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OPTIMAL SIZING OF A COMPLEX ENERGY SYSTEM INTEGRATING MANAGEMENT STRATEGIES FOR A GRID-CONNECTED BUILDING

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ABSTRACT

This paper presents the simultaneous design and energy management of a complex energy system (heating, air conditioning, PV using battery bank) for a grid-connected building. The thermal comfort, determined by a low order dynamic thermal envelope model, and the life cycle cost (LCC) will be taken into account as optimization criterions meanwhile the load demand covering requirement will be considered as a constraint. The complex problem with a lot of parameters and constraints can be quickly computed using a gradient based optimization software. A case study is a building that is being constructed in South-East of France.

INTRODUCTION

The building sector is the most important consumer of energy in the world. In France, it also consumes 43% of primary energy and 66% of electrical energy of which the cooling and heating section accounts for 50%. Besides, solar photovoltaics is growing rapidly in the world. Between years 2008 and 2013, the installed solar photovoltaic power was multiplied by 8, from 15.8 GW to 136.7 GW (e.g. Report IEA-PVPS T1-24:2014).

Considering a global energy system design depending on its use, in the actual state of art, the design is very sequential. Firstly the building with its thermal envelope is designed, then, a heating and air conditioning (HAC) system is sized, and at last an energy generation system is taken in consideration. The energy management is then designed just before the operation phase. But we would like to show that considering it earlier at the design stage, can bring new design opportunities.

In this paper, we investigate a HAC-PV-battery bank system design and management all together. Our approach considers all the constraints at the same time and therefore we can hope to find solutions with best compromises (between comfort and global cost, between investment and energy cost, etc.) for the multi-objective problem. We also would like to see, in final results, the interaction between the heating-air conditioning load management and the renewable energy production. In this study, a low order thermal envelope model is constructed, which allows to determine the thermal comfort according to the heating power, the internal gains and the weather. Battery charge and discharge management depends on the energy generation from PV, appliances and HVAC system consumption, electricity prices. The

global cost for optimization is taken into account over the life cycle including the investment cost, maintenance cost, replacement cost and the cost of energy consumed from the grid.

The modelling for optimization purpose will be presented in the first part of this paper. The second section will focus on the multi-objective optimization problem formulation. In the final stage, the results of sizing and management strategies will be given and discussed.

CASE STUDY

Building presentation

The case study is the building which is in the ADEME¹ research project "COMEPOS²" aiming at constructing twenty five positive energy buildings in France by 2018. This house is built with more than 200 m² of ground surface, one heated zone, one garage and two basements. It is designed with the good insulation materials to save the energy consumed by heating and air conditioning systems.

An energy management system based on optimal predictive control will be installed by Vesta-System³. Then, we would like to apply our new methodology to size the energetic system based on the fact that it would be managed optimally.

Description of the thermal envelope model

A first model (Figure 1) which enables the dynamic thermal simulation was developed by our partner LOCIE⁴ laboratory, using EnergyPlus⁵ (E+) software.

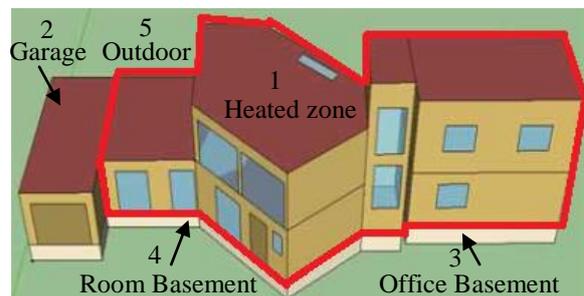


Figure 1 Energy Plus model

This model is considered as a reference model from which we built a reduced order model in the form of

¹ www.ademe.fr

² www.comepos.fr

³ www.vesta-system.fr

⁴ www.polytech.univ-savoie.fr/locie

⁵ <http://apps1.eere.energy.gov/buildings/energyplus>

an equivalent electrical circuit (9R5C) for optimization purpose.

