Provision of Frequency Containment Reserves with Batteries and Power-to-Heat

Julien Jomaux, Thomas Mercier, and Emmanuel De Jaeger
Center for Research in Energy and Mechatronics (CEREM)
Institute of Mechanics, Materials and Civil Engineering (iMMC)
Universite catholique de Louvain (UCL)
Louvain-la-Neuve, Belgium
{julien.jomaux, thomas.mercier, emmanuel.dejaeger}@uclouvain.be

***Abstract*—Frequency Containment Reserves (FCR), previously referred to as primary reserves, are an important component for the safe operation of the Continental Europe grid. The growing share of renewables represents a forthcoming challenge since FCR are generally provided by synchronous generators. In this paper, batteries are associated with a power-to-heat system (P2H) composed of electrical resistances, allowing a very high flexibility as well as a valorization of the generated heat. They are controlled to react first, leading to a significant reduction of the battery use while allowing a satisfactory regulation of the battery's stored energy. This is made possible by adding an offset that allows the proposed system to consume power in average. In addition, batteries are controlled to only provide downward regulation and they are consequently smaller than in other propositions. An economic modelling has been realized and based on time simulations with actual frequency data.**

***Index Terms*—Battery Energy storage, Energy management, Power system reserves.**

I. Introduction

The Continental Europe (CE) grid is currently undergoing a shift from mainly carbon emitting generation to more renewable generation such as photovoltaics and wind power. This important change impacts the operation of the power grid in various ways, including the Frequency Containment Reserves (FCR), previously referred to as primary reserves. These reserves are one of the major element for ensuring the safe operation of the CE grid.

The required 3000 MW of FCR [1] are mostly provided by large synchronous generators distributed across the CE grid. With the growing penetration of renewable generation, it will be increasingly difficult to source these reserves only with large synchronous generators. Indeed, when renewable penetration will reach a significant level, there will be a risk of having a shortage of FCR providers, which will result in higher FCR prices. Therefore, an incentive exists for the provision of FCR with original techniques. Such alternative solutions could take various forms, including wind turbine control [2], [3], demand-side management [4], [5], mutual support between AC grids via HVDC interconnectors [6], [7] as well as grid-scale storage [8]–[12]. Any alternative bears some drawbacks. Wind turbine controls require a power derating in order to provide FCR in both directions leading to suboptimal power generation. Demand-side management disturbs the process associated with consumption, while only specific loads are fitted for the provision of primary control. Mutual grid support via HVDC interconnectors, e.g. between the CE grid and the United Kingdom, requires an adaptation of the converter control as well as an underutilization of the line capacity on energy markets. In addition, impacts of one power system on another have to be carefully considered. Finally, concerning batteries, the energy content has to be regulated either directly, e.g. via a slow-moving energy provider, or either indirectly by a report on other power reserves.

In this paper, a potential alternative for the FCR provision is presented. This alternative is the combination of a grid-scale battery with a power-to-heat system (P2H), i.e. an element transforming electric power to heat as it is the case with electrical resistances or heat pumps. Because FCR request fast variations of the power output, only electrical resistances will be considered as a suitable P2H solution. The generated heat would not be wasted but would instead be used in a heat process such as water heating for domestic use or in industrial processes.

The paper is structured as follows: section II presents the main FCR characteristics and their provision with storage, section III describes the proposed system, i.e. the battery, the P2H and the associated control, section IV explores the solution design based on an economic modelling and time simulations, and finally, some elements on the practical implementation are discussed in section V.

II. Frequency containment reserves

In this section, a brief review of the main requirements and characteristics of primary control in the CE grid is performed. The activation profile, i.e. the distribution of power activation, is retrieved from historical data of grid frequency in France [13]. From this activation profile, consequences for the FCR provision with storage are drawn and are the main motivations for the proposed system.

A. Main requirements

FCR are activated by applying a proportional coefficient to a local measurement of the grid frequency. Grid codes have been established for describing the minimal requirements that FCR must fulfil [1], [14]. First, FCR must saturate at a frequency

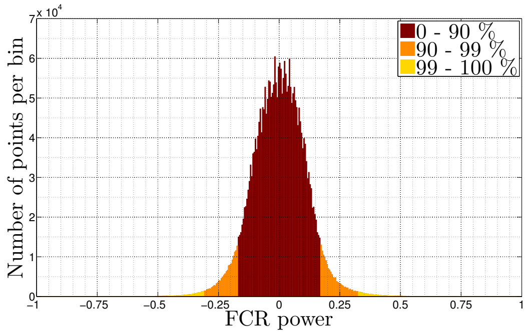

Fig. 1. Distribution of the FCR activation based on historical data of the grid frequency in France.

