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"Smart buildings" integrated in "smart grids": A key challenge for the energy transition by using physical models and optimization with a "human-in-the-loop" approach

Le « bâtiment intelligent » intégré dans les « réseaux intelligents » : un défi clé pour la transition énergétique. Modèles physiques et optimisation associés à une approche intégrant l'acteur humain dans la boucle

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ABSTRACT

The big challenge for the 21th century is to decrease fossil energy use and to increase renewable energies in the framework of the climate constraint. The paper will show that smart buildings, connected to smart grids, can significantly contribute to this objective. Indeed, buildings are, on one side, the biggest consumers of energy in the electrical grid and could be among the greatest producers of renewable energy, especially thanks to the concept of energy positive buildings, and this by offering at the same time high flexibility in energy demand. That is why the paper focuses on methodologies using physical models and optimization for smart design and smart supervision for valorizing those buildings energy properties and contribute thus to the emergence of the concept of smart buildings (SBs) integrated in smart grids (SGs): we will give an overview of the mathematical optimization method used and of the kind of physical models we have developed over 10 years of active research in order to propose by this way a smart software dedicated to those SBs integrated in SGs. We explain also our global research strategy for improving this smart software, by a so-called "human-in-the-loop" approach, in which we consider that they there will be no "smart building" without "smart users". This means a complex multi-disciplinary research that we develop in a "living lab", in which the inhabitants are involved as "pro'sumers", i.e. as active and implicated designers and users.

RÉSUMÉ

L'enjeu du XXI^{e} siècle est de faire décroître la consommation des énergies fossiles au profit des énergies renouvelables sous la pression climatique. Ce papier montre que les bâtiments intelligents (*smart buildings*), intégrés dans des réseaux intelligents (*smart grids*),

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Abbreviations: ADEME, French Agency for Environment and Energy Management; ESP, Energy Sketch Phase; ESOT, Energetic Sketch Optimization Tool; HVAC, Heating Ventilation and Air conditioning; MILP, Mixed Integer Linear Programming; PV, Photovoltaics; IOT, Internet of Things; SB, Smart Buildings; SG, Smart Grids; SQP, Sequential Quadratic Programming; STEP, "Station de transfert d'énergie par pompage"; V2H, Vehicle to Home.

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peuvent significativement contribuer à cet objectif. En effet, les bâtiments sont, d'une part, les plus grands consommateurs d'énergie dans le réseau électrique et pourraient devenir l'un des plus grands producteurs d'énergie renouvelable, en particulier grâce au concept de bâtiment à énergie positive, et ceci en offrant dans le même temps un important gisement de « flexibilité » en demande énergétique. C'est pourquoi cet article se focalise sur des méthodologies utilisant des modèles physiques et l'optimisation pour une conception et une supervision « intelligentes », afin de valoriser les propriétés énergétiques de ces bâtiments et contribuer ainsi au concept de *smart building* intégré dans des *smart grids* : nous donnerons un aperçu des méthodes mathématiques d'optimisation utilisées et des types de modèles physiques que nous avons développés au cours d'une recherche qui s'est déroulée sur plus de dix ans, de manière à proposer ainsi des approches logicielles dédiées à ces *smart buildings* intégrés à des *smart grids*. Nous détaillerons aussi notre stratégie globale de recherche pour améliorer ce type de logiciel « intelligent », par une approche dite « humain dans la boucle » (*human in the loop*), dans laquelle nous considérons qu'il n'y aura pas de « bâtiments intelligents » sans « utilisateurs intelligents ». Ceci implique une recherche interdisciplinaire complexe, que nous développons dans un *living lab* dans lequel les usagers sont impliqués comme consom'acteurs (*pro'sumers*), c'est-à-dire comme concepteurs et usagers actifs.

1. The necessity of an energy transition for the climate

Energy transition is a well-known necessity due to the climate constraints for the next century. This was the main objective of the COP21 conference.[1]

2. The smart grid as part of the solution for climate issues

Faced to this urgency of energy transition, electrical engineering aims to bring a big contribution thanks to the concept of "smart grid" (SG): SG should allow collecting and use smartly intermittent renewable energies thanks to an energy network in which the fluxes of energy will be multidirectional and massively orchestrated thanks to information and communication technologies (i.e. internet massive use)[2] [1,2]. This results in a new scheme and new architecture for the electrical network. The new specificities are a huge introduction of decentralized production, especially renewable energy, with small unities producing energy from wind and sun, like wind turbines, PV panels, small hydraulic plants... The resulting problematic of management of intermittent energy will be solved in SG by using software and communications allowing an active and smart coordination between consumption and production units.

3. "Smart buildings" as key partners of the "smart grid" for the energy transition

3.1. The concept of "smart building"

"Smart building" (SB) can be first seen as the adaptation of the SG concept at the level of the building micro-grid. The idea is to propose a multi-source, multi-load, and multi-storage system, all of it massively orchestrated by information and communication technologies. This concept should also be based on the emerging revolution of IOT and Big Data.

From an electrical and physical engineering point of view, the SB can thus be seen as an energy micro-grid connecting micro-turbines, PV panels, wind turbines, fuel cells, energy storage capabilities, electrical vehicles, global building loads.... This micro-grid should be managed by software that will use information like energy market constraints (energy price), weather forecast, and other external and internal constraints.

With no doubt, if the previous view could be the entry view as an electrical or energy engineer, we must also define what could be a SB for the building's users, in other words for the inhabitants. Fig. 1 is a proposition in which the users and inhabitants are the input and center point. They basically need and want to live in a building offering them services through equipment usage, and this under fundamental comfort requests and constraints (provided by the building envelop and the use of energy systems for heating, cooling, ventilation...).

Thus, SBs are indeed a complex system, involving of course physical law, technological systems, software, but also inhabitants as human actors. Those inhabitants need help to find the best compromise between their comfort feeling and energy consumption.

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[1] http://www.cop21.gouv.fr/.

[2] See also "Technology Roadmap Smart Grids" from the AIE (Agence International of Energie) available at https://www.iea.org/publications/freepublications/publication/smartgrids_roadmap.pdf.

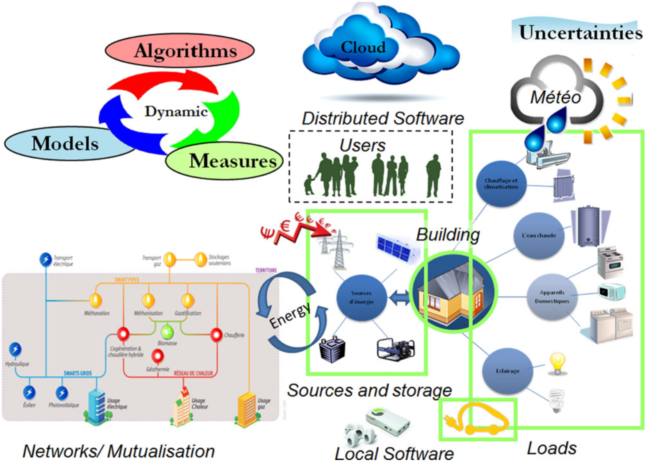

Fig. 1. “Smart building” at the interfaces of energy networks and external environment.

Fig. 2. An example of “smart building” (SB) – The CANOPEA building winner of the 2012 Solar-Decathlon edition.

