Impact of a tariff based heating load control on energy, comfort and environment: a parametric study in residential and office buildings

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IMPACT OF A TARIFF BASED HEATING LOAD CONTROL ON ENERGY, COMFORT AND ENVIRONMENT: A PARAMETRIC STUDY IN RESIDENTIAL AND OFFICE BUILDINGS

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Abstract

In the perspective of systematic deployment of smart meters and smart HVAC systems, energy price is a possible incentive to automatically shift consumption from a constrained time-slot (e.g. around 7:00 pm) to a relaxed one (in the night). Such load shedding mechanisms are already in place in France for domestic hot water usage and are likely to be broadened to heating systems. This paper investigates the impact of an automatic tariff-based heating load control on the energy consumption, load curve, thermal comfort and environmental impact for the end-user. To achieve this study a method has been developed to assess the performance of a control strategy associated with a tariff signal through simulations. This method has been applied to different control strategies and tariff signals for several combinations of buildings and heating control systems. This work focuses on the existing building stock – with its main variations in terms of insulation, typology or heating control under different climatic conditions – while capturing the fundamental of building thermal response with the help of thermal simulation. This paper explains the methodology and the parametric study and shows that load shedding has limited advantages in terms of spared energy and comfort but can have a real effect on the heating load curve. Due to its systematic coverage this work aims at completing the current literature focused either on one technology or on control strategies.

CONTEXT AND OBJECTIVES

Every winter, European power grid operators are focused on weather channels: a single drop in temperature could lead to local or even national blackouts. To avoid these consumption peaks the main solution is to reduce the energy demand during constrained time-slots and shift it to relaxed times, e.g. during the night. Such load shedding mechanisms are already in place in France for domestic hot water usage and are based on a low tariff between 10pm and 6am. However this solution is now widely implemented in the country and is not enough to reduce the energy demand during the day, especially in cold winter evenings. Other techniques are needed and energy providers and flexibility aggregators offer similar solutions adapted to domestic electric heating: either through price incentives to reduce heating during peak days or through load curtailment where the heating power demand is completely turned off. With the deployment of smart meters these solutions become easier to implement and there is a need to assess their efficiency so that the energy industry, control systems manufacturers and consumers can actually work together to reduce peak loads.

This paper investigates the impact of an automatic tariff-based heating load control on the energy consumption, load curve, thermal comfort and environmental impact for the end-user. The goal of this work is to provide a methodology to estimate those impacts and to give a feedback to the energy and building communities about how such load shedding solutions perform when they are applied on various buildings in simulation. The proposed methodology considers the association of a tariff signal – when should the building reduce its heating load – and a control strategy – how should the signal be interpreted.

The methodology has been applied to different control strategies and tariff signals for several buildings, which represent the existing building stock – with its main variations in terms of insulation, typology or heating control under different climatic conditions – while capturing the fundamental of building thermal response with the help of thermal simulation. The paper is organized as follows: after a literature review on the subject, we first present the indicators chosen to assess the impact on energy, power, comfort and environment; then the developed methodology is explained; two case studies are presented and their results are discussed; final sections present the conclusions and the perspectives of this work.

LITERATURE REVIEW

Previous studies have focused on energy management optimization at the building level (Favre & Peuportier, 2014) or on the assessment of flexibility in an integrated grid model such as buildings equipped with heat-pumps in a modeled electrical grid where flexibility is managed through direct control or dynamic time-of-use pricing (Patteeuw et al., 2016). The assessment methodology proposed by Saker is based on the comparison between a simulation with load control and a simulation without, on a stock of 500 buildings (Saker, 2013). In these simulations the load of electric convectors, domestic hot water tanks and electric vehicles is controlled and optimized to assess the potentialities of Demand Side Management strategies. A building stock approach has also been conducted in (Da SILVA, 2012) to assess the flexibility of domestic electric loads. For this work, variability in the simulated buildings has been introduced through heat transfer coefficients differentiation based on the building construction period.

The approach hereby presented focuses more on developing a generic methodology to assess the performance of load shedding mechanisms from the building point of view. A similar with-and-without load control simulation approach is proposed in this work, with a focus on the thermal and electric response at the building level for various building configurations. Simulating at the building level instead of the stock level allows the use of a complex building model and gives an overview of the specific behaviors of each building configuration.

