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Use of model predictive control for short-term operating reserve using commercial buildings in the United Kingdom context

Henri Bittel, Colin Neil Jones, Alessandra Parisio

Abstract-Flexibility, particularly in terms of reserve services, is an essential requirement of power systems with high penetration of renewable electrical generation, which can reduce undesirable curtailment and enable higher integration of clean electrical power from renewable generation. Reserve services are related to additional active power sources available to the grid operator in the form of either increased generation or demand reduction. There is increasing evidence that commercial buildings can provide such reserves. In this paper we present a Model Predictive Control approach to optimization of flexibility afforded by commercial buildings for the provision of reserve services, in particular for Short-Term Operating Reserve from the National Grid in the United Kingdom. This reserve scheme is only required during selected hours of the day and involves turning down consumption for a few hours at the request of the National Grid with a slow response time (< 5 minutes). Commercial buildings equipped with heat pumps and back-up gas boilers are considered. The proposed robust Model Predictive Control framework enables commercial buildings to provide Short-Term Operating Reserve without compromising the comfort of the occupants. Simulation are performed with a high-fidelity building model derived from Energy Plus through the software OpenBuild including real market data. Results show that a commercial building can provide Short-Term Operating Reserve and yield an economic benefit in a robust manner, without violating the indoor comfort of occupants.

I. INTRODUCTION

A. Motivation

Demand Response (DR) is the ability of appliances and assets to alter their operations in response to price/incentive or grid operator signals and hence influence the energy demand. DR is expected to grow as wind and solar are entering the market at a large-scale [1], [2]. The security of supply is today ensured by frequency regulation services, such as primary, secondary and tertiary frequency control, and historically provided by generators. However, evidence suggests that loads can also participate in reserve markets and at a lower cost [3], [4]. A large number of technologies compete for DR, and the three main questions that remain to be answered are: 1) how to quantify the need for DR and the efficient tools to incentivise it; 2) how to assess the potential of each technology; 3) how to assess the economic potential of DR for each technology. It has been shown that power to heat systems in commercial buildings (CBs) can be flexibility providers in a cost-effective manner [5]. CBs are interesting as well for the following reasons:

- larger loads than residential buildings;
- more advanced Heating, Ventilation and Air Conditioning systems (HVACs), which allow power to be varied continuously compared to switched control in residential buildings [6];
- Building management systems (BMS), enabling the implementation of advanced control algorithms [7].

Additionally, the large thermal mass of CBs could be used as a virtual storage, making them especially interesting in a smart grid framework [8], [9]. Such virtual storage could provide ancillary services, shift its consumption to appropriate times or help the distribution grid with peak load shifting services [10].

However, CBs are in competition other technologies such as Lithium-Ion batteries for providing services to the grid. Power to heat systems have the disadvantage of requiring a complex modeling environment and need to be aggregated and coordinated. Lithium-Ion batteries on the other hand are not environmentally friendly, have a limited life-time and do not tackle the problem of energy efficiency in the heating, ventilation and cooling of buildings. Thus the two technologies have their respective advantages to provide flexibility to the grid.

Reliable and economic use of DR for security of supply remains an open question. In the United Kingdom (UK), one of the solutions decision makers have chosen is the Short Term Operating Reserve (STOR), where almost 2-4 GW of power is tendered depending on the season. This service is only required during selected hours of the day during which the supply margin is expected to be tighter. During these socalled "windows", the service provider has to be available all throughout the window and upon request, should lower its consumption for up to two hours. Moreover, the STOR participant has a contractually obligated time to react (usually less than 5 minutes). This means that this flexibility might not be needed, although it provides security of supply and the flexibility provider is rewarded for its commitment.