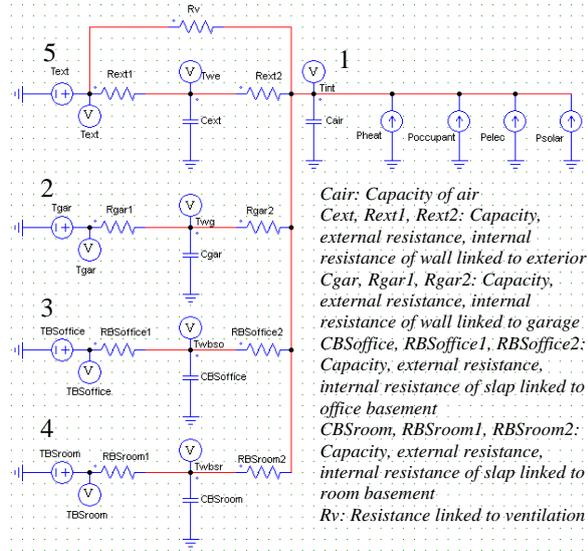


Figure 2 Electrical equivalent circuit

The electrical equivalent circuit is firstly integrated in PSIM software as shown in Figure 2. Then a “netlist” is parsed, which is a standard format for electrical circuit description. Next, the model equations and simulation are able to be automatically generated thanks to Thermotool software (e.g. Boussey et al., 2015). Indeed, the equation system is transformed using a dedicated scheme for time integration of the form :

$$A.T(t) = B.U(t) + C.T(t-1) \quad (1)$$

Where $T(t)$ and $T(t-1)$ contain heated zone inside air temperature (T_{int}) and walls temperatures ($T_{we}, T_{wgar}, T_{wbsr}, T_{wbso}$) at hour t and $t-1$ respectively; $U(t)$ includes sources of gains from heating, solar, occupants, electrical equipments ($P_{heat}, P_{solar}, P_{occupant}, P_{elec}$); Outdoor Dry Bulb temperature (T_{ext}) and unheated zone air temperatures ($T_{gar}, T_{BSoffice}, T_{BSroom}$); A, B, C are incidence matrix that represents all the circuit elements and nodes to which they relate. The equation (1) can be solved by the LU algorithm at each time step.

Identification of parameters of the low order envelope model

An optimization procedure has been implemented in order to identify the model parameters R (K/W) and C (J/K). This identification uses the SQP⁶ algorithm (quasi Newton approach) aiming to minimize the difference between the computed heated zone inside air temperature and the simulation result under

energy plus. We use data profile of one year for the identification then validate the parameters obtained for another year data.

Table 1
Identified parameters R, C

PARAMETERS	IDENTIFIED VALUES
C _{air}	3747281.44
C _{ext}	38832547.60
C _{gar}	233332.53
CBS _{office}	3038849.96
CBS _{room}	8110949.64
R _{ext1}	0.00789
R _{ext2}	0.00417
R _{gar1}	0.17195
R _{gar2}	0.16600
R _v	0.00738
RBS _{office1}	0.06713
RBS _{office2}	0.01350
RBS _{room1}	0.12775
RBS _{room2}	0.00220

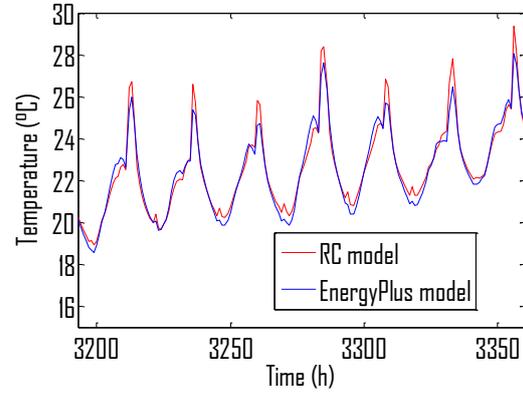


Figure 3 Temperature by Energy Plus and RC model

Table 1 presents the identified parameters R, C of low order envelope model. Figure 3 shows the difference between the temperature calculated by electrical equivalent model from parameters identified and energy plus simulation result for 1 summer week. The mean error value over 1 year entre the two models is about 0.48°C .

ENERGY SYSTEM MODEL

Photovoltaic panel model

The hourly power output of the PV generator, P_{PV} can be calculated by equation (e.g. Kaabeche et al., 2010):

$$P_{PV} = \eta_{PV} \cdot S_{PV} \cdot G_{PV} \quad (2)$$

Where η_{PV} is the PV generator efficiency, S_{PV} is the PV panel area (m^2), G_{PV} represents the global incident irradiance on the titled plane (W/m^2).

The last element G_{PV} is given by (e.g. Ahmad et al., 2010):

⁶ SQP : Sequential Quadratic Programming

$$G_{PV} = I_D \cdot r_b + I_d \cdot \frac{1 + \cos(\beta)}{2} + I \cdot \rho \cdot \frac{1 - \cos(\beta)}{2} \quad (3)$$

In which, I_D , I_d and I are the horizontal direct, diffuse and total irradiance respectively (W/m^2); β is tilted angle of plane (rad); ρ is the reflection coefficient of ground; r_b is ratio between the direct irradiance on the titled plane and the horizontal direct irradiance, which is given by:

$$r_b = \frac{\cos(\theta)}{\cos(\theta_z)} \quad (4)$$

θ is incident angle of direct radiance on the tilted plane (rad) and θ_z is the solar zenithal angle (rad). The combination of (2), (3), (4) allows to size PV area with the input data of horizontal solar irradiance.