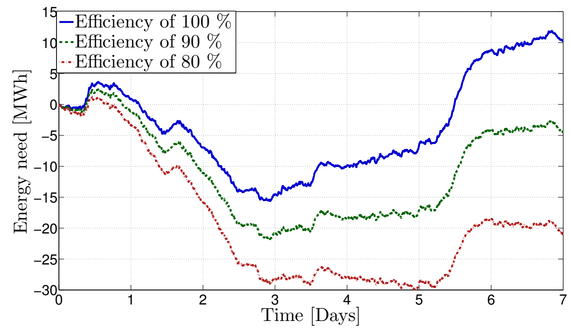

Fig. 2. Example of the energy requirement for the provision of 1 MW during seven consecutive days for three different storage efficiency. The energy need is a function of the distribution of the grid frequency and the storage efficiency.

deviation of ± 0.2Hz. Second, the relation between frequency deviations and FCR power is linear and symmetrical. It results that it is possible to directly determine the amount of FCR power when the frequency deviation is known. Third, FCR providers must be able to fully be activated in maximum 30 seconds. Fourth, a frequency deadband of ± 0.01Hz with no expected reaction is accepted. It should be noted that this deadband is not considered in the present paper because (i) the proposed system is able to deliver FCR without the deadband and (ii) it has a negligible impact on the final results.

B. Activation Profile

From the historical frequency data, the activation profile can directly be retrieved. Fig. 1 shows the distribution of FCR activation. Because the frequency quality in the CE grid is very high, i.e. the frequency is generally close to its nominal value, the FCR activation is generally low, whether it be in consumption or generation. Indeed, for 90 % and 99 % of the time, the activation is respectively equal or lower to 17 % and 31 % of the maximal power activation. Therefore, by adding a relatively small negative power offset, the FCR activation could be shifted so as to remain most of the time in the downward direction, i.e. power consumption. This characteristic has been used for the proposed system.

C. Storage for FCR provision

Storage and in particular batteries are one of the potential alternative for the FCR provision. The energy regulation should carefully be considered because the energy requirement for FCR is not known in advance and because the storage has inherent losses. Fig. 2 presents an example of the energy requirement for the provision of 1 MW of FCR during seven consecutive days for a storage with a one-way efficiency of 100 %, 90 % and 80 %.

Various solutions exist to regulate the energy deviations. They can be classified as either indirect, i.e. the report on other power reserves such as secondary reserves or intra-day market, or direct, i.e. effectuated by the FCR provider.

The indirect regulation can be realized by filtering the grid frequency or adding a component such as a moving-average. Such a technique should be foreseen in the grid code and special attention should be given to the impact on the other power reserves.

The direct regulation is referred to as the association of the battery with another element such as a generator or an electrical load. In this paper, the regulation is realized directly by controlling the P2H setpoint. It should be noted that all elements do not have to be located on the same site. Indeed, batteries, generators and loads including P2H could be geographically separated and aggregated in a common pool.

III. Description of the Proposed System

This section presents the proposed system. It should be noted that the originality of the proposition lies in the system control with the addition of an offset to the frequency signal allowing three major advantages. First, the P2H can solely regulate the energy content of the battery. Second, the P2H is controlled to react before the battery allowing a drastic reduction in the number of battery cycles. Third, the elements will be selected in order for the battery to be only used for upward regulation resulting in smaller battery size.

A. Battery

Different technologies exist for grid-scale batteries, e.g. lead-acid, lithium-ion, nickel-cadmium or sodium-sulfur. Extensive comparison has been realized for grid-scale applications [15], [16] taking into account many aspects such as efficiency, lifetime, response time, capital cost, maintenance cost, etc. In this paper, lithium-ion batteries have been chosen because they present low charge and discharge times, a relatively high number of cycles and they are already used in grid-scale applications. Nevertheless, further investigations should be considered for selecting the proper battery technology and improving the modelling of the battery. Regarding the sizing of the battery, its power rating P_{bat}^{max} and energy content E_{bat}^{max} will be determined by simulations in section IV.