B. Literature review

The use of flexible loads such as power to heat systems has been extensively investigated in literature. Recent investigations show how power to heat loads could participate in classical frequency regulation markets. The potential of flexible loads, such as refrigerators, to provide primary frequency control (PFC), which requires very fast actuation and response (<30 seconds), has been investigated by serveral authors (e.g., [11], [12]. However, power to heat systems are usually slow and are not able to respond on such short notice,

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making them more suitable for secondary frequency control (SFC) and tertiary frequency control, depending on the technology used. Secondary reserve have been widely researched in the literature for thermal controllable loads (TCLs). They consist of a regulation signal which allows a slower response than PFC, and which has a low energy content, meaning that its implementation should not result in a higher or lower energy consumption. Authors in [13] use electric heaters to participate in the SFC market in Switzerland with a twostage and multi-stage stochastic optimization. Authors in [6] investigated the potential of using the fan power to provide SFC and conclude that the fan power can be offered as reserve without loosing any comfort. This approach was extended in [5] to aggregators and further improved by taking into account the energy of the signal into the constraints of the building [14]. The participation of a building with a chiller and a stratified thermal storage in the SFC market has been studied in [15] by computing separately a thermal flexibility and after an electrical flexibility, as the thermal problem is linear and the electrical problem is non-linear. Finally, aggregation of buildings has been also considered to provide SFC, as usually SFC markets require a minimal power to take part. Authors in [16], [17], [18] investigate this topic by adopting a centralized optimization approach. On the other hand, tertiary reserve provision is not a wellcovered topic in literature. Authors in [19] consider domestic hot water boilers to provide tertiary reserve in Switzerland. This study addresses the tertiary reserve provision from CBs in the UK context. Among the various approaches adopted within the energy management literature, Model Predictive Control (MPC) [20] has received particular attention, because of its capability to integrate economic, social and environmental aspects, handle the future behavior of the system, compute control actions based on an optimal control problem including technical and operating constraints, as well as make the controlled system more robust against uncertainty [21]. In this paper, a novel MPC framework enabling CBs to participate in STOR without violating the indoor comfort for occupants is illustrated.

C. Statement of contribution

The main contribution of this paper is the modeling and optimisation of the flexibility afforded by commercial buildings with advanced heating systems, namely their ability to shift their heating consumption. The flexibility is provided to the Transmission Network Operator, which is National Grid (NG) in the UK context, as a down flexibility without compromising the occupant's comfort. By minimizing the total costs of operating the building, the controller will enable the building to participate in the reserve provision without wasting any energy. The main novelty of this work is to consider the DR signal for STOR, which is a type of tertiary reserve, which has a high energy content and it is more challenging to the occupants' indoor comfort. Existing works mainly focus on DR signals for secondary frequency response, with very small energy content. Moreover, the flexibility commitment is shifted to times of grid need. This approach will be applied to STOR and the current market in the UK, but it could be applied more generally to time limited down flexibility periods. To the best of authors' knowledge, one paper can be found in the literature, which deals with the modelling of buildings for STOR in the UK context [22], however no control framework is proposed. T Thus, the novelty and the main contribution of this study is the modelling and the economic optimization of high energy content down flexibility signals in an MPC framework, using state of the art building models. This paper also assesses the influence of non-electric based auxiliary heating systems to support the provision of higher reserve.

II. SYSTEM MODELLING

In this paper a building is modeled with a heat pump (HP) and a back-up gas-fired boiler.

A. Heat Pump

The heat pump is modeled at steady state. The heat power is modeled as:

$$Q_{HP} = COP \cdot P_{HP} \tag{1}$$

where the coefficient of performance (COP) is modeled with a combination of the supply and outdoor temperature as in [23]:

$$COP = c_0 + c_1 T_{amb} + c_2 T_{supply} + c_3 T_{amb}^2 + c_4 T_{supply}^2 + c_5 \cdot T_{amb} \cdot T_{supply}$$
(2)

where the coefficients are obtained from a polynomial regression in [23], T_{amb} is the ambient or outside temperature. The supply temperature T_{supply} is set constant at 40°C to obtain a linear model, in this way the COP can be predicted prior to the optimization.

The constraints on the heating power are modeled as follows:

$$0 \le Q_{HP} \le Q_{HP}^{max} \tag{3}$$

B. Peak boiler

The peak boiler is modeled at steady state:

.

$$Q_B = \eta_B \cdot \dot{m}_{NG,B} \tag{4}$$

where $\dot{m}_{NG,B}$ is in kWh per hour. In the case of an A-grade condensing gas boiler, which is considered here, the gas to heat efficiency is equal to $\eta_B = 90\%$ [24]. The constraints on the power are modeled as follows:

$$0 \le Q_B \le Q_B^{max} \tag{5}$$

C. Building modelling

A state space model for the CB is derived from the OpenBuild software [25], developed at EPFL. This software can derive state space models from high fidelity models developed using EnergyPlus software.