Last but not least, SBs dimension is an issue, since SB is not a closed and isolated system. As illustrated in Fig. 1, SBs are connected to a complex external environment:

- first of all, SBs are under weather influence; they protect the inhabitants from external conditions, and the energy consumption is highly dependent on the latter;
- even if some SBs can be isolated with the outside world, SBs will be most often connected
  - to energy grids (electrical and thermal): when available, those grids first offer the access to energy, but those same grids will, in the future, offer new services of sharing and exchanging of energy between SBs, in the emerging paradigm of SG;
  - to information networks, thanks to the Internet, thus offering new possibilities of software coordination by data management and exchange.

Fig. 2 gives an example of a prototype of a SB: the CANOPEA building winner of the 2012 Solar–Decathlon edition[3] [3].

3.2. The weight and potential of “smart building” in the “smart grid” as energy consumers

3.2.1. Buildings: main energy consumers in France and over the world

The main part of the final energy in France and over the world is consumed in buildings. An ADEME report [4] indicates that buildings in France are among the greatest emitters of CO_2, with a 20% ratio, and represent 45% of the total final energy consumption. France is far from being an exception; all over the world, buildings are among the main energy consumers with globally an increase in the needs, and this tendency is independent of the place in the world and of the kind of climate. For the USA, the building sector, including residential, commercial, and institutional buildings, accounts annually

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[3] See http://www.g2elab.grenoble-inp.fr/grand-prix-international-solar-decathlon-2012--497448.kjsp, or http://www.g-scop.grenoble-inp.fr/accueil/la-team-rhone-alpes-remporte-le-solar-decathlon-europe-2012-499021.kjsp, http://www.echosciences-grenoble.fr/articles/la-team-rhone-alpes-remporte-le-solar-decathlon-2012.

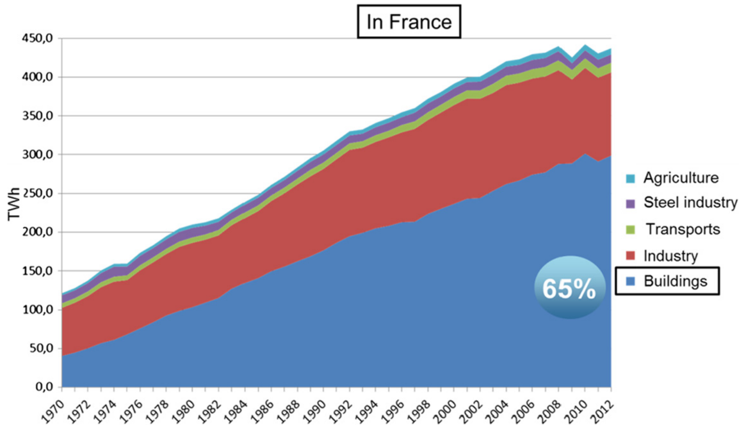

Fig. 3. Evolution of buildings total electricity consumption in France. Buildings are the main consumers (65%) with a constant increase since 1970. From [5].

for about 41% of the primary energy usage, 47% of it is used by the space heating and cooling system.[4] In Canada, more than 55% of the total annual energy consumption of the residential sector is for space heating and cooling.[5] At last, in Brazil, the building sector consumes 47,6% of the electrical energy used for hot water production (shower – 24%), air conditioning (HVAC – 20%), refrigerators (22%), lightning (14%), TV (9%) and freezers (5%).[6]

3.2.2. The picture of buildings final energy consumption in France: the predominance of carbonized and fossil energy

The picture of buildings' final energy consumption in France is given by [5]. Typically, in 2013, the repartition was: electricity 37%, gas 32%, oil 16%, renewable 15%, and coal 0.4%. Thus, a big part of this energy remains fossil fuel, which means non-renewable energy.

3.2.3. Buildings: main electrical energy consumers

The buildings consumption impact in the electricity sector is the most important, since it represents 65% of it, and its importance is still increasing over the years since 1970 (see Fig. 3).

Reference [4] indicates that the heating ratio has significantly decreased between 1990 and 2012 (from 77% to 64%), probably due the improvement in the thermal insulation of buildings. But, at the same time, specific electrical consumption due to electrical equipment has quite doubled (from 9% to 17%), in the global and massive increase in the total energy consumed by buildings, as shown in Fig. 3.

Those figures are evidences that buildings are a main topic of interest regarding sustainability and energy, and that they have, from an energetic point of view, a massive impact, as being a main consumer of energy with a global impact that is significantly increasing over years, especially since 1970.

3.3. Buildings can be energy positive

Firstly, we should define rapidly what a positive energy building is: a building that produces more energy that it consumes over a given period of time (usually one year is considered, corresponding to a complete natural cycle of use).

The concept of positive energy is at the center of the future thermal regulation in France and Europe for 2020.[7] This concept is central in the big French research programs submitted, like COMEPOS,[8] which aims to prototype and pre-industrialize energy positive buildings for energy regulation in new buildings in France from 2020 onwards.

3.4. Buildings have the potential to become one of the greatest producer of renewable energy

If buildings can be energy positive as explained before, it means that the building sector will be able to cover its own energy needs, and even produce more energy for other sectors, like mobility.

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[4] DOE (Departement of Energy) 2012 2011 Buildings Energy Data Book cited by [42].

[5] Secondary Energy Use by End-Use. Office of Energy Efficiency (OEE) of Natural Resources Canada (NRCan) cited by [42].

[6] "Relatório de Avaliação do Mercado de Eficiência Energética no Brasil – Sumário Executivo", Centro Brasileiro de Informação de eficiência énergetica, http://www.procelinfo.com.br/main.asp?View=%7B5A08CAF0-06D1-4FFE-B335-95D83F8DFB98%7D&Team=&params=itemID=%7B99EBBA5C-2EA1-4AEC-8AF2-5A751586DAF9%7D;&UIPartUID=%7B05734935-6950-4E3F-A182-629352E9EB18%7D#.

[7] Réflexion Bâtiment Responsable 2020–2050, dans le cadre du plan bâtiment durable, responsable, préparation de la RT2020 (Règlementation thermique 2020) https://rbr20202050.wordpress.com.

[8] See http://www.comepos.fr/.

A study of the French agency ADEME [6] proposes an estimation of the potential of renewable energy in France for producing electricity, and it gives more especially an idea of the PV Panels potential at buildings roofs. In this study, which aimed at answering if it is possible to go toward a pure electric renewable energy mix in France for 2050, we find that:

- firstly, the global potential of renewable energy in France is estimated at 1268 TW h per year, knowing that the report estimates the energy consumption for 2050 in France at 422 TW h.[9] In other words, the potential is estimated to be three times higher than the anticipated electrical energy needs;
- secondly, the report tries to anticipate different scenarios with different mixes of renewable energy between solar, wind, hydraulic.... An interesting scenario is the one considering the possibility of 100% renewable energy, with a so-called "good social acceptability" obtained by using as much as possible the existing surfaces, like typically the roofs of the buildings. In this case, PV at the roofs of building could be the main energy production capability by representing up to 34,8% of the global capacity of the network with an amount of 68,3 GW for a global estimated capability of 196 GW.

3.5. *Buildings can valorize their excess of energy locally*

If building can be energy positive and a main producer of energy, the question is then what can be done with the excess of energy they can produce. At the local level, i.e. inside or around the buildings, some interesting propositions can be formulated, like:

- at the level of the micro-grid of the building, producing energy for mobility, by typically recharging batteries of electrical vehicles connected to home and dwellings, letting thus emerge the concept of Vehicle to Home (V2H) [7,8]. By this way, energy is at the same time stored, and usable for mobility;
- at the level of the micro-grid of eco-districts, buildings can share electricity through the network, at the scale of eco-districts or cities, for other very near consumers, typically neighbors. This possibility is open since very recently in France thanks to a new regulation allowing collective auto-consumption.[10] Some local storage facilities, shared at the level of the eco-district, can be probably imagined also.