B. Power-to-Heat

A power-to-heat element allows the conversion of electricity to heat. Mainly two technologies are possible. On the one hand, electrical resistances are a simple technique for the conversion but with a coefficient of performance (COP), defined as the ratio between heat energy and electrical energy, of maximum 100%. They are broadly used in many applications, e.g. domestic appliances or water heating. On the other hand, heat pumps, which are designed to transfer heat from a cold source to a warm source, exhibit COP larger than 100 %. Some authors have investigated on P2H for various reasons such as the enhancement of the flexibility of combined heat and power plants [17], the use of heat flexibility for wind integration [18], [19], as a flexibility option for an electricity system [20] or as in combination with a cogeneration plant [21].

In the present paper, it has been considered that the P2H system is a set of electrical resistances that could modulate power consumption from 0 to P_{P2H}^{max} with a conversion efficiency η_{P2H} close to 100% and with sufficient ramping for providing primary control. This choice is motivated by the fact that resistances are a simple and inexpensive technology and they allow a maximal flexibility from zero to their maximum with high ramping rates. Their lower efficiency as compared to heat pumps has limited impact in this application with regards to the economic evaluation of section IV. Besides, electrical resistances are considered to be much less restricted in term of intensity of use in comparison with batteries and their limited number of cycles. The system control will consequently be designed for using as much as possible the resistances before the battery.

It should be noted that the generated heat could be used for water heating in domestic houses and public buildings or be used in industrial applications. The resistances could be spread geographically and aggregated. In addition, smart controllers could activate the resistances in function of the actual heat required for each application. The integration of the generated heat in heat systems has been considered out of scope and should be investigated in future research.

C. Control

A key element of the proposed system is the addition of an offset power, written P_{off}, to the FCR signal. This offset is considered to be constant and allows the resulting signal to be shifted to target an average consumption. It should be noted that without this offset power, the resistances would not have been able to regulate in both directions resulting in a much higher use of the batteries. With the introduction of the offset, it is possible to determine the minimal capabilities of each element for providing primary control. Indeed, in generation mode, the battery should at least be able to generate a maximal power of $P_{bat}^{max} \geq P_{FCR}^{max} - P_{off}$ with P_{FCR}^{max} being the maximal FCR power to be delivered. Inversely, in consumption mode, the battery and the P2H should at least be able to consume $P_{bat}^{max} + P_{P2H}^{max} \geq P_{FCR}^{max} + P_{off}$ with P_{P2H}^{max} being the maximal power that the P2H system can consume. These requirements have to be matched in order for the system to be able to provide the requested FCR power in both directions.

Generally, batteries are controlled in order to be the first element to react for the provision of primary control or for other flexibility products. Nevertheless, their limited number

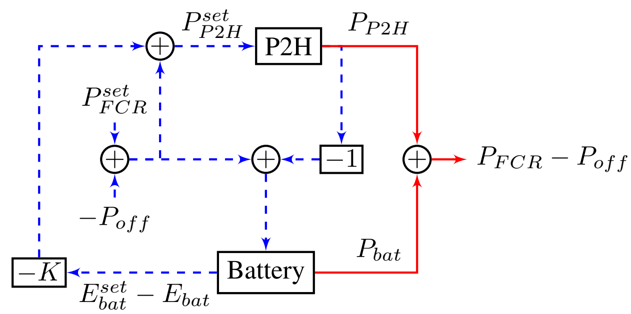

Fig. 3. Control of the proposed system with the FCR setpoint P_{FCR}^{set} summed with the offset $-P_{off}$ as input. The dashed blue lines are control signals and the plain red lines are actual power provision.

of cycles is limitative for FCR provision [11]. On the other hand, resistances do not exhibit such cycling limit. Therefore, there is a clear advantage to use P2H as much as possible and limit the burden on the batteries.

The proposed control is presented on Fig. 3. First, an offset is added to the FCR signal. Then, a signal regulating the energy content of the battery is added. This signal is simply the difference between the setpoint of the energy content E_{bat}^{set} and the actual energy content of the battery E_{bat} with a coefficient K. The result P_{P2H}^{set} is the P2H setpoint. If the latter is able to respond to the signal, i.e. if the command is within its consumption ability, the difference $\Delta P_{P2H} = P_{P2H}^{set} - P_{P2H}$ is null. In this case, the command of the battery is simply the regulating signal of its energy content. Inversely, if the difference is not null, i.e. P2H is unable to respond to its command, the battery complements by delivering or absorbing power. Therefore, because the proposed control consists in using the batteries when the resistances are unable to provide the primary control with the offset, the number of cycles of the battery is lower and a smaller battery could be installed.