The model used is the following:

$$\begin{cases} x_{k+1} = Ax_k + Bu_k + Dd_k \\ y_k = Cx_k \end{cases}$$
(6)

where $u = [u_z, u_{sys}]'$, $u_{sys} = [\dot{Q}_{HP}, \dot{Q}_B]'$, u_z is the heat input to each zone, x is the state of the building and the thermal storage, y includes the temperature of each of the three zones of the building and the thermal storage, and d is the disturbance vector. Moreover, $x_k \in \mathbb{R}^{n_x}$, $u_k \in \mathbb{R}^{n_u}$, $d_k \in$ \mathbb{R}^{n_d} , $y_k \in \mathbb{R}^{n_y}$. Also, the states and inputs are constrained as follows

$$\begin{cases} u_k \in \mathcal{U} \ \forall k = 0, ..., N - 1\\ y_k \in \mathcal{Y} \ \forall k = 0, ..., N - 1 \end{cases}$$
(7)

where \mathcal{U} takes into account constraints on u_z as well equations (3-5), and \mathcal{Y} takes into account constraints on the heat storage as well as comfort constraints in the building zones. \mathcal{Y} also takes into account a slack variable ϵ to relax the indoor temperature constraints.

III. DEMAND MANAGEMENT SCHEME FOR SHORT-TERM OPERATING RESERVE

In this section we will describe the energy balance as well as the grid interaction. Then, we will describe the modeling of the reserves and of the economical objective. Finally, we will formulate the scheduling and MPC problems.

A. Energy balance

The heat production, which is the heat energy balance is modeled as:

$$\dot{Q}_{heating} = \dot{Q}_{HP} + \dot{Q}_B \tag{8}$$

we can thus reformulate $\dot{Q}_{heating}$ as:

$$\dot{Q}_{heating} = G_{h,bal} \cdot u_{sys} \tag{9}$$

where $u_{sys} = [\dot{Q}_{hp}, \dot{Q}_B]'$ and $G_{h,bal} = [1, 1]$. The link between the energy input to the system and the state is directly included in the formulation of matrix B in equation (6).

B. Grid Interaction

The electrical energy balance is modeled as:

$$P_{grid} = P_{HP} \tag{10}$$

Thus, the relation between the grid power and the heating power to the building is linear:

$$P_{grid} = G_{el,bal} \cdot u_{sys} \tag{11}$$

where $G_{el,bal} = [1/COP, 0]$.

C. Reserve modelling

There are two reserve provisions to model in order to handle well the energy reserve implementation:

- Grid capacity reserve
- Heating energy reserve

The constraint on the minimal grid power of the heating system is time varying:

$$(R_{STOR,k} - \epsilon_{STOR,k}) \le P_{grid,k} \text{ if } \mathbf{k} \in \mathcal{W}_{call}$$
(12)

where $R_{STOR,k}$ is the contracted reserve power and ϵ_{STOR} is a slack as STOR rules allow the delivery of the reserve to fluctuate around plus or minus 10%:

$$0 \le \epsilon_{STOR} \le \frac{R_{STOR}}{10} \tag{13}$$

The call from NG for STOR is modelled as $w_{call,k} \in W_{call}$, where W_{call} is the set of all admissible realizations of w_{call} . Moreover, the reserve can be modeled as follows:

$$R_{STOR,k} = \begin{cases} R_{STOR} \text{ if } \mathbf{k} \in \mathcal{W}_{call} \\ 0 \text{ otherwise} \end{cases}$$
(14)

As for the second reserve provision, when the NG instructs the CB for STOR, the provision of demand reduction has to be sustained for at least two hours. The impact of STOR on the internal thermal comfort has to be accounted for in order to not violate it. A constraint tightening is applied to guarantee the comfort constraints in the event of a call from the grid operator.