3.6. *Buildings can valorize their excess of energy at city or country scale thanks to the grid*

Thus buildings could become a key node of the SG of the future by using and sharing their surplus of energy locally through the network, as seen before. But share and exchange of energy must also be imagined at the country and continental levels. This must be typically done for massive storage at level of the national network, and this at different time scale:

- storage at the level of weeks thanks to STEP (pumping of water in hydraulic station) [6];
- storage at the level of the seasons, and especially from summer to winter, thanks to power to gas (production of gas with the excess of energy of summer that can be re-used in winter especially in co-generation units) [6].

3.7. *Buildings are also a major reserve of flexibility and demand response*

Flexibility and demand response are, respectively, the capability of adapting and decreasing the demand for energy. This is a very useful property that can be offered by SBs in SGs, for adapting the demand of energy to the production capability, especially in case of renewable energy, since this energy is basically intermittent. Here again, SBs are the main source of flexibility and demand response. This is confirmed by different studies and experience feedbacks:

- modulating the heating energy use of new and existing buildings could provide 10 to 20 GW of flexible load in France according to the literature and demonstrator projects (see [9–12])[11];
- [6] evaluates especially in detail what could be the potential of flexibility with 4 GW of hot water tank, 14 GW for heater and HVAC, 0.695 GW for oven and washing machine, the total representing roughly 18 GW.

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[9] The ADEME study anticipates a reduction of 14% of the electricity needs for 2050 compared to the actual needs typically of 483 TW h in 2016 (see http://www.rte-france.com/sites/default/files/2016_bilan_electrique_synthese.pdf).

[10] L'ordonnance du 27 juillet 2016 relative à l'autoconsommation d'électricité: https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000032938257&categorieLien=id, Loi de février 2017 relative à l'autoconsommation d'électricité: https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000034080223&categorieLien=id, Décret d'application relatif à l'autoconsommation d'électricité: https://www.legifrance.gouv.fr/eli/decret/2017/4/28/DEVR1707686D/jo/texte.

[11] See also the report http://www.rte-france.com/sites/default/files/rei_abrege_2017.pdf, explaining at page 25 that if the actual demand response capability is limited to 3 GW, it should increase up to 9 GW in 2030.

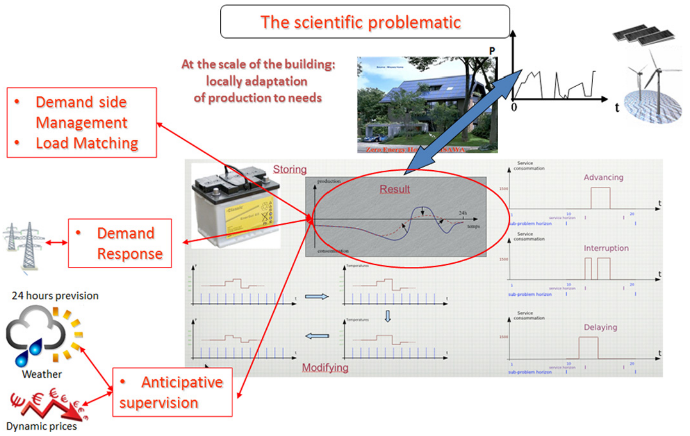

Fig. 4. A first proposal for scientific problematic to address for a more efficient integration of SBs in SGs.

This potential must be compared, at the French level, to the global need for power. If we take the historical pic demand of 102 GW of 8 February 2012,[12] the potential of flexibility[13] of SBs represents then from 10 to 17%. This brief evaluation confirms the real potential of SB as a main and significant source of flexibility and demand response, even in the more critical energy situations at the level of the country.

4. The “smart” behavior that SBs can offer integrated in SG

The previous sections show us that buildings are the main consumers of energy, and have a potential for becoming one of the main producers of renewable energy, whereas they can offer also a great and significant source of flexibility. Thus, they can really be associated with SG, constituting a key pillar of the scenario for the energy transition. This is particularly true in the scenario considering the possibility of pure use of renewable energy [6].

To be helpful in the SGs, building must help to manage the “intermittence” of renewable energy and this at two levels: the local production level of the energy produced inside or around the building, and the global production level for the energy produced at the level of the network.

For the energy produced at the level of the building, SB must be able to adapt as much as possible renewable production to local consumption. This problematic can be addressed with key words and concepts, like production management, demand side management, load matching after having done anticipative management.

For the energy produced at the level of the grids and networks, SB must be able to respond to the signals sent by the network, and should then be able to offer to the network services and capabilities with the following keywords and concepts:

- demand response or flexibility, which means increase in energy demand (when there is an excess of energy and especially renewable energy in the grid) and decrease in the demand of energy (when there is a peak demand and/or a lack of energy in the network),
- ancillary services, like the supply of active power for balancing power at the level of the grid.

5. Scientific and technologic developments toward the concept of smart building (SB) using optimization and physical models

5.1. *A first proposal of formulation of the scientific problematic addressed for the SB*

Fig. 4 illustrates the scientific question we have addressed thanks to our research as to SB could be equipped with a “smart” software layer offering the needed “smart” behavior for being integrated in SG: the goal is, at the level of the building:

- to locally adapt the production to the consumption, by using all the existing degrees of freedom (storage, thermal inertia, advancing, interruption and delaying of charge...);
- by responding to the signals sent by the network (prices...);

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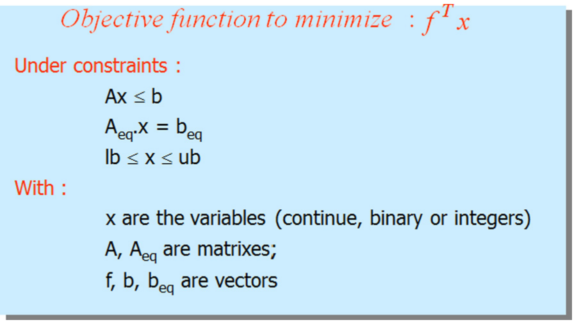
[12] See http://www.rte-france.com/sites/default/files/2016_bilan_electrique_synthese.pdf, page 11.

[13] Flexibility can here be briefly defined by saying that it is the ability of the charge to modulate its consumption. The concept will be reused and explained again later in the paper.



Objective function to minimize : $f^T x$

Under constraints :

$Ax \leq b$

$A_{eq}.x = b_{eq}$

$lb \leq x \leq ub$

With :

x are the variables (continue, binary or integers)

A, A_{eq} are matrixes;

f, b, b_{eq} are vectors

Fig. 5. Canonical form of a linear optimization problem.

- by taking into account outside constraints (like weather) in order to offer global functions like “demand management”, “load matching”, “demand response”. . . .

One important question is the horizon time of the interaction between the grid and the building. In our work, we consider mainly two horizon time: from one day ahead horizon time or “24 hours” (anticipative management) to very short time (typically about 1 min for considering reactive management). So our work is regarding supervision, and not instantaneous control.

With this formulation, the idea is to explore the vision of a SB seen as a complex system, submitted to physical laws, constraints, and managed at last by software. The key question is then to explore scientific proposals for this software.

5.2. Linear and non linear optimization as a proposal for the “smart software layer of SB”

As a proposal for the “smart” software layer, we explored the use of optimization techniques. Optimization is a branch of applied mathematics that is likely interesting to introduce since it offers:

- the formalism for formulating the problem in a generic way, by defining the objectives, the constraints, and the variables of the problem;
- generic algorithms able to solve the previous generic formulated problems.