Finally, given what has been discussed so far, it makes no doubt that the proposed hybrid system has more value, from a FCR perspective, than the sum of the individual values of the battery and the P2H system.

IV. Solution Design

This section presents a methodology to select the battery energy and power capabilities, the offset power and the P2H maximal power consumption. A description of the different parameters and an economic modelling are realized in respectively the first and second parts. Afterwards, simulations based on actual frequency data [13] are run in order to find the parameters minimizing the overall cost.

A. Design parameter

In this paper, the offset power has been considered as the design criteria for the proposed system since its selection allows the determination of the other parameters. Indeed, the minimization of the battery power leads to the selection of a battery power equal to the difference between the FCR power and the offset power. Also, the maximal power of P2H is chosen to be the sum of the offset power and the FCR power in order to be able to provide all the spectrum of downward FCR, i.e. FCR in consumption. This implies that the battery is never used for downward regulation and and is therefore regulated so as to charge whenever possible. It should be noted that it differs from other propositions in which the battery energy setpoint is the half charge. This is clearly an advantage because the present system can use smaller batteries than other propositions while providing similar frequency regulation.

Three ways are considered for selecting the energy content of the battery. First, a worst-case scenario could be estimated based on simulations of the system. This straightforward method has the important drawback that future frequency data could experience much larger and longer deviations. Second, a minimal energy content based on the maximal number of cycles and the number of years could be calculated from simulations. This estimation is function of the frequency quality over the whole simulation period. Third, an arbitrary limit on how long the battery must be able to provide full FCR power can be set. This limit has been set to 15 minutes and is based on the present grid code. In order to respect simultaneously all three criteria, the energy content is set to the maximal value amongst these three limits. Finally, considering the objective of minimising the overall provision cost, the battery power is set to the minimal value for FCR provision which is the difference between FCR power and the offset power.

B. Economic modelling

The aim of the economic modelling is to compute the overall cost of the system, C_T, expressed as a cost in euro per hour for the provision of 1 MW of FCR. The overall cost is the sum of (i) the capital cost reported on the investment period with a discount rate, (ii) the Operation and Maintenance cost, (iii), the cost of power purchase for the offset and (iv), the heat valorization. The latter is considered as a negative cost. Since the interest lies in the cost, the revenues are considered independent of the design selection. Table I summarizes all the economic parameters used for the simulation.

First, the capital cost is the sum of the capital cost for the battery and the P2H. This cost is paid once and is spread over the whole period with the discount rate. Concerning the battery, the capital cost is divided into a component proportional to the energy content and a component proportional to the power capability. In practice, this perfect dissociation is an approximation and it has only been used to have two independent degrees of freedom. The capital cost for the resistances is simply a cost proportional to the maximal power consumption.

Second, the Operation and Maintenance cost is calculated as a constant premium per year proportional to the capital cost. The coefficient is similar for the battery and the P2H.

The cost for the procurement of the offset power is calculated by the multiplication of the number of functioning hours per year, the offset price and the offset power. In first approximation, the electricity price has been considered constant. Finally, the heat valorization is considered as a negative cost and is expressed by taking into account the power-to-heat conversion efficiency, the valorization price and a coefficient γ corresponding to the energy consumed by the P2H. This coefficient is almost equal to the offset energy but differs slightly due to the inherent losses of the battery and the non-neutrality of the FCR energy content.

TABLE I
ECONOMIC PARAMETERS

Name	Value	unit	Variable
Discount rate	6	%	i_d
Number of years	10	Years	n_y
Power-to-Heat capital cost	100[a]	k€/MW	π_{P2H}
Offset Energy cost	60[b]	€/MWh	π_{off}
Heat valorization	25[c]	€/MWh	π_{heat}
Battery Power capital cost	300[d]	k€/MW	π_p
Battery Energy capital cost	800[e]	k€/MWh	π_e
Operation and Maintenance	6	%	K_{OM}

[a] 10-kW domestic electric boiler can be found at around 2000 €. It has been considered that the cost can be cut in half.

[b] That corresponds to the price for electricity with a premium.

[c] The heat valorization reflects how much gas or oil for heating is displaced. The value was found by taking a gas price of 7 €/GJ.