Battery bank model

At any hour the state of battery is related to the previous state of charge and to the charge or discharge power during the time from t-1 to t. The available battery bank capacity at hour t can be described by (e.g. Diaf et al., 2007):

$$C_{bat}(t) = C_{bat}(t-1) \cdot (1 - \sigma) + P_{bat}(t) \cdot \Delta t \quad (5)$$

In which, $P_{bat}(t)$ (W) depends on energy production, consumption and grid:

$$P_{bat}(t) = \left(P_{grid}(t) + P_{PV}(t) - \frac{P_{load}(t)}{\eta_{inv}} \right) \cdot \eta_{bat} \quad (6)$$

$P_{bat}(t)$ represents the charging and discharge process corresponding to its positive and negative value respectively; $C_{bat}(t)$ and $C_{bat}(t-1)$ are the available battery bank capacity (Wh) at hour t and t-1 respectively; σ is the self-discharge rate of the battery bank; Δt is the time step (h); $P_{grid}(t)$ is the electrical power bought from grid (W); η_{bat} is the battery efficiency; η_{inv} is the inverter efficiency; $P_{load}(t)$ is the total load demand at hour t (W), which is sum of appliances load and heating or cooling load:

$$P_{load}(t) = P_{elec}(t) + P_{heat}(t) \quad \text{for winter} \quad (7)$$

$$P_{load}(t) = P_{elec}(t) + P_{cool}(t) \quad \text{for summer}$$

ECONOMIC MODEL

Besides the physical criterion, the economic indicator plays an important role in order to size the energy system. In our study, we use the life cycle cost (LCC) which takes into consideration the initial capital cost,

the present value of replacement cost, the present value of operation and maintenance cost of the whole energy system and the energy cost bought from the grid. Therefore, LCC (€) is expressed as follows:

$$LCC = C_{inv} + C_{rep} + C_{OM} + C_{buy,grid} \quad (8)$$

Initial capital cost

The initial capital cost of the whole system C_{inv} (€) is the total of the initial capital cost of each system component:

$$C_{inv} = (C_{bat,nom} \cdot c_{unit,bat}) + (S_{PV} \cdot c_{unit,PV}) + (P_{heat,nom} \cdot c_{unit,heat}) + (P_{cool,nom} \cdot c_{unit,cool}) \quad (9)$$

$C_{bat,nom}$ and $c_{unit,bat}$ are the nominal capacity (Wh) and unit cost (€/Wh) of the battery bank; $c_{unit,PV}$ is the unit cost (€/m²) of the PV array; $P_{heat,nom}$ and $c_{unit,heat}$ are the nominal power (W) and unit cost (€/W) of the heating system; $P_{cool,nom}$ and $c_{unit,cool}$ are the nominal power (W) and unit cost (€/W) of the air conditioning system.

Replacement cost

The present value of replacement cost of a system component depends on its life cycle. In our study, the heating and cooling system, battery bank are included in the total replacement cost but the PV replacement cost is negligible because its life span is considered as the building life span L_p (30 years).

The replacement cost of a system component $C_{rep,cpn}$ (€) can be expressed by (e.g. Kamjoo et al., 2012):

$$C_{rep,cpn} = C_{cpn,nom} \cdot c_{unit,cpn} \cdot \sum_{i=1}^{N_{rep}} \left(\frac{1+f}{1+k_d} \right)^{LC \cdot i} \quad (10)$$

In which, cpn express the component name (battery, heating or cooling); f is the inflation rate (8%) of component replacements; k_d is the annual real interest rate (4%); LC is the life cycle of component (years); N_{rep} is the number of component replacements over the building life period, which can be given by the following equation (e.g. Ramoji et al., 2014):

$$N_{rep} = \text{floor} \left[\frac{L_p - 1}{LC} \right] \quad (11)$$

The total replacement cost of system is so deduced by:

$$C_{rep} = \sum_{bat,heat,cool} C_{rep,cpn} \quad (12)$$

Operation and maintenance cost

The present value of operation and maintenance cost C_{OM} (€) is taken into consideration for all system components:

$$C_{OM} = k.C_{inv} \cdot \frac{1+f}{k_d - f} \left[1 - \left(\frac{1+f}{1+k_d} \right)^{L_p} \right] \quad k_d \neq f \quad (13)$$

$$C_{OM} = k.C_{inv} \cdot L_p \quad k_d = f$$

The value of k is assumed to be as 1%.