As we will see it by the overview of our research, we can distinguish two families of optimization approaches:

- linear optimization: Fig. 5 gives the canonical form of a linear optimization problem;
- non-linear optimization.

To be more concrete, if we focus on Fig. 5, we can say that the **x** vector represents the unknown variables. It can typically include the hourly operating power of each source: charge power or discharge power of a battery, consumed grid power, surplus power, controllable load power, non-controllable load power. Each variable is limited by its lower (lb) and upper (ub) bounds. **A**, **b**, $\mathbf{A}_{eq}$, $\mathbf{b}_{eq}$ represent the inequality and equality equation constraints of **x**, mainly resulting from the writing of the physical economical equations modeling the system (see especially [8,13,14]). **f** is the vector of the objective function.

The problem can also be nonlinear. The mathematical relations between the optimization variables, the cost and the constraints, will then be nonlinear. Those problems can be solved by numerical techniques:

- for linear optimization problems, many generic algorithms exist, and we use more especially MILP (Mixed Integer Linear Programing Technic) [3,7,8,13–16];
- for nonlinear optimization problems, generic algorithms exist, and we have more particularly explored SQP (Sequential Quadratic Programing) (see [17] for a precise explanation of the mathematical principle of SQP and the powerful of the approach as well as [18–20] for applications);
- some specific algorithms and strategies can be defined by combining the previous categories of algorithms together, or by adding specific strategies implemented in an algorithm (this approach is especially used in [21]).

Besides the formulation, and the solving of the optimization problem, the big challenge is the definition of a model, i.e. the mathematical expression able to link together the parameters, the constraints, and the objectives.

The next sections are a selection of research works using the optimization developed in our group for the “smart software layer of SB”, and this for two key steps in the life cycle of SB:

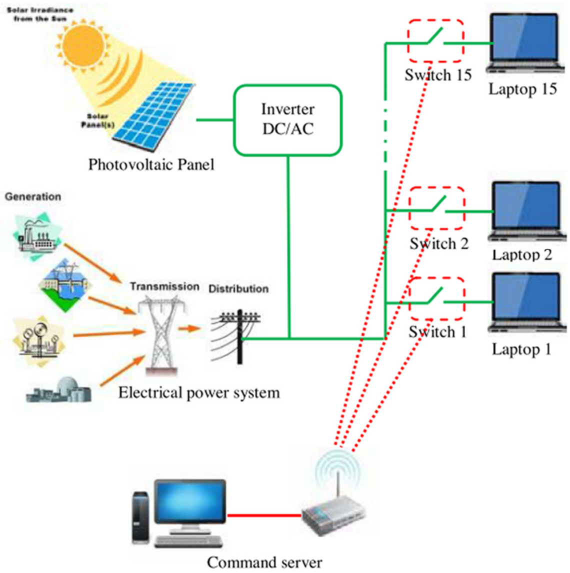


Fig. 6. Real-time control of the charging/discharging phases of 15 laptops for demand response. An approach for "load matching".

- the use time, or the "everyday" management of the building, in other words the supervision that can be reactive (no less than 1 min of horizon time) or anticipative functions (1 day ahead or 24 h) for typically production management, load demand; load matching and anticipative management…;
- the design time, and especially the sketch-phases, i.e. the early steps of the design process of the SB. A key challenge is here to take the good decisions for the choice and the design of the energy systems, and this by taking into account the smart optimal control behavior that should occur during the use time of the building.

Our goal, in this paper, is to give an overview of those contributions. We will more specifically give some details about the optimization approach by detailing the formulation of the problem, the physical models developed, and some results obtained.

5.3. The smart control of SB using optimization approaches: production management, load demand; load matching and anticipative management formulated and solved as an optimization problem

5.3.1. Anticipative, reactive production and load matching seen as an optimization problem

We present here an example of a quite complete approach addressing anticipative management, reactive production and load matching. The use case is illustrated in Fig. 6 and is completely described in [21]. The objective is the optimal control of laptops charging/discharging to fit local PV production. This experiment was done in our first experimental platform (see paragraph 7.1), in which 15 laptops inside one of the room of the building, which was a teaching room, were among the main electrical energy consumers. So the idea was to equip each laptop with a switch that can be interrupted by a central server. This central server runs with "smart" software, so that the following functions are implemented:

- *load matching*: as illustrated on the left-hand side curve of Fig. 7, the local total consumption by the laptops is more or less equal to the local PV production when this production is occurring during the day;
- *anticipative management*: to be able to deal with the previously described "load matching" function, an anticipation of the production of the next 24 hours is done by using weather forecast and prevision of the solar irradiation on one side. On the other side, an anticipation of the use of the laptops is also done, based on the estimated occupancy of the building. If there is a prevision of lack of energy, a pre-charge of the battery is done, as illustrated on right curve of Fig. 7. The pre-charge is done on the network and during the night: it corresponds to the hours where the prices of energy on the network were supposed to be the lowest;
- *"reactive management":* the realization of the "load matching" function supposes also a reactive supervision with a time step of 6 min. As shown in [21], this is implemented by using a quite fine model of the Li-ion batteries, used to evaluate the SOC (state of charge) of the laptop. This allows deciding which laptop will be connected, or disconnected, so that the global consumption curves follows as closely as possible the current local PV production.

As a consequence, and as we can see on right curve of Fig. 7, the installation is autonomous from the network quite all the time, except from 3 to 5 h in the night for pre-charging the batteries.

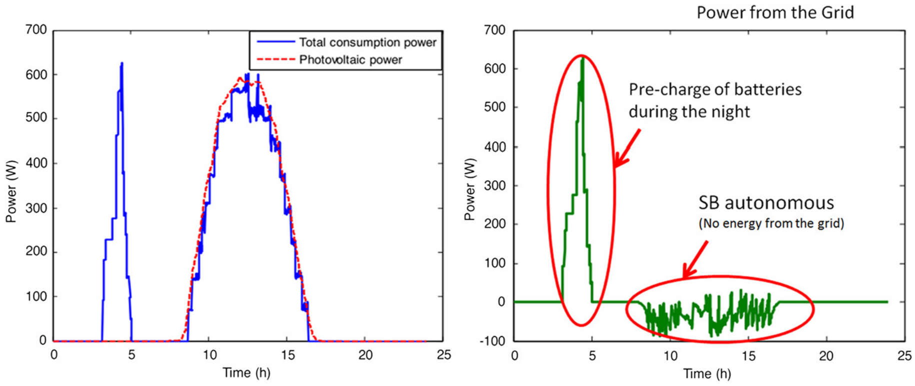


Fig. 7. Total consumption power of the laptops vs PV production (left) and power from the grid (right). From [21].

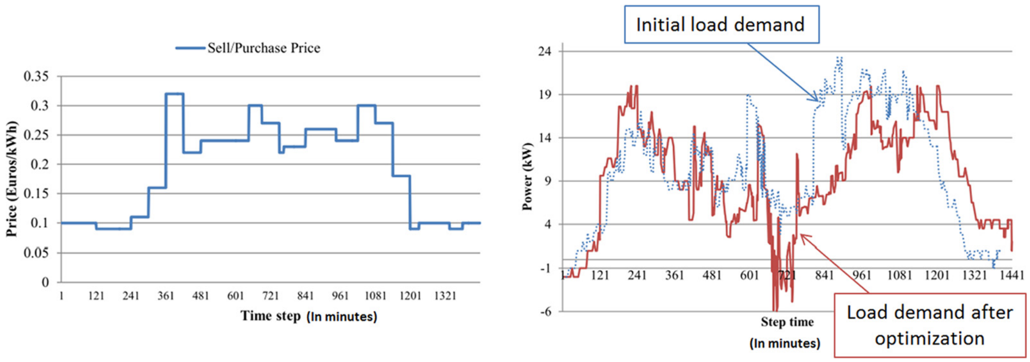


Fig. 8. Price of energy for the next 24 h (left-hand-side curve). Load demand after a MILP smart optimization (right-hand-side curve). From [16].