INDICATORS

From the power system point of view, the main incentive for load shedding is the reduction of the power used during the peak period. However it should not be the only indicator to assess the performance of such a mechanism. Acting on the heating load can become a real challenge for the building to maintain a reasonable indoor temperature: the impact on the occupants' comfort should also be assessed. Like many other smart energy mechanisms, load shedding is often presented as a way to reduce the overall consumption and the environmental impact of the building: such indicators are also needed to measure the performance of load shedding. The proposed indicators involve a ref value and a $shed$ value, the former is obtained when the building is simulated without load shedding while the latter is obtained with load shedding. The global indicators are computed on one year simulated data. For convenience energy and power indicators are normalized to the building surface.

Energy

Because the studied load shedding mechanism acts on the heating load of a dwelling, the indoor temperature will slowly decrease during the load shedding and some of the curtailed energy is very likely to be used after the load shedding period to bring back the dwelling to the temperature set point due to the rebound effect (Binswanger, 2001). This may actually reduce the energy savings that could be expected. Therefore, to assess the energy performance of load shedding the *annual Curtailed Energy* (aCE) and the *annual Load Shedding Efficiency* ($aLSE$), are proposed and described in equations (1) and (2).

The *Curtailed Energy* (CE) of a given load shedding period L is the consumption difference between the reference and the load shedding simulations during the load shedding period (between start and end times, denoted $s[L]$ and $e[L]$). It is computed from the cumulated energy consumption $C^t_{ref/shed}$ (at a given time t) and represents the amount of energy which was not consumed during the period. The sum of this *Curtailed Energy* over all load shedding periods in an annual simulation forms the *annual Curtailed Energy*.

$$\begin{cases} CE[L] = \left(C^{e[L]}_{ref} - C^{s[L]}_{ref}\right) - \left(C^{e[L]}_{shed} - C^{s[L]}_{shed}\right) \\ aCE = \displaystyle\sum_{L \in LoadSheddings} CE[L] \end{cases} \tag{1}$$

The *annual Energy Savings* (aES) is calculated as the annual consumption difference between the reference and the load shedding simulations (between the simulation's $start$ and end times). The *annual Load Shedding Efficiency* is then calculated as the ratio between the *annual Energy Savings and* the *annual Curtailed Energy*.

$$\begin{cases} aES = \left(C^{end}_{ref} - C^{start}_{ref}\right) - \left(C^{end}_{shed} - C^{start}_{shed}\right) \\ aLSE = aES/aCE \end{cases} \tag{2}$$

Power

To assess the impact of the operation on the load curve, the *Maximal Curtailed Power* (MCP) is observed for each day where load shedding has occurred. This indicator is defined in equation (3) where Δt is the simulation time-step and $LStimes[d]$ represents the load shedding times of the day d.

$$MCP[d] = \frac{\max_{t \in LStimes[d]} \left\{\left(C^{t+1}_{ref} - C^{t}_{ref}\right) - \left(C^{t+1}_{shed} - C^{t}_{shed}\right)\right\}}{\Delta t} \tag{3}$$

Comfort

To better understand how occupants perceive indoor temperature the PMV and PPD indicators have been developed (Fanger, 1970) and are now part of a French standard on thermal comfort (AFNOR, 2016). This standard defines comfort *zones* (I, II, III and IV) related to the level of thermal dissatisfaction of occupants (PPD): this work considers *zone II*, for which the dissatisfaction should be below 10%. This comfort zone corresponds to a comfort vote (PMV) between -0.5 and +0.5 on a scale from -3 (cold) to +3 (warm).

For a given case (ref or $shed$) and a given time, a cold discomfort ($D_{c,case}^{t}$) and a warm discomfort ($D_{w,case}^{t}$) indicators are described in equations (4) and (5). Discomfort is only computed when people are in the building and active (i.e. for "active presence" times during the year of study, denoted $APtimes$). These indicators mimic the PPD indicator with a saturation to $PPD_{lim} = 10\%$ according to the chosen comfort zone. Then when two cases are both "comfortable" (i.e. their dissatisfaction is below 10%), the difference between indicators is 0.