The present value of buying electricity from grid

The electricity bill at the initial year C_{grid0} (€) is described by:

$$C_{grid0} = \sum_{t=1}^T \left(\frac{P_{grid}(t)}{1000} \cdot c_{grid}(t) \right) \cdot \frac{8760}{T} + c_{subs} \quad (14)$$

Where $c_{grid}(t)$ express the electricity unit price (€/KW) at step t; c_{subs} is the subscription cost (€) with the electrical producer; T is the computing period.

As a result, the cost of buying electricity over the building life period is deduced by:

$$C_{buy,grid} = \sum_{i=1}^{L_p} \left[C_{grid0} \cdot \left(\frac{1+f}{1+k_d} \right)^{i-1} \right] \quad (15)$$

PROBLEM FORMULATION AND DESIGN SCENARIO

Objective function

In order to size optimally the global energy system, we would like to determine optimum configurations for maximizing the inhabitant comfort and minimizing the life cycle cost in satisfying the load demand (equation 6). In other words, it deals with multi- objective optimization problem which can be formulated as follows:

$$\min fobj = \alpha \cdot \overline{discomf} + (1-\alpha) \cdot \overline{LCC} \quad (16)$$

Where \overline{LCC} is the global cost normalized:

$$\overline{LCC} = \frac{LCC}{LCC_{max}} \quad (17)$$

LCC_{max} can be chosen thanks to the simulation such that \overline{LCC} and $\overline{discomf}$ have the same order of

magnitude. $\overline{discomf}$ expresses the sum of winter thermal discomfort normalized $\overline{discomf}_{winter}$ (°C) and summer thermal discomfort normalized $\overline{discomf}_{summer}$ (°C) which are defined as follows:

$$\overline{discomf}_{winter} = \frac{1}{T_w} \sum_{t=1}^{T_w} \frac{e_T(t)}{\max |e_T(t)|} \quad (18)$$

for $e_T(t) > 0$

$$\overline{discomf}_{summer} = \frac{1}{T_s} \sum_{t=1}^{T_s} \frac{e_T(t)}{\max |e_T(t)|} \quad (19)$$

for $e_T(t) < 0$

With $e_T(t)$ is the difference between the heated zone inside air temperature and the set point temperature at hour t:

$$e_T(t) = (T_{set}(t) - T_{int}(t)) \quad (20)$$

T_S and T_W are the computing period in winter and summer respectively. The thermal discomfort is increasing when the building inside temperature is smaller, respectively greater, than the set point value in winter, respectively in summer.

$\alpha \in [0;1]$ is the weight adjusting the compromise between the 2 optimization criterions.

Design scenario

In this paper, appliances load profiles and weather data supporting to the design are derived from one typical winter day ($T_w=24$) and one typical summer day ($T_s=24$) with the time step of one hour (Figure 4, 5, 6, 7).