In the event of a call, the heating to the system will change in the following way:

$$Q'_{heating} = Q_{heating} + \Delta \dot{Q}_B - COP \cdot (R_{STOR} - \epsilon_{STOR})$$
(15)

where $\Delta \dot{Q}_B$ is the remaining available heat power from the boiler, constrained by:

$$0 \le \Delta \dot{Q}_{B,k} \le \dot{Q}_B^{max} - \dot{Q}_{B,k} \tag{16}$$

One can see the third term of the equation (15) as the energy lost to the realization of the DR signal. The remaining available heat power from $\Delta \dot{Q}_B$ will reduce the effect the reserve call will have on the system state. Therefore, it can also be seen as a tool to enhance the flexibility provision of the optimizer, such that it will be able to select a higher STOR capacity without compromising more the occupants comfort. The state of the system after the STOR call is modeled as:

$$\begin{aligned} x'_{k+1} &= Ax'_k + Bu_k + Dd_k + B_{aux}u_{aux,k} \\ &- B_R \cdot (R_{STOR} - \epsilon_{STOR,k}) \end{aligned}$$
(17)

where $u_{aux,k} = [\Delta \dot{Q}_{B,k}]'$ and the term $B_{aux}u_{aux,k}$ refers to the heat that could be added or not to the system if the peak boiler is turned on once the DR signal from the NG is received. $u_{aux,k} \in \mathcal{U}_{aux}$, which is the set of constraints that refers to equations (16).

In that matter, we can now formulate (17) the constraint as:

$$\begin{aligned} x'_{k+1} &= Ax'_{k} + Bu_{k} + Dd_{k} + (B_{aux}u_{aux,k}) \\ &- B_{R} \cdot (R_{STOR} - \epsilon_{STOR,k})) \cdot w_{call,k} \end{aligned}$$
(18)

The difference between equations (18) and (6) will thus reflect the new state in which the system might find itself if there is a reserve call. By subtracting the two equations, we get the following:

$$\begin{cases} \Delta x_{k+1} = x'_{k+1} - x_{k+1} = (B_{aux}u_{aux,k} - B_Rw_{R,k}) \cdot w_{call,k} \\ \Delta y_k = C \cdot (B_{aux}u_{aux,k-1} - B_Rw_{R,k-1}) \cdot w_{call,k-1} \end{cases}$$
(19)

where $w_R = R_{STOR} - \epsilon_{STOR}$. The second provision for the reserve modeling becomes:

$$y_k \in \mathcal{Y} \tag{20a}$$

$$y_k + \Delta y_k \in \mathcal{Y} \tag{20b}$$

D. Price and revenues modelling

The energy consumption price is modeled as follows:

$$c_{energy,k} = MIP [\pounds/kWh] + distribution costs [\pounds/kWh]$$
(21)

where the MIP is the market index price. The revenue from STOR is modeled as follows:

$$C_{av,STOR,k} = R_{STOR,k} \cdot c_{av,STOR} \tag{22}$$

$$C_{ut,STOR,k} = (R_{STOR,k} - \epsilon_{STOR,k})$$
⁽²³⁾

$$\cdot (c_{ut,STOR} + c_{energy,k}) \cdot w_{call,k}$$
 (23)

$$C_{STOR,k} = C_{av,STOR,k} + C_{ut,STOR,k}$$
(24)

where $c_{av,STOR}$ is the revenue from making the reserve available, in [£/kW/h], $c_{ut,STOR}$ is the revenue from utilization in [£/kWh]. $C_{ut,STOR,k}$ is the utilization revenue in £, which also takes into account the grid power you do not have to pay anymore as the STOR call will reduce your electric consumption. $C_{av,STOR,k}$ is the availability revenue and finally $C_{STOR,k}$ the total revenue for the reserve. The gas cost is modeled as follows:

$$C_{gas,k} = c_{gas} \cdot \frac{\dot{Q}_{B,k}}{\eta_B} \tag{25}$$

where c_{qas} is the price of the gas, in £ per kWh.