[d] It includes the power electronics costs and system integration costs.

[e] This cost is taken from [22] and could be considered conservative because Li-Ion battery cost is decreasing.

TABLE II
TECHNICAL PARAMETERS

Name	Value	unit	Variable
Battery charge efficiency	90	%	η_{cha}
Battery discharge efficiency	90	%	η_{dis}
Maximal number of cycles	3000	Cycles	n_{cyc}
P2H Conversion efficiency	97	%	η_{P2H}
Simulation duration	1	Year	D

C. Results

The total cost in function of the offset power is calculated thanks to the economic modelling, frequency data and time simulations of the proposed system. Technical parameters for the simulations are shown in table II. Fig. 4 presents the overall cost as well as its breakdown in four categories: P2H capital cost, battery capital cost, operation and maintenance and the difference between the offset cost and the heat valorization. From there, we find that the value minimizing the total cost is 0.111 MW for the provision of 1 MW of FCR.

In the cost breakdown of Fig. 4, two singular points are present and correspond to a change in the criteria for selecting the battery energy content. Fig. 5 presents the battery energy content in function of the three different criteria, which are (i) the worst-case scenario, (ii) the cycling limit and (iii) the 15 minutes at full FCR power. For low offset power, the worst-case scenario is preponderant. For high offset power, the 15 minutes criteria is the most restrictive criteria. For a range of offset power, the cycling limit of the battery is the criteria to select the battery energy content.

Finally, the simulation has shown that the best result is for a system with an offset power of 0.111 MW, a battery of

0.889 MW/0.222 MWh and a P2H of 1.111 MW. The energy content of the battery corresponds to a period of 15 minutes at full power. With this design, the overall cost is close to 11 €/h for the provision of 1 MW of FCR. This cost can be compared to the FCR market prices. There is a weekly tender for FCR provision used by the transmission system operators of Germany, Switzerland, Netherlands, Austria and Belgium [23]. For the 52 weeks between early November 2015 and end October 2016, the mean of the weekly average capacity price and the mean of the weekly marginal capacity price were respectively 15.73 €/h and 17.14 €/h for the provision of 1 MW of FCR. The mean of the required FCR over this period was 798.27 MW corresponding to 26.6 % of the total requirement for the CE grid.

V. Implementation of the Proposed System

A. Simulation of the selected design

The proposed system is simulated with the design of section IV. The P2H power and the battery energy are shown for six consecutive hours in Fig. 6. Two observations can be made. First, the P2H takes all the effort excepts when $P_{FCR}^{set} > P_{off}$ and second, the battery energy content is regulated to remain at its maximal energy content.

B. Integration in a heat system

The heat generated by the P2H can be valorized in various ways such as water heating for domestic use or within an industrial process. The heat generated by the P2H cannot be the only source of heat due to its unpredictability. A simple heat system, composed of a boiler, a heat tank and a heat demand H_{out}, is presented in Fig. 7. Similarly to the battery regulation, the energy content of the heat tank, E_H, is regulated via a proportional control of the difference between the setpoint E_H^{set} and E_H.

The size of the heat storage is function of the heat demand and the heat generated by the resistances. Based on time simulations that are not presented in this paper, the required heat tank should at least equal an energy of 1 hour of offset power with the optimal design if the heat demand is at least four times higher than the offset power. A detailed assessment of the interaction between generated heat, the required heat

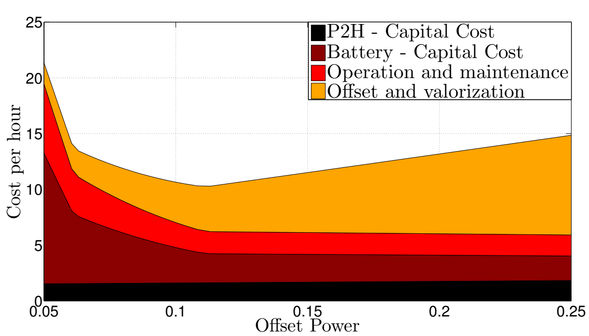

Fig. 4. Cost repartition in function of the offset power.