In this example, we do not use a generic optimization algorithm, but more a rule-based approach. But this example is very complete and covers the smart functions from “anticipative management” to “reactive management” to perform an efficient “load matching”. Thus, it is a very good illustration of the concept of “load matching” of the local demand with the local production of solar energy. A use of a generic optimization algorithm could also be proposed as an interesting perspective. This experiment was done in our first experimental building (see paragraph 7.1) and should be duplicated again in our new experimental building (see paragraph 7.4).

5.3.2. Demand side management or load demand seen as an optimization problem

Here we consider typically a micro-grid of a building. This kind of examples is typically described in [15,16]. The “demand side management”, or “load demand” function is implemented using a deterministic MILP optimization approach, where the planning horizon is 24 hours with one-minute time steps. The principle is to indirectly control the demand by a signal that is the pricing of energy for the next 24 h (see right curve in Fig. 8). To do so, the work described in [16] identifies and proposes a physical modeling compatible with the MILP approach for different sources of flexibility in the micro-grid: Curtailable Load Demand (CLD, also called schedulable), which can be controlled with an on/off status, Reschedulable Load Demand (RLD, also called shiftable), which can be displaced in time. Based on those degrees of freedom, the flexibility on the load demand is obtained for each minute by using the MILP optimization approach with objective functions that are: the cost of the purchased energy on the network in [16] and a more global cost that integrates especially the ageing of the battery in [15]. This is why reference [15] introduces also a detailed physical modeling of the Li-ion batteries, considering the degradation cost associated with the operation, controllable and uncontrollable charging ramps, as well as other limits and operating characteristics given by the manufactures of those batteries. Reference [15] gives a good idea of the size and complexity of the “smart” optimization problem solved: the MILP problem solved in this work has 21,795 variables (14,492 continuous and 7303 binary ones).

The typical results obtained are illustrated in Fig. 8: the right-hand-side curve shows the pricing of energy for the next 24 h, the left-hand-side one shows the “Load Demand” obtained after Smart Optimization using the MILP approach. We can see the impact of the global demand of the SB, which has significantly decreased during the hours where the energy price is high.

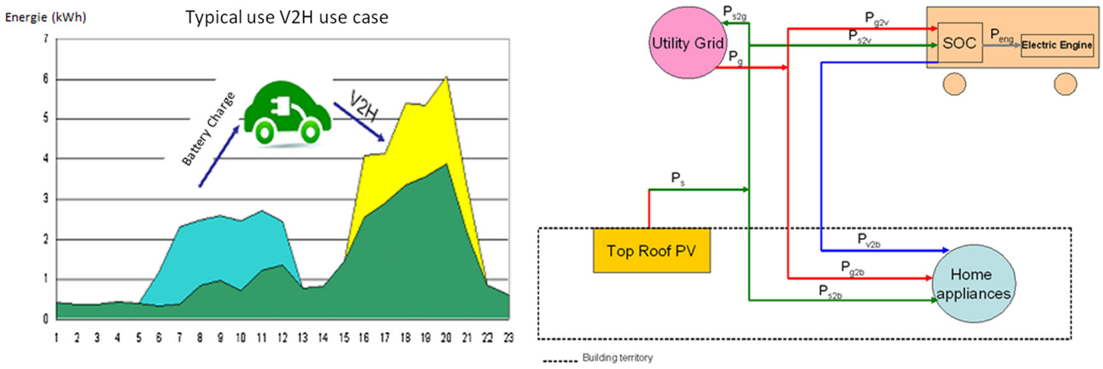


Fig. 9. Principle of V2H concept (left-hand-side graph). Schematic diagram of a V2H infrastructure (right-hand-side curve). From [7,8].

5.3.3. *Focus on the V2H problem seen as an optimization problem*

The idea of V2H (Vehicle to Home) is to make a combined management of a building and of an electrical vehicle connected to it. The principle is more precisely to allow the charging of the battery with carbon-free energy during the day, and then to use the energy stored in the battery for shaving the peak demand of the evening, as illustrated on the left-hand-side curves of Fig. 9.

Thus, the energy storage of the electric vehicle's devices helps SB to offer flexibilities to the SG. This is typically what is done in [7,8], where the purpose is to develop an optimal energy management strategy for a consumer connected to the power grid equipped with a Vehicle-to-Home (V2H) power supply and PV panels. The problem of energy flow management is formulated and solved as an optimization problem using a MILP linear programming model. The total energy cost of the consumer is optimized. The simulation results demonstrated that, if the optimal decisions are made regarding the V2H operation and managing the produced power by solar panels, then the total energy payments are significantly reduced.

The typical size of the problem solved is: 185 inputs, 1211 continue variables, 576 binary discrete variables, and 4273 constraints.

5.3.4. *Demand response problems and the question of ancillary service for SG solved as an optimization problem*

In [13], we explicitly study the question of the services that SB could offer to SG. This paper proposes indeed a formulation and a solving as a linear optimization problem of SB offering to the network ancillary services, like, typically, taking part in the markets for balancing power at the level of the grid. This is done despite the negative impact on profit of several types of uncertainty, notably the intermittent nature of the PV source. Again, a MILP approach is used. Reference [2], by using again MILP approaches, demonstrates the advantages in future for the SG to have SBs able to help it to reduce the peak current, reduce the voltage unbalance (due to neutral current) or respect the voltage magnitude constraints.

5.4. *Optimal design of buildings integrating smart control of buildings, especially in sketch phases*

If SBs must be optimally supervised and controlled, they must be, first of all, optimally designed. In our research, we more especially outlined the importance of the first steps of the design process, as in [19], where we explained that initial sketch steps in design process represent a small part of the final project's cost (roughly 5%). Nevertheless, those initials sketch steps are critical because stakeholders take decisions that determine 75% of the total project's expenses [22]. It is therefore important to investigate, in these early phases of the design process, as many possibilities as possible. It is important also to have a view as complete as possible, which should integrate especially the SB properties and behaviors like "demand side management", "demand response".... The goal is thus synthesized in Fig. 10: making as soon as possible a systemic design, by designing simultaneously the envelope, the energy system, and the optimal control strategy.

5.4.1. *From sketch energy design to optimal supervision of SB thanks to optimization formalism and tools*

To reach the goal, we proposed in [19,20] the introduction of a concept of energetic sketch (the so-called ESP or "Energy Sketch Phase") equivalent to the sketch of architects when they are designing the envelope of the building. As an optimal and efficient "smart" tool to instrument this ESP, we propose also the concept of "Energetic Sketch Optimization Tool" (ESOT). The precise characteristics of an ESOT are: it is a tool dedicated to the very early steps of the design process (preliminary design, study of feasibility of projects, of programs...) using optimization techniques for exploring the highest numbers of possibilities of design (the more solutions are explored, the better it is).

This kind of approach has also been proposed in [14], where we precisely show that there is in fact a scientific continuity between the optimization problem that can be formulated in the ESP phase and the optimization problem that can be solved in the supervision phase (or "operation scheduling phase"). The same formulation, physical model, and solving algorithm (MILP for [14]) are used for design (ESOT) and supervision. The only difference is that sizing values (like size of PV modules, battery capacities...) are degrees of freedom during the ESP phase, whereas they become constant during the supervision phase.