$$D_{c,case}^{t} = \begin{cases} 0 \text{ if } t \text{ not in } APtimes \\ PPD_{lim} \text{ if } PMV_{case}^{t} \geq -0.5 \\ PPD_{case}^{t} \text{ otherwise} \end{cases} \quad (4)$$

$$D_{w,case}^{t} = \begin{cases} 0 \text{ if } t \text{ not in } APtimes \\ PPD_{lim} \text{ if } PMV_{case}^{t} \leq 0.5 \\ PPD_{case}^{t} \text{ otherwise} \end{cases} \quad (5)$$

The *annual Discomfort Variation* presented in equation (6) is a global indicator of discomfort difference between the ref and the $shed$ cases. aDV_c computes the cold discomfort, the formulation for warm discomfort aDV_w is similar.

$$aDV_c = \frac{\sum_{t \in APtimes} D_{c,shed}^{t} - D_{c,ref}^{t}}{\sum_{t \in APtimes} D_{c,ref}^{t}} \quad (6)$$

Environment

In this work, the environmental impact of a given consumption is represented by the *Global Warming Potential* (GWP in $kgCO2_{eq}$) caused by the greenhouse gases emitted to produce and transmit energy. For a case consumption (ref or $shed$) the GWP impact (see equation (7)) is computed from the production impact I_{prod}^{gwp} of each production source in $prod\_sources$ in combination with the energy mix at each time (mix_j^t) and the transmission impact I_{tr}^{gwp}.

$$GWP_{case} = \sum_{start \leq t \leq end-1} (C_{case}^{t+1} - C_{case}^{t}) \cdot \left(I_{tr}^{GWP} + \sum_{j \in prod\_sources} mix_j^t \times I_{prod}^{GWP}[j] \right) \quad (7)$$

To compare two cases, the *Global Warming Potential Variation* is proposed ($GWPV$ in equation (8)) between the reference case and the case with load shedding.

$$GWPV = \frac{GWP_{shed} - GWP_{ref}}{GWP_{ref}} \quad (8)$$

PERFORMANCE ASSESSMENT METHODOLOGY

The method to assess the performance of a load-shedding control system associated with a tariff signal is based on the comparison of ref and $shed$ simulations as presented in Figure 1. The starting point of this methodology is to define the tariff signal and the control system. The tariff signal is the information sent to the building, e.g. through an Energy Management System (*EMS*), and describes when the heating load should be reduced. The control system represents any regulation system which receives the tariff signal and controls the heating system (e.g. embedded in an *EMS*, the heating system itself or an external device).

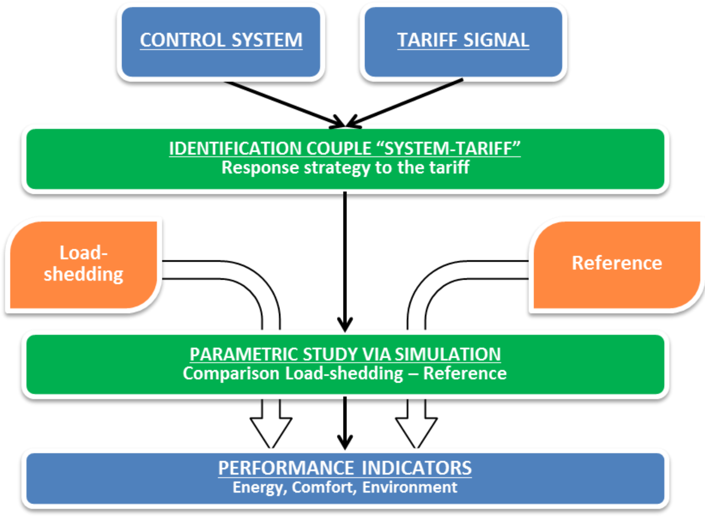

Figure 1. Load shedding assessment methodology

Step 1: Identification

The first step of the methodology aims at identifying the response strategy of the control system to the tariff signal. This characterization is needed to properly model how the heating command will be calculated in the simulator. For this work, two types of tariff signal are considered: *FIXED* signal and *MARKET-DRIVEN* signal. With a fixed signal, the heating load is reduced on a regular basis (e.g. every working day between 6pm and 8pm) while a market-driven signal should reduce the heating load when it is the most profitable from a user point of view. Two kinds of response strategies are proposed:

- Load curtailment (*LC*): during load shedding the whole heating system is turned off ;
- Heating set point decrease (*HSD*): during load shedding the temperature set point is decreased by a fixed or variable value which could be set by the user or the control system's manufacturer.