The operating cost of u_{aux} in case of a call from NG is modeled as:

$$C'_{gas,k} = c_{gas} \cdot \frac{\Delta \dot{Q}_{B,k} + \dot{Q}_{B,k}}{\eta_B}$$
(26)

The total economical objective is thus modeled as:

$$\phi_{eco,k} = (c_{energy,k} \cdot P_{grid,k} + C_{gas,k}) \cdot (1 - w_{call,k}) + C'_{gas,k} \cdot w_{call,k} - C_{STOR,k}$$
(27)

E. Scheduling formulation for reserve

For the control problem considered in this paper, we consider first a scheduling problem which selects the STOR windows and optimizes the STOR capacity. The participation in the reserves is then sent to the NG a week ahead. An MPC problem is then solved with a 30-minute sampling time, which commits the CB to the reserve provision.

In the scheduling problem, R_{STOR} has to be optimized for all windows. R_{STOR} is an optimization variable which is the same for all windows. Then, the optimizer can select in which windows (morning or evening) it is best to participate, at the R_{STOR} capacity. Thus a binary variable is introduced to select the most appropriate windows for the week-ahead problem:

$$\tau_{STOR,k} = \delta_{STOR,j} \cdot R_{STOR} \tag{28}$$

with the following constraints, from [26]:

$$\begin{cases} \tau_{STOR,k} \leq R_{STOR} \\ \tau_{STOR,k} \geq 0 \\ \tau_{STOR,k} \leq P_R^{max} \cdot \delta_{STOR,j} \\ \tau_{STOR,k} \geq R_{STOR} - P_R^{max} (1 - \delta_{STOR,j}) \end{cases}$$
(29)

where P_R^{max} is the maximal reserve of the system, namely here P_{HP}^{max} . Equations (19), (12) are reformulated as:

$$\Delta y_{k+1} = C \cdot (B_{aux} u_{aux,k} - B_R \cdot (\tau_{STOR,k} - \epsilon_{STOR,k})) \cdot w_{call,k}$$
(30)
$$(\tau_{STOR,k} - \epsilon_{STOR,k}) \le P_{grid,k} \text{ if } \mathbf{k} \in \mathcal{W}_{call}$$
(31)

Thus, we can formulate the set of feasible inputs as:

$$\mathcal{H}(x, \mathbf{d}, \mathbf{w}_{call}) = \begin{cases} \mathbf{u}, \mathbf{u}_{R}, \mathbf{u}_{aux} \\ \mathbf{u}_{R}, \mathbf{u}_{aux} \end{cases} \begin{vmatrix} x_{k+1} = Ax_{k} + Bu_{k} + Dd_{k} \\ y_{k} = Cx_{k} \\ (1), (2), (8), (10), (13), \\ (14), (29), (30), (31) \\ y_{k} \in \mathcal{Y} \\ y_{k} + \Delta y_{k} \in \mathcal{Y} \\ u_{k} \in \mathcal{U} \\ u_{aux,k} \in \mathcal{U}_{aux} \\ x(0) = x, \\ \forall k = 0, ..., N - 1 \end{cases}$$

$$(32)$$

where $\mathbf{u}_R = [\boldsymbol{\delta}_{STOR}, R_{STOR}].$

The following optimization problem is considered:

$$\min_{\mathbf{u},\mathbf{u}_{R},\mathbf{u}_{aux}} \phi = \sum_{k=0}^{N-1} \mathbb{E}[w_{call,k}]\phi_{eco,k} + \rho \cdot \epsilon_{k}$$
(33a)
subject to $(\mathbf{u},\mathbf{u}_{R},\mathbf{u}_{aux}) \in \mathcal{H}(x,\mathbf{d},\mathbf{w}_{call}) \forall \mathbf{w}_{call} \in \mathcal{W}_{call}$ (33b)

where ϵ_k is the slack variable for the temperature comfort constraints, indirectly expressed in \mathcal{Y} as described in section II.C.

Problem (33) is a robust problem with respect to W_{call} , since the obtained reserve are such that the building is able to commit to any admissible call from NG without violating the comfort constraints.