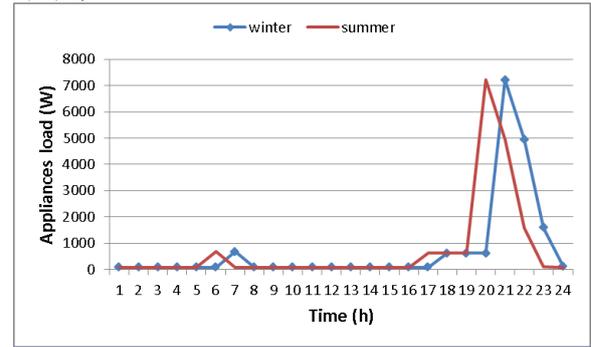


Figure 4 Appliances load demand

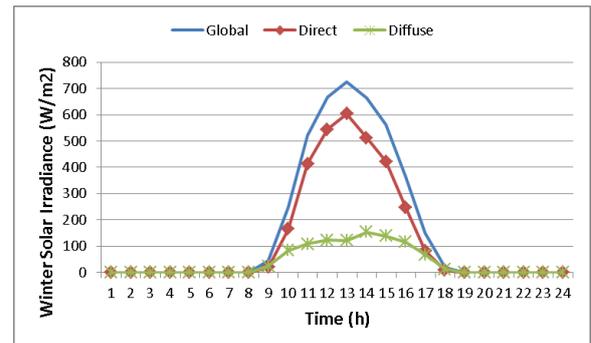


Figure 5 Winter horizontal solar irradiance

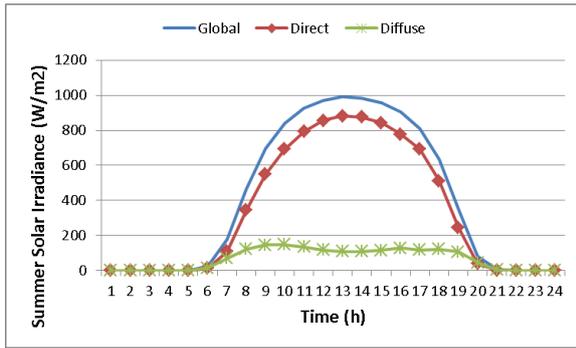


Figure 6 Summer horizontal solar irradiance

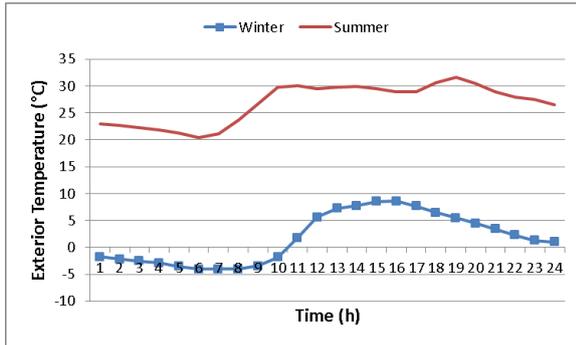


Figure 7 Outdoor Dry Bulb temperature

It is noted that the curves in Figure 4 only present the appliances loads without the heating and cooling loads. The form of load is unchanged over a year, in which there are consumption peaks in the evening due to electric cookers, microwave oven etc. However, there is a time shift between the summer and winter hour in France.

Table 2

Costs and lifetime for the system components

SYSTEM	INITIAL COST	MAINTENANCE & OPERATION COST	LIFE TIME (YEAR)
Heating	1.27 (€/W)	1% of price	6
Cooling	1.27 (€/W)	1% of price	6
PV array	187.5 (€/m ²)	1% of price	30
Battery bank	0.11 (€/Wh)	1% of price	6

Table 3

Electricity subscribed and unit price

SUBSCRIPTION POWER (KW)	ELECTRICITY UNIT PRICE (€/KWH)	SUBSCRIPTION COST (€)
6		102.39
9		121.69
12	0.1593 (€/KWh)	208.53
15	for peak hour	244.72
18	0.1048 (€/KWh)	280.91
24	for off-peak hour	470.21
30		570.57
36		670.93

Table 2 and 3 above introduce the technical and economic configuration of the system components. As shown in table 3, the subscription cost of electricity varies in terms of power signed with the electricity producer (EDF). The off-peak price is 66% of the peak price.

Design parameters and constraints

In our study, there are 104 design and management parameters, and 196 constraints. It is an optimization problem of big size. Table 4 below illustrates some design parameters:

Table 4

Optimization parameters

ITEM	PARAMETER	RANGE OF VALUES
1	$S_{PV}(m^2)$	[0;80]
2	$C_{bat,nom}(Wh)$	[0;60000]
3	$P_{heat,nom}(W)$	[0;20000]
4	$P_{cool,nom}(W)$	[0;20000]
5	$P_{heat}(t=I:T_w)$	[0;20000]
6	$P_{cool}(t=I:T_s)$	[0;20000]
...

Regarding the constraints, a typical example is:

$$0 \leq C_{bat}(t) \leq C_{bat,nom} \quad (21)$$

meaning that the available battery bank capacity at each time t can not exceed the nominal capacity of this battery.

To solve this problem of big size, we use the Cades software⁷ in which the envelope, PV, battery, cost models are developed as modules and connected:

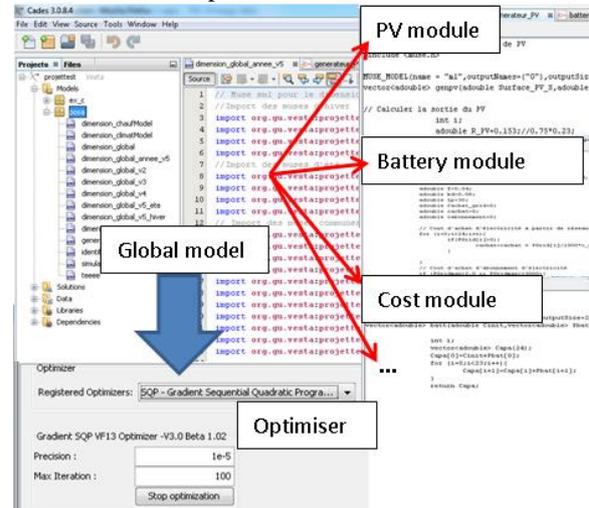


Figure 8 Optimization Implementation in Cades

In this study, we are varying the weight α of the multi-objective optimization problem from 0 to 1 with a step of 0.1 to look for the different optimum solutions appropriating to the need of comfort or the budget. Consequently, 11 optimizations are automatically run using SQP algorithm.