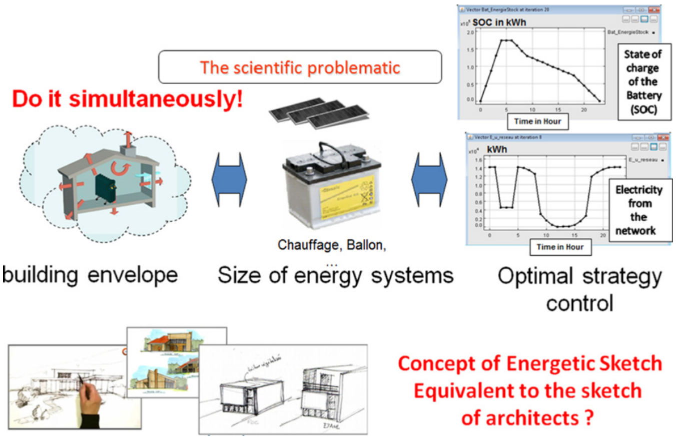


Fig. 10. The concept of a sketch design for SB for a global and systemic design as early as possible in the design process.

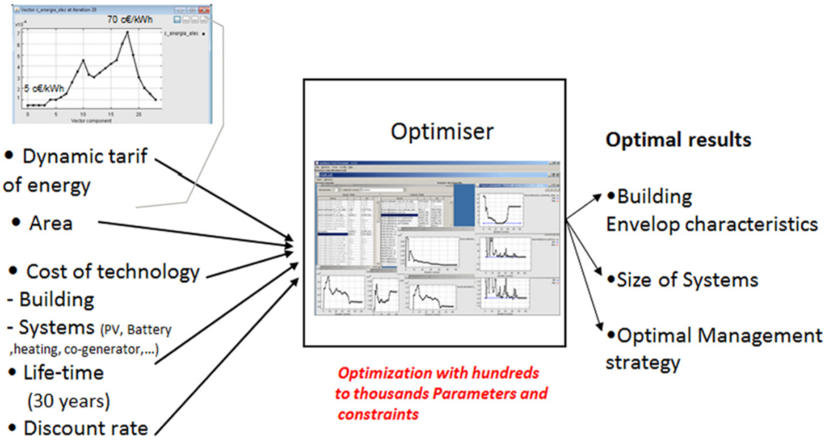


Fig. 11. Structure of an ESOT (Energetic Sketch Optimization Tool) developed for ESP (Energy Sketch Phase) of positive-energy railway stations (from [19]).

5.4.2. Some examples of design of buildings in sketch phases integrating smart optimal control strategies

To conclude this part, we will give here briefly an overview of some references addressing the ESP phase with ESOT tools using linear and non-linear optimization approaches.

Optimal sizing for residential buildings with linear optimization approach Linear approaches are really adapted. We demonstrated it more specifically for residential buildings [14], but there is no doubt that the same approaches can be used for tertiary buildings.

Optimal sizing for residential buildings with a non-linear optimization approach We explored non-linear approaches for residential buildings: see [18] and [17]. Those references not only demonstrate the efficiency of nonlinear optimization approaches, but also demonstrate the efficiency of first-order deterministic optimization algorithms (i.e. algorithms like SQP, which uses the first derivatives and Jacobians of the models) for solving the optimization problems. Indeed, since the solving of those problems must simultaneously optimize the size of the envelope, of the energy systems, and find the optimal control strategies, the number of optimization parameters can be very high. Typically, in [18] there are 104 degrees of freedom, and 196 constraints, and in [17] we solved problems up to 337 degrees of freedoms and 504 constraints. We show that the solving of those last big optimization problem was inaccessible to zero-order optimization algorithms (typically genetic optimization algorithms like NSGAII [23]) that are, however, the most commonly used, as shown by the state of the art [24]. The main reasons to go beyond the state of art are widely explained in [17] in which we give arguments regarding the importance of developing formal right approaches for computing the derivatives of the models, which represents a big effort practically never done for the moment.

We explored also non-linear approaches for residential buildings in [20], while in [19] we address the problem of a positive-energy railway station. Fig. 11 describes the structures of the ESOT developed for this application.

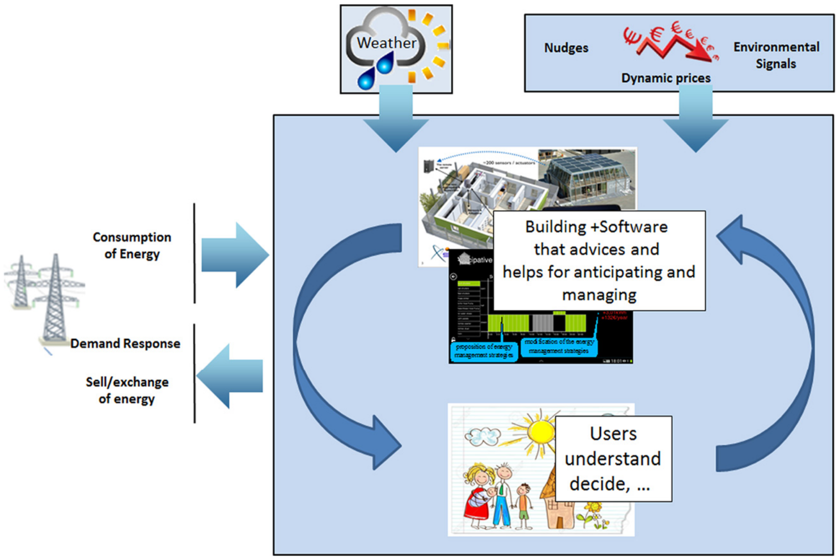


Fig. 12. Our vision of the SB: "Human in the loop" in interaction with the building and software.

6. SB: a complexity calling a new scientific approach: the need to study the system with a "human-in-the-loop" approach

6.1. From the hypothese of a smart building completely designed and controlled by automatic software using physical models and optimization algorithms

The previous section has illustrated how powerful can be the approach of instrumenting "smart" functions associated with SB with software using powerful mathematical optimization and physical modeling, and this from the very early design phase to the management and supervision phase. Thanks to the apparent objectivity of physics, and the calculation efficiency of optimization, it could seem reasonable to ask if SB can be completely and smartly automatized with those kinds of software.

6.2. To a new approach with the hypothesis of the need for the "human in the loop"

Our answer to the previous question by imagining SB only managed by software without implication of the inhabitants of the buildings is a naïve and non-effective approach. In other words, we are convinced that the previously described software solution (using physics and optimization) is an interesting and probably an inevitable key approach to go towards SB. Nevertheless, we work under the hypothesis that one has to consider it only as a piece of the solution in a more global system integrating the human actors. In fact, our entire research is considered under the assumption that "humans must be put in the loop", as illustrated in Fig. 12, in order to study a global system, in which the human being interacts with software. This defines a new level of the system, integrating human actors, and a specific kind of complexity linked to those actors.

We will, in the next sections, give some arguments about this necessity, resulting on one side from the limits of the pure physical and mathematical vision, and on the other side from empirical considerations coming from our experience feedback (comforted by literature references) as well as a more global consideration that the concept of SB will grow associated with the concept of active and implicated inhabitants (the so-called "pro'sumer"). We will see then what are the consequences for software solutions using optimization and physical models. We will detail also how such a "human-in-the-loop" approach can be scientifically deployed and studied, and at last, what are the first results we have obtained with such deployments.