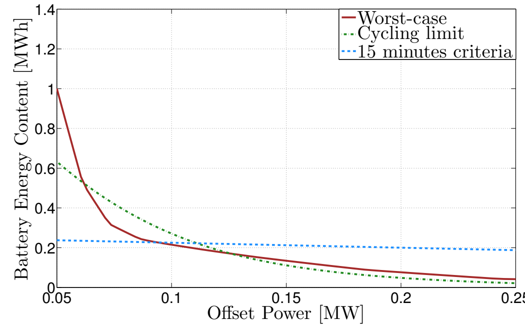

Fig. 5. Representation of the three criteria for selecting the battery energy content in function of the power offset.

tank and the heat demand with its seasonality was out of the scope of the present paper but should be carefully considered in future research.

VI. Conclusion

Frequency Containment Reserves are an important feature for the safe operation of the CE power system. With the growing penetration of renewables, current provision of FCR, i.e. with large synchronous generators, is likely to be increasingly difficult and expensive. A potential alternative is to use batteries. Nevertheless, two issues could arise. First, the energy content has to be regulated either directly by an energy provider or either indirectly by the power grid reserves via for example frequency filtering. Second, batteries providing primary control might too rapidly reach their maximal number of cycles.

This paper investigates the association of P2H with batteries for tackling both issues simultaneously. The P2H is simply composed of electric resistances able to modulate their power consumption without restriction from zero to a maximal value. Since they can only consume power, an offset is added to the frequency deviation signal. The result is that the whole system is in average consuming power and consequently, the resistances are able to modulate the battery energy in both directions. In addition, it is controlled in such way that the

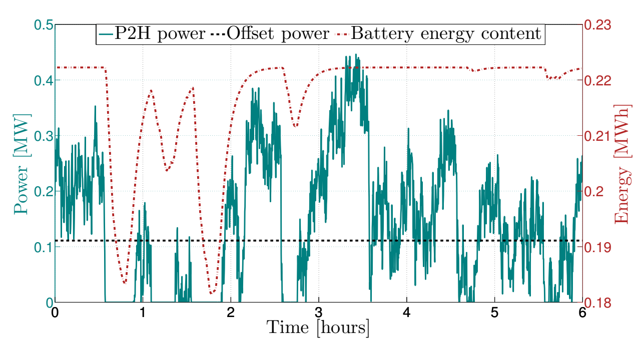

Fig. 6. P2H power and energy content of the battery during six consecutive hours for the provision of 1 MW of FCR.

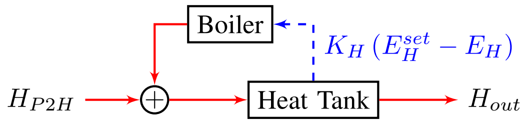

Fig. 7. Proportional regulation of the energy content of a heat tank via a boiler. Plain red lines are heat fluxes and the dashed blue line is a control signal.

resistances react before the batteries in order to drastically reduce their use and consequently, safeguard their lifetime.

Time simulations based on an economic modelling have been carried out to select a proper value for the offset power. It has been shown that, in the limits of the assumptions made, the offset power should be 0.111 MW for the provision of 1 MW of FCR. In addition, the battery should have a power of 0.889 MW and an energy content which equals 15 minutes of full power. With this design, the batteries will experience 3000 cycles after having run 10 years without interruption. Also, the P2H has a maximal power consumption of 1.111 MW allowing the battery to never provide downward FCR.

With this design, the FCR cost is relatively low. By taking a discount rate of 6 % on a period of 10 years, we find that the system cost is approximately 11 €/MW/h. Such result is promising since the average FCR price is 15.73 € between early November 2015 and end October 2016 for the common weekly market between Germany, Switzerland, Netherlands, Austria and Belgium corresponding to approximately one quarter of the total requirement for the CE grid.

Further investigations should be carried out to validate the proposition. First, complete modelling of the electrical components has to be realized. Indeed, only the high-level regulation is presented here. Second, because the paper objective is not to realize a precise business plan, the economic modelling is relatively simple and supplementary efforts should be undertaken. Also, an economic comparison with other solutions for FCR provision with storage could be undertaken to see if the proposition really offers a comparative advantage in term of overall system cost. Third, a prospective analysis of the different possibilities for adding the proposed system to a heat demand should be undertaken. Such an analysis should also question in depth the consequences for the heat provision.

Finally, the proposed system could be implemented by aggregating smaller geographically spread P2H and batteries. Indeed, the batteries and the P2H could, for example, be located in domestic houses and be coordinated through communication channels. Such dispersion could eventually offer other services such as voltage support for the distribution grid or back-up power in case of blackout. This proposition could therefore be seen as part of a smarter grid.

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