⁷ www.vesta-system.fr

RESULTS AND DISCUSSION

Table 5
Optimization results

OPTIM	α	GLOBAL COST (€)	WINTER MEAN DISCOMFORT (°C)	SUMMER MEAN DISCOMFORT (°C)	$P_{heat,nom}$ (W)	$P_{cool,nom}$ (W)	S_{PV} (m ²)	$C_{bat,nom}$ (Wh)
1	0	19572	2.56	4.30	0	0	0	0
2	0.1	19572	2.56	4.30	0	0	0	0
3	0.2	44576	0.69	2.62	1800	1461	26	17856
4	0.3	64753	0.33	0.84	2318	3402	43	21905
5	0.4	74061	0.22	0.28	2458	3574	50	28498
6	0.5	74571	0.21	0.26	2486	3621	51	28541
7	0.6	90135	0.006	0.02	4216	4590	63	34918
8	0.7	90295	0.001	0.0018	4298	4594	64	35371
9	0.8	91365	0	0	4313	4787	67	37508
10	0.9	91365	0	0	4313	4787	67	37508
11	1	91365	0	0	4313	4787	67	37508

Once optimiser runs, we obtain the result of 11 optimisations within a short time (1m55s). It is due to the use of partial derivatives (e.g. Delinchant et al., 2007) of the variables of interest in relation to design parameters, including the dynamic integration.

Table 5 shows all design results according to the weight α . When the value of α is equal to 0 (no requirement of comfort), the optimiser indicates that no energy system is necessary. In contrast, the heating, air-conditioning, PV and battery bank system should be installed with the nominal capacity of 4313 (W), 4787 (W), 67 (m²) and 37508 (Wh) respectively for the maximal comfort.

For the other values of α , the nominal capacity of system components is shown in the last 4 columns of Table 5. The columns 3, 4, 5 of this table present the compromise between the thermal comfort and the global cost, which can be graphically illustrated as below:

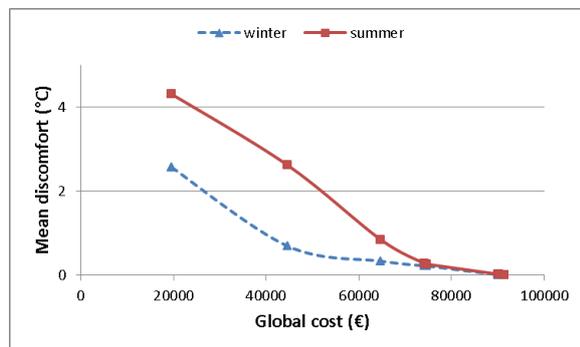


Figure 9 Pareto curve

In Figure 9, we only see 6 results instead of 11 because some optimization results are very similar. It is found that the more money we spend the more comfort we receive in winter and summer. This compromise can be also seen in the analysis of desired temperature response.

Indeed, in winter, the building interior temperatures in Figure 10 depend on the heating powers in Figure 11 for different cases of α .

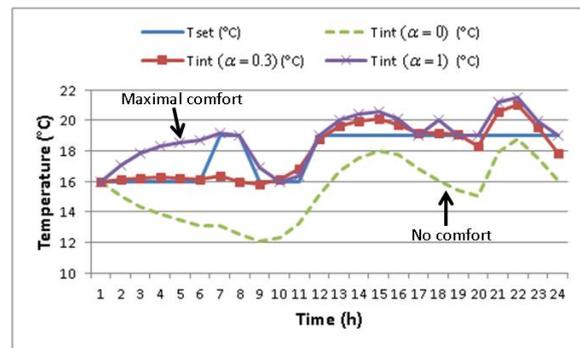


Figure 10 Winter interior temperature with $\alpha = 0; \alpha = 0.3; \alpha = 1$