6.3. The limits of the pure smart automatized approach with only software using physics and optimization

6.3.1. Physical and mathematical approaches, even if useful and mandatory, cannot be sufficient, since users are the main sources of unpredictability and uncertainty

As the literature and studies confirmed it, users and inhabitants are one of the main sources of uncertainty and unpredictability. For instance, for heating energy [25–27] and [28] outline that completely identical houses can have a heating consumption that varies by a factor of 2–3 depending on user practices, and thus that user practices are at least as important as the building's physics. For electricity energy, [25] outlines that data analysis on electricity consumption for lighting and appliances suggests that this is more dependent on user practices than on energy efficiency, especially if the number of appliances is counted as part of the user practice. Especially, when comparing households living in similar houses, electricity consumption can vary by a factor of 5, thus indicating that electricity consumption is even still less linked with the building size type than with heating consumption.

Such statements appear to be still valid for low-energy-consumption buildings. Indeed, [29] relates that in the UK similar studies of 26 low-energy houses with post-occupancy evaluation show that those using the least consume 46 kWh/m^2 and those using the most consume 144.9 kWh/m^2 for space and water heating, which is equivalent to a factor 3 in variations in heat consumption, depending on user practices.

These references clearly confirm that if physics and the physical characteristics of the systems are mandatory for understanding and explaining consumption and the associated trends and tendencies, physics alone cannot be sufficient and must be associated with an understanding and an implication of human behavior.

6.4. Why is it necessary and legitim to consider a "human-in-the-loop"approach?

Thus the human are the main source of uncertainty and must be implicated as active actors of the SB integrated in the SG. But other strong reasons developed below argue about this necessity and this from the design and investment phase to the management phase.

6.4.1. Implication of inhabitants to avoid the risk of rejection

Our research activity in SB, developed since more than 10 years, especially in real buildings and platforms (see paragraph 7) has provided us with an experience feedback, showing us that inhabitant need to understand the behavior of the automated software and system. If they have the feeling that they do not understand, the risk is rejection of the system, or emergence of strategies for "short-circuiting" the system. This empirical observation seems validated by academic work that outline similar conclusions [30,31] in a research linked to "smartcities" and "smart buildings". Reference [32] explains, in a study linked to demand response in smart grids: "*Better explanation of all these benefits to the consumer may be necessary to achieve effective residential sector demand response*." Inhabitants should also have the feeling that can they decide, i.e. that they have at last the control of the system, as illustrated in [28], where the author especially outlines: "*Since people in homes have more possibilities for thermal adaptation and have higher levels of perceived control, they are generally more satisfied with their environment than in their offices*."

6.4.2. Implication of inhabitants that will become active pro'sumers from the design to the use of the energy system

6.4.2.1. Smart building & human in the loop. The concept of pro'sumer as an active consumer "Pro'sumer" is a neologism more and more used, especially in commercial offers of industrials selling automated systems and software for SB and SG. The previous developments give some scientific experience feedback of the need to introduce, to study, and to define as correctly as possible this concept, especially so that it corresponds to a real approach with effectively the human being as an active actor in the loop. This is mandatory since, as we show it, this actor is the main consumer of energy all over the world and holds, through its behavior, the key to consumption compatible with the intermittent rhythms imposed by renewable energies.

6.4.2.2. Smart building & human in the loop. The user as an active investor The concept of pro'sumer seems particularly pertinent when we notice that the final consumer will not only be active as final consumer of energy, but also as investor in systems for energy production. This is a logical consequence of the fact that the building where he consumes the energy for the service he needs could also be a significant producer of renewable energy (see paragraph 3.4) by installing renewable producing systems (like PV Panels), and this individually or collaboratively thanks to cooperative actions.[14] So, the pro'sumer is called to be more and more active, even in the sketch phases (see paragraph 5.3) where the investments are decided.

6.4.3. Smart building & human in the loop: the real key-pillar of the energy transition?

The question is then: has the concept of SB with "human in the loop" the potential to be a key pillar of the energy transition. Paragraph 3 argues that from the point of view of the potential and impact (on consumption, on production of renewable energy and of "the flexibility of the demand"), the answer is clearly yes. This analysis is consolidated by economic analysis and anticipations, like the 3rd industrial revolution popularized by Jeremy Rifkin [33]. In this vision, five pillars for the energy transitions are identified. The second one is Transforming the building stock of every continent into green micro-power plants to collect renewable energies on-site. It is especially anticipated that citizens in "smart buildings" could create cooperative able, by aggregation, to be as big and powerful than the existing group of production and distribution of energy and electricity. Other analysis and scenarios coming from science of politics and territories anticipate that final consumers grouped together in cooperatives should be significant new actors in the economy for the energy transition [34].

6.5. The consequence for approaches using models and optimization for a "human-in-the-loop" approach

If pro'sumers must be involved, from the investment phase to the management one, we must then see what are the consequences on the tools based on physical models and optimization.

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[14] See the example of the "Centrales villageoises" http://www.centralesvillageoises.fr, a French cooperative and citizen initiative of local cooperative for producing renewable energy by mainly installing PV installation on the roofs of buildings.

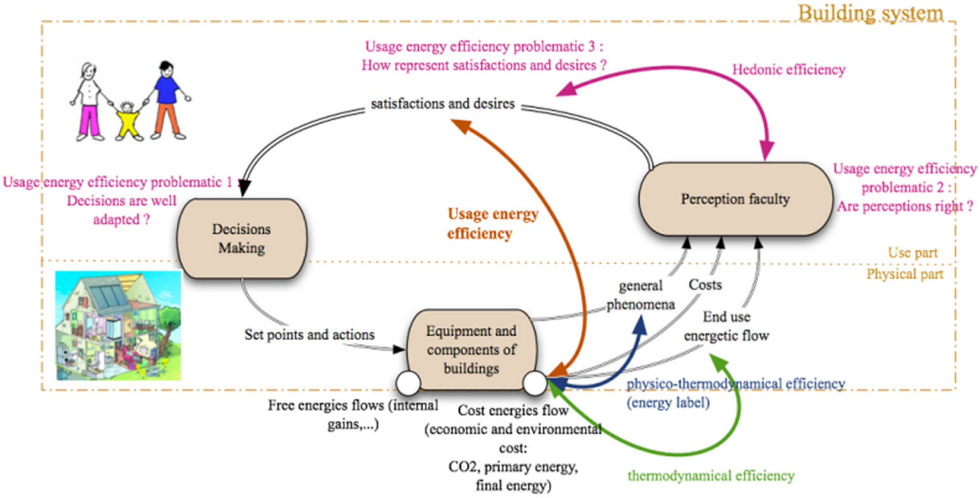

Fig. 13. Qualitative model of the use of a SB with the human in the loop – From [38].

6.5.1. *Models must have the good compromise in complexity*

Physical models must have the good level of complexity, i.e. be associated with a good compromise between "not-too-fine" and "not-too-coarse" models. This point of view has been confirmed by the experience feedback of scientists working in the development of physical models, like Trčka and Hensen [35], who demonstrated that models must be elected with the good compromise between complexity and objective. This has been confirmed by empirical researches searching the right level of complexity of models, and showing that there is a compromise in complexity [36]. But we have to add to those previous physical arguments the need that models should offer a kind of understanding and vision to all users of buildings, and not only to physicists. This legitimates the value of models that might seem simple, like analytic or even qualitative models, but that have a great value in the perspective of SB with active pro'sumers in the loop, who will be "everybody".

6.5.2. *The tools must be ergonomic and persuasive*

Besides the question of the model, the tools implementing those models associated with optimization algorithms must be understandable for the final inhabitants: therefore, such tools should be ergonomic and persuasive for those final users. As explained in [28], referring to [37], understanding the links between feedback, behavior and subjective comfort is important if we are to effectively influence behaviors (like energy-saving, demand response…) and get engagements, since the perceived and understood effects are a major impediment to end-users accepting feedback and advice.