The *LC* strategy is easier to implement than *HSD* and is the most common in the market at the moment. This identification step also includes the characterization of the heating system's physical response to the load shedding strategy: applying an *LC* strategy to a heat pump is more complex than applying it to electric radiators. To address this challenge, various solutions can be proposed such as (a) expert knowledge, (b) laboratory characterization or (c) in-situ characterization.

Step 2: Parametric study

Once the tariff signal, the control system and its response strategy, the heating system's response model are identified, the second step of the methodology is the parametric study to analyze the behavior of a variety of buildings with or without load shedding. To avoid mixing non-coherent results, the parametric study is limited to a given building sector and a given type of heating system (e.g. electric radiators in residential buildings, heat pump with fan coils in office buildings…). The parameters to study are defined upon using the methodology, it can include usual parameters such as building type, climatic zone, construction period…

The output of such parametric studies is evaluated through the indicators defined to assess the performance of the load shedding with the couple "control system – tariff signal" under various conditions.

CASE STUDIES

Electric Convectors in Residential buildings (EC-R)

A main case has been prepared to test the methodology and get results for parametric variations of the building. Laboratory characterization has been carried out to tune the control loop response to LC or HSD strategies. The tariff signal used for this case is a FIXED signal (only on peak-days (22 per year) from 6pm to 8pm) with LC response strategy.

For this case the parametric variations are described in Table 1. The climatic zone variations correspond to three zones related to the French thermal regulation with conventional meteorological data. The normal temperature set point is 21°C and the night setback operated from 10pm to 7am with a temperature set point of 18°C.

PARAMETER	VARIATIONS
Building type	Multiple-dwelling housing (95m²) Individual Housing (100m²)
Climatic zone	Nancy Rennes Nice
Construction Period	1980-1990 2000-2005 After 2012 (BBC)
Setback	No setback Night setback

Table 1. Building variations

The building type variations are based on two buildings developed within the HOMES project (Schneider Electric et al., 2012) (see Figure 2). Their model takes into account the heat transfers between rooms and simulates the systems and thermal response of the building on a sub-minute time-step.

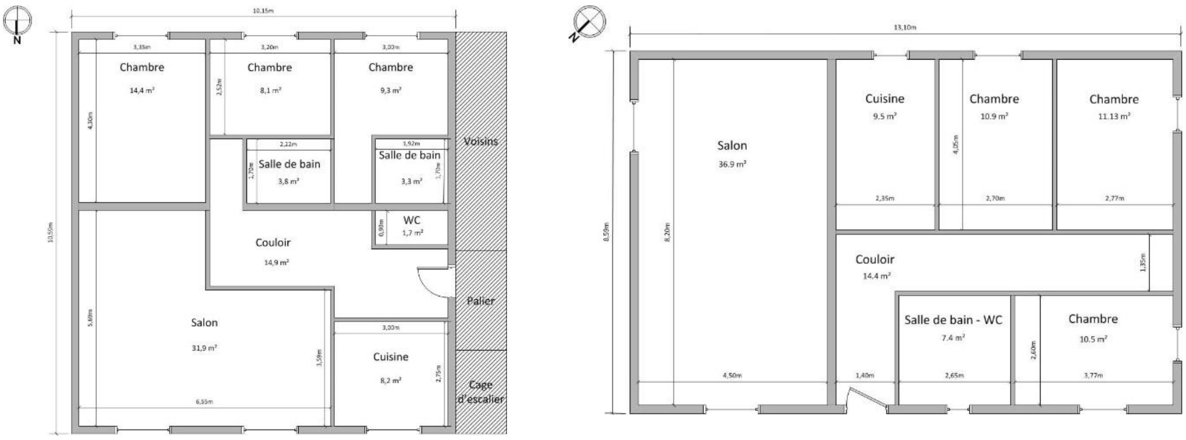

Figure 2. EC-R buildings representation (left: multiple-dwelling, right: individual)

Heat Pump in large Office buildings (HP-O-exp)

An exploratory study has been carried out to evaluate the performance of various tariff signals and response strategies on a given building configuration. For this case an Air/Air heat pump model based on expert knowledge is used.