F. MPC formulation

Once the STOR reserves have been obtained by solving Problem (33), and MPC controller is designed to enable the building to commit to those reserves in case of a STOR call from NG. The computed reserves Then the set of feasible inputs (32) is:

$$\mathcal{Q}(x, \mathbf{d}, \mathbf{w}_{call}) = \begin{cases} \mathbf{u}, \mathbf{u}_{aux} & x_{k+1} = Ax_k + Bu_k + Dd_k \\ y_k = Cx_k \\ (1), (2), (8), (10), \\ (12), (13), (14), (19), \\ y_k \in \mathcal{Y} \\ y_k + \Delta y_k \in \mathcal{Y} \\ u_k \in \mathcal{U} \\ u_{aux,k} \in \mathcal{U}_{aux} \\ x(0) = x, \ \forall k = 0, ..., N - 1 \\ (34) \end{cases} \end{cases}$$

The MPC problem formulation is:

$$\underset{\mathbf{u},\mathbf{u}_{aux}}{\text{minimize}} \phi = \sum_{k=0}^{N-1} \phi_{eco,k} + \rho \cdot \epsilon_k$$
(35a)

subject to
$$(\mathbf{u}, \mathbf{u}_{aux}) \in \mathcal{Q}(x, \mathbf{d}, \mathbf{w}_{call})$$
 (35b)

Here we consider the same set W_{call} as in the scheduling problem. Indeed, no additional information on the set is supposed to be revealed closer to real-time, which is a relevant hypotheses as the CB will not know when it might be called. Moreover, the horizon N considered here is much shorter than the one considered in the scheduling problem.

IV. NUMERICAL EVALUATIONS

A. Simulation setup

The disturbances vector d consists of solar irradiation, sky temperature and dry bulb, are provided with the model and are assumed to be perfect forecasts.

The system considered can be viewed as:

where the temperature bounds of each thermal zone are



Fig. 1. Heating Scheme Layout

taken as:

$$T_{low} = \begin{cases} 15^{\circ}C \text{ from 6pm to 8am} \\ 20^{\circ}C \text{ from 8am to 6pm} \end{cases}$$
(36)

$$T_{high} = \begin{cases} 30^{\circ}C \text{ from 6pm to 8am} \\ 25^{\circ}C \text{ from 8am to 6pm} \end{cases}$$
(37)

The thermal storage can vary from $0^{\circ}C$ to $50^{\circ}C$.

The CB considered here is a model of a single storey CB is used that is compromised of three separate zones and a thermal storage [27]. The building has a total surface of 1350 m^2 and has a heating system made up of a thermo active building system (TABS). The flow rate in the heating water pipes is considered as constant. The heat storage is integrated explicitly, where heat is directly applied from the heating system, and then distributed to the building. A model with the 77 states for the three zones is derived from the OpenBuild software.

The STOR windows are the following:

Morning window: 07:00-13:30 (WD), 10:30-13:30 (NWD) Evening window: 16:30-21:00 (WD & NWD)

(38)

where WD and NWD stand for Week day and Non-Week dav.

The probability of call is modeled using the actual STOR volume data available on Elexon Data portal [28] for STOR season 10.6, divided by the total tendered capacity for the same season [29]. Then an average week-day and non-weekday is computed and used as probability of call. No other public information is however available. Indeed, the integration of the signal over the week is equal to 5.4 settlement periods (SP). However, the NG asks all participants to be available for at least three calls [30] and the probability is adapted resulting in 9 settlement periods over the week.

The cost of gas is taken as a constant as it varies very little around 2 ± 0.2 p/kWh [31]. The related costs to gas purchase including imbalance, distribution and transmission costs are neglected.

Finally, the electricity prices are taken as described in equation (21), and the market electricity prices, namely the MIP, are taken for the 30/01/2017 to 05/02/2017 week from the Elexon data portal [32]. The distribution costs are taken from available data in [33] and the balancing services use of system charges are neglected as they account only for three percent or less of the total cost.