6.5.3. *A multi-disciplinary-approach understanding for modeling and measuring the performances and interactions of the tools with the human in the loop*

At this point emerges the need for making a multi-disciplinary research for:

- *understanding and maybe modeling, in some ways, the behavior of the human in the loop*. This a typically the kind of work that has been done in [28,32,38] with the introduction of physiological (linked to comfort), and psychological (linked to perceptions and feelings) aspects. See Fig. 13 for a model proposed for a qualitative approach of the use of a SB with the human in the loop. Reference [28] proposes a quite similar model.
- *Measuring the performance of the global system with the human in the loop*. This has still been done in experimental economy with studies that try to measure, with the human-in-the-loop approach, aspects like the compromise between cost, constraints, and comfort of the final economical pro'sumers [39].

All those multi-disciplinary studies could and should be revisited with the kind of tools we propose using models and optimization, in order to improve those tools and to measure the benefit they provide in the complete complex system integrating the "human in the loop".

6.5.4. *A multi-disciplinary approach that must allow one to formulate the wishes and beliefs of the users*

Over qualitative models like the one in Fig. 13, more intended to be proposals for giving an understanding, the inter-disciplinary research can and must also result in the formulation of quantitative proposals of models and formulation of objectives and constraints. Reference [38] is typically a quantitative formulation proposal of new indicators for finding the best compromise between cost (or energy consumption) and efficient use of energy as could be perceived by the inhabitants by taking into account wishes (linked to comfort) and perception of efficiency (linked to the expression of what is a good

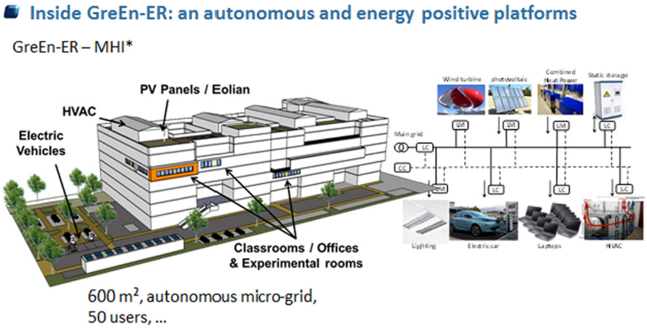

Fig. 14. PREDIS–MHI platform located in the GreEn-ER building.

perceived use of energy for the final user). For this, the paper proposes a formulation of so-called satisfaction function for the user, mixing a satisfaction function linked to comfort and a satisfaction function liked to a perceived efficient use of energy.

7. From the concept of experimental platform to living lab

7.1. From the classical concept of experimental platform for the characterization of physics and systems

To develop our approach, we have historically worked on a first experimental platform described in [44].[15]

7.2. To the concept of living lab for studying the complexity of the system with the human in the loop

For studying the SB with the "human-in-the-loop" approach, we propose also to introduce the concept of living lab that has emerged in the early 2000s at the Massachusetts Institute of Technology [40,41].

7.3. The GreEn-ER building: our living lab at the level of a building

GreEn-ER is a building of 22,000 m^2, with 2000 inhabitants, which is highly energy efficient and massively equipped with sensors. Fig. 14 gives a view of the global building. We have decided to fully deploy in GreEn-Er the concept of living lab (see [40,41]), with the following principles to have a fully "human-in-the-loop" approach:

- *co-creation*: co-design and innovation by users and producers;
- *exploration:* discovering emerging usages, behaviors;
- *experimentation:* implementing live scenarios within communities of users;
- *evaluation:* assessment of concepts, products, and services, and especially the tools based on models and optimization that we propose in this paper, according to socio-ergonomic, socio-cognitive, and socio-economic criteria.

7.4. The Predis-MHI platform: our living lab at a level of an energy positive platform

Inside the global GreEn-ER building, we have implemented a platform called PREDIS–MHI.[16] This platform is energetically isolated from the rest of the building. It has a surface of 600 m^2 (see Fig. 14), with 30 to 50 possible users/inhabitants, and was specifically designed to reach zero-energy building, to study the building's or the neighborhood's exchange of energy, and integration as a SB integrated in SG. This platform hosts a microgrid integrating 22 kW of PV installed on the roof of vehicles, and other PVs are planned to be installed on the building's roof. Other electrical productions are available in the PREDIS platform such as a combined heat & power (CHP), which is also able to heat our platform. Storage capabilities have also been designed to reach zero-energy building. This platform is designed to be highly flexible, so that its researchers and users can, as easily as possible, alternate from the role of researchers, designers, users in order to have a "living lab" experimental facility as efficient as possible.

7.5. Typical results and experiments obtained in our living lab

We can give at least a brief overview of some results obtained with the living lab approach. The right part of Fig. 15 gives an example of diagnostic of malfunction made by the users of the platform, using equipment like thermal cameras. As illus-

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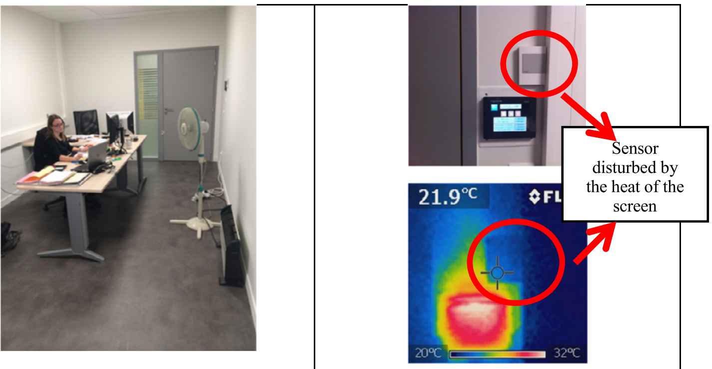
[15] See also the following link for complete and technical description of the platform http://predis.grenoble-inp.fr/.

[16] PREDIS is a global platform dedicated to energy located in the GreEn-ER Platform see http://www.g2elab.grenoble-inp.fr/predis/ and MHI is the French acronym for "Monitoring et habitat intelligent", which means "Monitoring and Smart Use with Inhabitants".



Experience of measurement of compromise comfort vs energy consumption with the human in the loop by using or not ceiling fans (see [43])

Diagnostic made by users using a thermal camera – Problem of heating detected by the users due the installation of the temperature detector close to a control screen that disturbs the sensor

Fig. 15. Overview of some results obtained in the PREDIS-MHI platform used as a living lab.

trated on the left part of Fig. 15, an experiment has been conducted to measure feelings and compromises between comfort and energy consumption [43]. For the analysis of the result, we use a methodology of experimentation and statistical analyses inspired from those performed in experimental economy [39] to characterize the behavior of the global system with the "human-in-the-loop" approach. The roadmap is now to apply this approach to the tools using models and optimization, proposed by this paper, as a candidate for being the smart software used interactively by smart pro'sumers in SBs.

8. Conclusion and perspectives

The first objective of this paper was to demonstrate that SBs in interaction with SG have the potential to be key pillars of the energy transition by offering typically services of production, storage, load demand, load matching. . . .

We have then reviewed the main scientific and technological developments that we have considered to propose a "smart" software using physical models and optimization.

Thanks to this, some proposition of "smart" software tools exist. But we have also exposed, and argued, that this research must be performed "with a human-in-the-loop approach". This is why the strategy will be now to be continued to develop, characterize, experiment, and improve the piece of software, with an implication of the final users in the design, the tests, and the measures. This strategy will be more especially deployed in our living lab GreEn-ER.

Acknowledgement

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