The building configuration is described in Table 2. This case was simulated for the year 2012, with real meteorological data, which presented a rather cold winter. Several response strategies and signals have been tested such as HSD strategy with various values for temperature set point decrease or MARKET-DRIVEN signals with load shedding periods of maximum 1 hour long or maximum 2 hours long. For the sake of readability only the results for the following "strategy – signal" combinations are presented:

- 1. *FIXED* signal: only on peak-days (22 per year) from 11am to 1pm
    - 1.1. *HSD* strategy: 0.5°C decrease
    - 1.2 *HSD* strategy: 2°C decrease
    - 1.3 *LC* strategy
    - 1.4 *LC* strategy and overheating 2 hours before load shedding (1°C increase)
- 2. *MARKET-DRIVEN* signal: 1-2 hours long load shedding slots resulting in 250 hours selected on working days between November and Mars based on Critical Peak Pricing (2012 EPEX SPOT day-ahead price fixing)
    - 2.1 *HSD* strategy: 2°C decrease
    - 2.2 *LC* strategy
    - 2.3 *LC* strategy and overheating 2 hours before load shedding (1°C increase)

PARAMETER	CONFIGURATION
Building type	Office (6470m²)
Climatic zone	Lyon (2012)
Construction Period	2000-2005
Setback	Night & week-end setback

Table 2. Building configuration for office exploratory case

The simulated building is a typical building proposed in Task 27 of IEA Solar Heating and Cooling Programme. The simulation model includes two offices (north and south side) and the corridor segment which separates them (see Figure 3). The walls between adjacent offices are considered adiabatic.

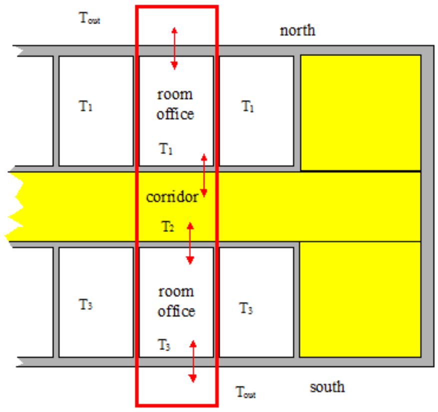

Figure 3. HP-O-exp building representation

Normal temperature set point is 21°C while setback temperature is 16°C on week-ends and from 7pm to 6am on week days.

RESULTS AND DISCUSSION

The Performance Assessment Methodology has been applied to the case studies presented above. Matlab/Simulink tool SIMBAD developed by CSTB (Husaunndee et al., 1997) was used for simulations in EC-R case and the Modelica-based BuildSysPro Library developed by EDF R&D (Plessis et al., 2014) was used for simulations in HP-O-exp case. Two simulators were used in order to illustrate the versatility of the methodology: since ref and $shed$ simulations are obtained with the same simulation tool within a case, it is reasonable to say that the choice of simulator does not impact significantly the results as long as the simulator is validated in its field of application. However one should be cautious when comparing results obtained with one simulator and results obtained with the other. This section presents and discusses the results.

Electric Convectors in Residential buildings (EC-R)

Given the parametric building variations (Table 1) 36 simulations were run for this case: statistical values (minimum, average and maximum) obtained over all the simulations are presented and kernel density estimation (*KDE*) was carried out to understand the importance of the different parameters.

Aggregated results in Table 3 show that the energy performance is relatively low since the curtailed energy is lower than 3 kWh/m²/year and the actual energy savings are 3% to 20% of this curtailed energy. Load shedding with *Load Curtailment* strategy means a huge drop in the needed power (up to 107 W/m² in our simulations), which makes it a good candidate in terms of power performance. From the comfort point of view, results show that during load shedding temperatures could decrease with almost 4°C, which is quite high. The increase of temperature (after the end of a load shedding period) is limited to 1°C over the reference simulation, showing that there is a limited overheating in response to the load shedding. Finally, the environmental performance is really low: *Global Warming Potential Variation* shows a maximal 1.4% decrease in CO_2 emission.