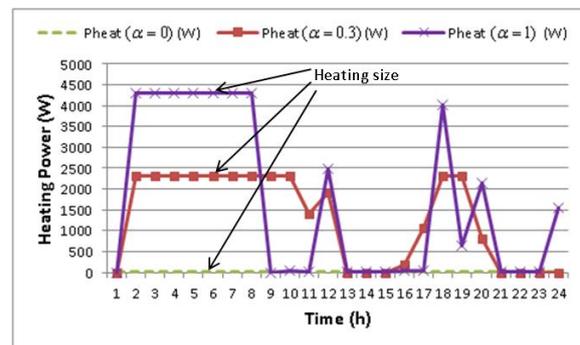


Figure 11 Winter heating power with $\alpha = 0; \alpha = 0.3; \alpha = 1$

With $\alpha = 0$, we do not provide the heating powers, the interior temperature is much lower than the set point for all time of winter day. In other words, the building is always in the situation of discomfort during 24 hours. With $\alpha = 0.3$, the building temperature is heated thanks to a heating system of 2.3KW but the desired temperature is not still

completely satisfied. With $\alpha = 1$, a heating system of 4.3KW produces more heating energy so that the building interior temperature respects perfectly the set point. As a result, we can see the different solutions of heating system (cheap or expensive) according to the need of comfort.

In summer, in the same way, we can find out the trade-off between the comfort and the cost generated by air conditioning system in Figure 12 and 13.

Furthermore, we would like to show another trade off: investment cost and energy cost. For example, we consider the case $\alpha = 0.3$ (Figure 12 and 13).

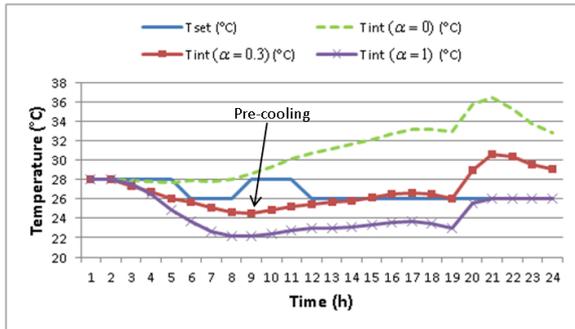


Figure 12 Summer interior temperature with $\alpha = 0; \alpha = 0.3; \alpha = 1$

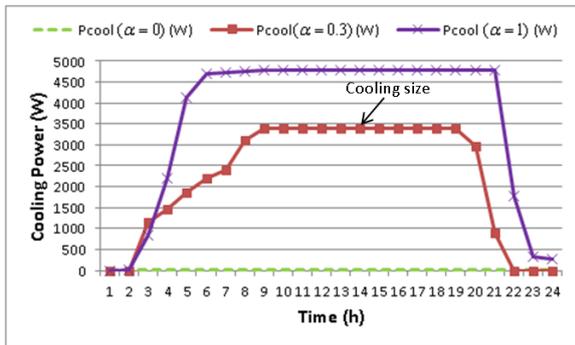


Figure 13 Summer cooling power with $\alpha = 0; \alpha = 0.3; \alpha = 1$

It is seen in Figure 13 that air conditioning system (red curve) is turned on early in the morning (pre-cooling) and not turn off when the heated zone inside air temperature (Figure 12) is better than the desired temperature (at 9h for instance). It causes a consumption increase but helps to avoid a peak power at the next time (at 14h for example), which will require a big investment cost of system. When the unit investment cost of cooling system is so small in comparison to the electricity unit price, we will undoubtedly obtain the bigger cooling size but consume the smaller total energy.

Finally, the global system management strategy in summer and winter can be presented in the figures below.

