaner Production 17 (10) (2009) 911–918.

[16] N.-K. C. Nair, L. Zhang, Smartgrid: Future networks for new zealand power systems incorporating distributed generation, Energy Policy 37 (9) (2009) 3418–3427.

[17] R. Hledik, Rediscovering residential demand charges, The Electricity Journal 27 (7) (2014) 82–96.

[18] B. Fardanesh, E. F. Richards, Distribution system production with decentralized generation introduction into the system, IEEE Transactions on Industry Applications 20 (1984) 122–130.

[19] R. C. Dugan, D. T. Rizy, Electric distribution protection problems associated with the interconnection of small, dispersed generation devices, IEEE Transactions on Power Apparatus and Systems 103 (6) (1984) 1121–1127.

[20] T. T. H. Pham, Influences de la production décentralisée sur la gestion des infrastructures critiques des réseaux de puissance, Ph.D. thesis, Grenoble INP, France (2006).

[21] M. A. Fontela-Garcia, Interaction des réseaux de transport et de distribution en présence de production décentralisée, Ph.D. thesis, Grenoble INP, France (2008).

[22] V. Courtecuisse, Supervision d'une centrale multisource à base d'éoliennes et de stockage d'énergie connectée au réseau électrique, Ph.D. thesis, Grenoble INP, France (2008).

[23] M. C. Alvarez-Hérault, Architecture des réseaux de distribution du futur en présence de production décentralisée, Ph.D. thesis, Grenoble INP, France (2009).

[24] H. Lund, E. Münster, Management of surplus electricity-production from a fluctuating renewable-energy source, Applied Energy 76 (1-3) (2003) 65–74.

[25] B. Paris, J. Eynard, S. Grieu, T. Talbert, M. Polit, Heating controls for energy management in buildings, Energy and Buildings 42 (10) (2010) 1908–1917.

[26] P. Bertoldi, B. Hirl, N. Labanca, Energy efficiency status report 2012, Electricity consumption and efficiency trends in the EU-27, Tech. rep., Joint Research Center, Institute for Energy and Transport (2012).

[27] Federal Energy Regulatory Commission, Assessment of demand response and advanced metering (2012).

[28] K. Spees, L. Lave, Demand response and electricity market efficiency, Electricity Journal 20 (3) (2007) 69–85.

[29] J. Torriti, M. G. Hassan, M. Leach, Demand response experience in europe: Policies, programmes and implementation, Energy 35 (4) (2010) 1575–1583.

[30] P. Palensky, D. Dietrich, Demand side management: Demand response, intelligent energy systems, and smart loads, Industrial Informatics 7 (3) (2011) 381–388.

[31] M. F. Haniff, H. Selamat, R. Yusof, S. Buyamin, Review of HVAC scheduling techniques for buildings towards energy-efficient and cost-effective operations, Renewable and Sustainable Energy Reviews 27 (4) (2013) 94–103.

[32] A. Garnier, J. Eynard, M. Caussanel, S. Grieu, Low computational cost technique for predictive management of thermal comfort in non-residential buildings, Journal of Process Control 42 (6) (2014) 750–762.

[33] L. Gelazanskas, K. A. A. Gamage, Demand side management in smart grid: A review and proposals for future direction, Sustainable Cities and Society 11 (4) (2014) 22–30.

[34] P. O. Kriett, M. Salani, Optimal control of a residential microgrid, Energy 42 (1) (2012) 321–330.

[35] E. Kremers, J. G. de Durana, O. Barambones, Multi-agent modeling for the simulation of a simple smart microgrid, Energy Conversion and Management 75 (2013) 643–650.

[36] M. Honarmand, A. Zakariazadeh, S. Jadid, Integrated scheduling of renewable generation and electric vehicles parking lot in a smart microgrid, Energy Conversion and Management 86 (2014) 745–755.

[37] République Française, Arrêté du 24 mai 2006 relatif aux caractéristiques thermiques des bâtiments nouveaux et des parties nouvelles de bâtiments (2006).

[38] S. A. Klein, Solar Energy Laboratory, University of Wisconsin, Madison, USA, TRNSYS 17: A transient system simulation program (2010).

[39] M. Salvador, S. Grieu, Methodology for the design of energy production and storage systems in buildings: Minimization of the energy impact on the electricity grid, Energy and Buildings 47 (2012) 659–673.

[40] W. DeSoto, Improvement and validation of a model of photovoltaic array performance, Ph.D. thesis, Wisconsin-Madison University, USA (2004).

[41] J. A. Duffie, W. A. Beckman, Solar engineering of thermal processes, Second edition, John Wiley and Sons, 1991.

[42] P. J. A. Quinlan, Time series modeling of hybrid wind photovoltaic diesel power systems, Ph.D. thesis, Wisconsin-Madison University, USA (1996).

[43] S. B. Bogdan, Z. M. Salameh, Methodology for optimally sizing the combination of a battery bank and pv array in a wind/pv hybrid system, IEEE Transactions on Energy Conversion 11 (2) (1996) 367–375.

[44] B. Ai, H. Yang, H. Shen, X. Liao, Computer-aided design of pv/wind hybrid system, Renewable Energy 28 (10) (2003) 1491–1512.

[45] Meteonorm, Database version 7. http://www.meteonorm.com.

[46] European Power Exchange, a power exchange at the heart of Europe, http://www.meteonorm.com.
[47] Electricité de France Energies Nouvelles Réparties, Panneaux photovoltaïques et énergies nouvelles. http://www.edfenr.com.