INDICATOR	UNIT	MIN	AVG	MAX
annual Curtailed Energy	Wh/m²	36	1120	3224
annual Load Shedding Efficiency	%	2.7	10.3	20
Maximal Curtailed Power	W/m²	2	43	107
Maximal temperature decrease[1]	°C	0.3	1.9	3.8
Maximal temperature increase	°C	0	0.2	0.7
Global Warming Potential Variation	%	-1.4	-0.3	-0.1

Table 3. Aggregated simulation results for EC-R case

The low energy, comfort and environmental performances can be partially explained by the few number of load shedding hours (44 over 8760 in a year) due to the chosen tariff signal. Allowing more load shedding hours could increase the energy and environmental performances. The low comfort performance is also responsible for the low energy performance: the significant temperature decrease during load shedding induces a large compensation when the heating system is turned back on which means a large quantity of energy needed to reach the normal set point temperature. Power performances should be carefully interpreted: load shedding does help in flattening the load curve during load shedding but the rebound effect due to the heating compensation can disturb the local power system.

Figure 4 presents kernel density estimation graphs to understand the statistical significance of each parameter on the *annual Load Shedding Efficiency* ($aLSE$) indicator. It appears that the climatic zone is not really influential but the three other parameters do have an impact:

- Building type: a higher $aLSE$ value for multiple-dwelling housing simulations is obtained, which can be explained by the simulator hypothesis stating that neighboring dwellings have the same average temperature than the simulated dwelling meaning that the heating needs of this dwelling after load shedding are partially covered by the other dwellings. Therefore the energy savings are slightly higher in this configuration.
- Construction period: older buildings present a higher $aLSE$ value because they usually have a higher installed heating capacity (to compensate their higher thermal losses) meaning that during load shedding a large amount energy will be curtailed.
- Setback: night setback (21°C to 18°C) allows for a higher load shedding efficiency mainly because this setback starts at 10pm and is likely to shrink the heating needs after the end of the load shedding period (8pm). This behavior is strongly related to the time distance between load shedding and setback.

[1] Discomfort indicators were not available for this case, it was replaced by a comparison of the indoor temperature between ref and $shed$ simulations

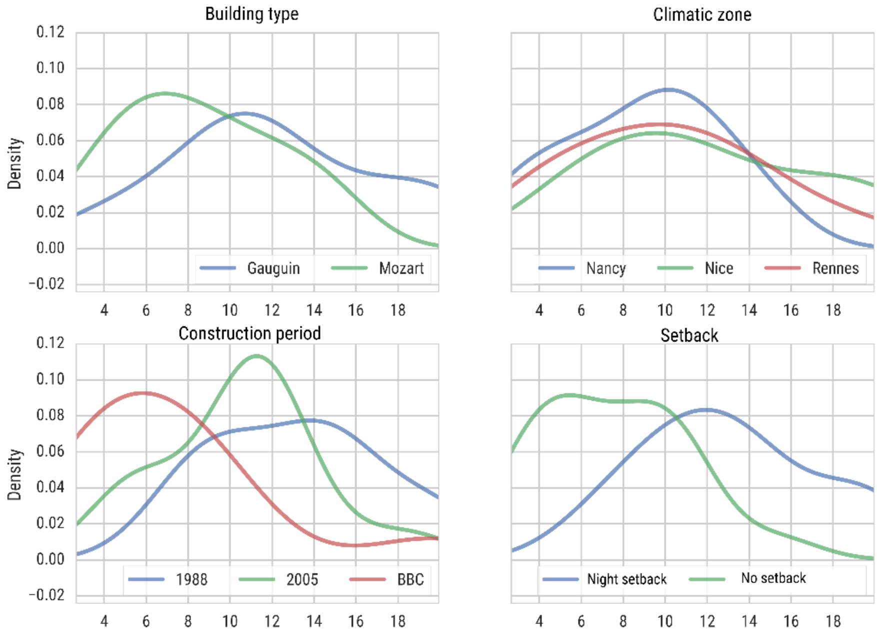

Figure 4. ***aLSE*** **related KDE plots for each parameter for EC-R case (x-axis represents *aLSE* in %)**

(Mozart = Individual Housing, Gauguin = Multiple-dwelling housing)

Heat Pump in large Office buildings – exploratory (HP-O-exp)

The parametric variations of the tariff signal and the response strategy defined for this exploratory case have been run through 7 simulations, whose results are presented in Table 4 (Global Warming Potential indicators were not available for this case).