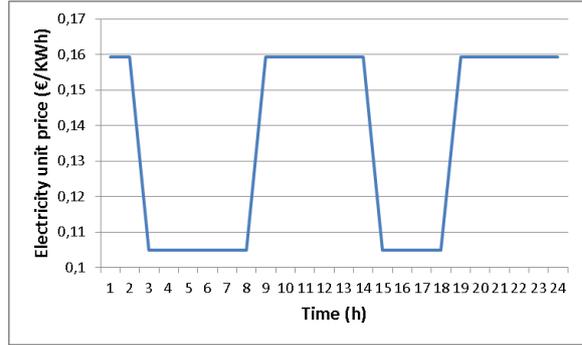


Figure 14 Summer and winter electricity unit price

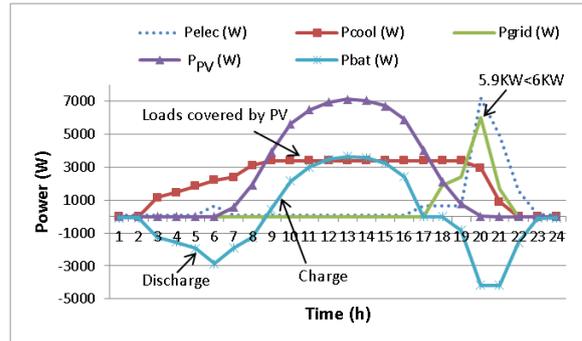


Figure 15 Summer management strategy with $\alpha = 0.3$

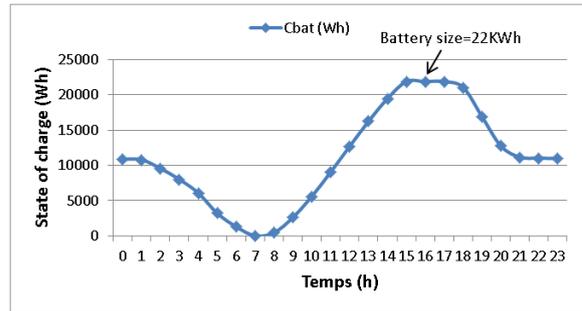


Figure 16 Summer state of charge of battery with $\alpha = 0.3$

In summer, the air conditioning system was nearly all the time activated when PV is producing (Figure 15). From 9h to 17h, all loads were covered by the renewable energy generation (auto-production). In the early morning, the battery was discharged to provide the energy to the load. When the sun is rising, the produced energy surplus is charged in the battery. At the end of the day, the discharge state is reestablished in order to mitigate the load peak. It is observed in Figure 15 that at 20h the electricity power bought from the grid was reduced from 10KW (total load) to 5.9KW thanks to the discharge of battery. Compared to Table 3 we see that the optimization is done such that the subscription power is the lowest (type of 6KW). It can be noticed that the electricity was not bought at the off-peak hour on account of battery bank sizing problem. An assumption is made, we buy the electricity at the off-peak hours, 3h-8h for example (Figure 14), the state of charge of battery will be higher than the actual

value (22KWh, Figure 16). As a consequence, the nominal capacity of storage will have to be bigger to ensure the battery operation, which takes a higher investment cost so that the global cost can be more expensive. Thus, a decrease of battery size is more effective than buying electricity from the grid in off-peak hours in this case.

Regarding the winter, we can see another optimal management strategy. Figure 17 shows that the PV production in winter is less than the one in summer. The heating system was primarily switched on at the moment of the cheaper cost of electricity. At this time, the load in the early morning was not completely covered by the discharge of battery bank.

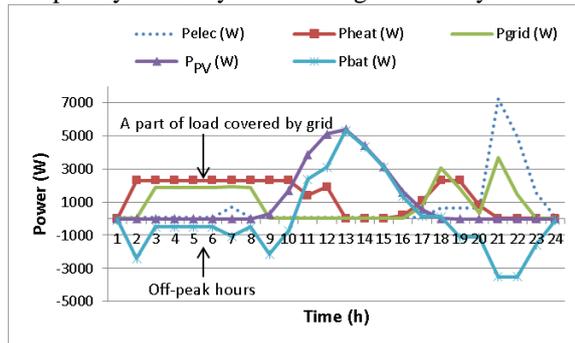


Figure 17 Winter management strategy with

$$\alpha = 0.3$$

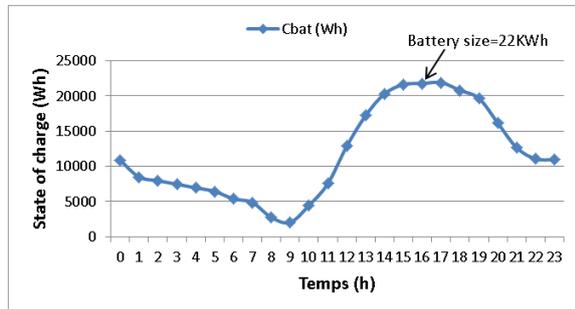


Figure 18 Winter State of charge of battery with

$$\alpha = 0.3$$

Indeed, a part of the load is satisfied by buying electricity from the grid at off-peak hours. That can increase the nominal capacity of battery, which is not desirable. The trade-off was solved by the fact that the electricity was bought with an enough quantity so that maximal state of charge of battery did not exceed the nominal storage capacity of summer. The battery bank also helps to cover a part of appliances load at the end of day.

Thanks to all analysis above, we demonstrated the interaction between the optimal management and design has an important effect on the size of system.

CONCLUSION

To conclude, this study proposes a new methodology for sizing a complex energy system integrating the management strategies for the grid-connected house. Our method shows a lot of trade-off to solve, which are between the human comfort and the cost over the

life span, between the investment cost and the energy cost etc. This paper also indicates the mutual influence between the optimal management and design in which a system sizing change can make changes on the management strategy and vice versa. We confirmed that all of that could affect to the optimization results. We also showed that the optimization problem considered has the big size with a lot of parameters and constraints and we succeed to solve it with the approach that we propose. Finally, this method proposed a lot of optimal solutions according to the need of comfort of user and the budget he wants to spend. The final decision belongs to him.

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