INDICATOR	UNIT	1.1	1.2	1.3	1.4	2.1	2.2	2.3
annual Curtailed Energy	Wh/m²	380	1000	500	58	1088	1080	687
annual Load Shedding Efficiency	%	7.9	0.1	0.2	-535	9.1	8.8	-77.4
Maximal Curtailed Power	W/m²	9	14	14	14	7.5	7.3	7.5
annual Discomfort Variation (cold)	%	0.5	1.0	1.0	0.3	5.1	5.1	0.3
annual Discomfort Variation (warm)	%	0	0	0	0	0	0	0.3
Global Warming Potential Variation	%	-	-	-	-	-	-	-

Table 4. Simulation results for HP-O-exp case

Simulations with a preheating phase (1.4 and 2.3) show high and negative load shedding efficiency (-535% and -77.4%): in those simulations the load shedding operations resulted in consuming much more energy during the year than the reference simulation. The preheating strategy does help in limiting the comfort impact (+0.3% in cold discomfort which is the lowest of all HP-O-exp simulations) but seems not adapted to the heat pump equipped systems.

Looking at the other simulations, it appears that those with a *FIXED* tariff signal (1.1 to 1.3) show lower $aLSE$ values than those with a *MARKET-DRIVEN* signal (2.1 and 2.2): the total number of load shedding hours (44 for *FIXED* simulations and 250 for *MARKET-DRIVEN*) can explain this result. On the other hand, the cold discomfort variation is higher for *MARKET-DRIVEN* signal simulations (5%) than for *FIXED* signal ones (0.5%). Because *FIXED* signal focuses on peak days (usually related to really cold days) the curtailed power is higher in simulations 1.1 to 1.3 than in simulations 2.1 and 2.2. It is noticeable that with a temperature decrease of 0.5°C (simulation 1.1) we obtain a saving of 30Wh/m² (7.9% of the 380Wh/m² curtailed energy), which is higher than all the other simulations. Such a *HSD* strategy allows for a relatively good energy performance while maintaining the indoor comfort (+0.5% in cold discomfort). However this energy performance is really low compared to the annual energy consumption of the reference simulation (15kWh/m²).

CONCLUSIONS

In this work a framework for the evaluation of load shedding operations has been defined: a set of indicators for Energy, Power, Comfort and Environment performances has been proposed and a Performance Assessment Methodology for load shedding operations has been designed. Starting with the identification of a tariff signal and the response strategy of the control system, this methodology is based on the performance assessment through parametric simulations and the comparison between reference and load shedding simulations. The Performance Assessment Methodology has been applied to two cases: one following the original philosophy of parametric variations in the building configuration and the other exploring variations on the response strategy and the tariff signal for a given building configuration. It appears that the energy and environmental performances are rather low due to the rebound effect which tends to compensate for the lack of heating during load shedding. In the comfort point of view it is possible to limit the cold discomfort increase with the Heating Set point Decrease strategy. On the other hand, the Load Curtailment strategy, a widely used strategy, can seriously damage the indoor comfort during load shedding. The power performance can be satisfying since load shedding can reduce the power used for heating but it should not be independently analyzed as it impacts the comfort and can also have a negative impact on the local power system because of the rebound effect.

In this paper six performance indicators were presented and other indicators can be defined to be used with the methodology. Similarly, the types of tariff signal and response strategy can be extended to meet the user's needs: the main limitation lies in the modeling capabilities of the tool used for energy simulations. The methodology's adaptability is also illustrated through the work presented here where two different energy simulation tools have been used by different research teams to run the simulations.

PERSPECTIVES

On the methodological level, the future work will focus on extending the framework to address the economic performance of such load shedding mechanisms and on proposing an adaptation to buildings and systems in operation. Also an in-depth analysis on the impact of using various simulation tools should be carried on to validate the concept of versatility of the methodology. Other applications could be investigated such as a full parametric study for office buildings or to assess innovative concepts of load shedding which take advantage of the new communication ways with buildings informing aggregators about their load shedding capabilities in real-time. Such a load shedding mechanism would help aggregators schedule shedding periods at the local or even national level while taking into account the buildings needs and limits.

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