The system evaluated in this paper is dimensioned as a typical heating system in a CB with a back-up boiler:

- $\dot{Q}_{HP}^{max} = 70 \text{ [kW]}$ $\dot{Q}_{B}^{max} = 30 \text{ [kW]}$

B. Simulation setup

All the simulations are done in Matlab and problems (33) and (35) are formulated as linear problems using the parsing tool Yalmip [34] and solved using the optimizer Gurobi [35]. As stated previously, the sampling time is of 30 minutes. Moreover, one can note that problem (33) is formulated as a MILP. The problems are solved on a 2.9 GHz Intel Core i5 with 16GB of RAM. The scheduling problem (33) is solved with a horizon of 336 steps, in 100 seconds approximately. The MPC problem (35) is solved in approximately 150 ms for each iteration, which is computed with a horizon of 24 hours, or 48 time-steps.

C. Reserve scheduler

In this section, the scheduling problem is assessed with perfect disturbance d and electricity prices forecasts, and with STOR bids based on previously accepted utilization and availability bids [29]:

- $c_{ut,STOR} = 75 \text{ [£/MWh]}$
- $c_{av,STOR} = 8 \text{ [£/MW/h]}$

The maximal reserve P_R^{max} at the lowest COP is equal to 36 kW, and for the highest COP 29 kW. The results are shown in figure (2).

First, the evening windows are never selected because the electricity costs are very high during these times and there is little or no heating needed thanks to the night/office out-of-hours setback. The two last windows on Sunday are selected as well. The optimal STOR capacity is equal to 27.1 kW, which is equivalent at some times to 94% of the



Fig. 2. Scheduling of STOR reserves

installed HP heating power. This means that at some times, the STOR power will be at almost the maximal heating installed capacity. The reserve bid also means that in order to meet the minimal requirement of the NG for STOR participation, an aggregator would have to aggregate 111 buildings of the same size, as the minimal bid in STOR is 3 MW for an aggregator [36].

D. MPC controller

In the case of the MPC problem, we simulate the case that there is randomly two STOR calls, of 1.5 hours each. Also, the simulation takes place only for six days, as the prediction horizon stops at seven days, after which no data for the disturbances is available. The simulation results are shown in figure (3) and (4).



Fig. 3. Real time control - grid interaction with two random reserve calls of one and a half hours each

We can first notice that the building reacts well to the two random reserve calls, as no constraints are violated. By looking at the grid interaction in figure (3), it seems that the CB is consuming only 90% of the STOR tendered power, meaning that the extra availability isn't worth it with respect to the probability of call. Interestingly, the restoration after the second call involves only using the boiler, as at those times the electricity prices are higher and thus using the boiler is cheaper than the HP. We can notice in figure (4) that again, the constraints are never violated.



Fig. 4. Real-time control of system

Economic performance

Even if the implementation of the reserves has been shown to be feasible, the economic aspect has also to be considered. In the following table, the results are compared for the case where the objective function of (35) are modified to first minimize the heating power consumption without reserves, secondly to minimize the economic objective with $R_{STOR} =$ 0 and finally with the normal MPC problem:

The table shows that the reserve case increases the energy

Perf. Obj.	Energy consumption [kWh]	Energy cost [£]	STOR av. [£]	STOR ut. [£]	Net energy cost [£]
Min power	4490.5	104.41	0	0	111.08
Min eco	4508.0	90.95	0	0	90.95
Reserve	4521.2	101.16	4.23	6.1	90.83

TABLE I Performance comparison

consumption, however results to a slightly lower cost than in economic optimization without reserves. At the same time, the CB is also providing a valuable service to the grid, provided at a cost similar to other technologies [29].

E. Discussion

The scheduling problem is formulated as a certainty equivalent problem with respect to the vector d and electricity price prediction for the week ahead. This is however not a realistic case as predictions tend to be more uncertain after one or two days. However, since this is just an assessment of

the economic potential of the building to participate in energy reserves, this assumption can be held for the assessment. On the other hand, the scheduling of the STOR capacity R_{STOR} is done in reality on a season-wide base and the selection of each windows is made on a week-ahead basis at the contracted capacity. Then, one would have to make a rough estimation of the expected disturbances over a whole season, and optimize the tendered reserve capacity such that the revenue from the reserves is maximized. Indeed, if the STOR power is selected too high, it might not be economical for the optimizer to select any window in the week ahead window selection.

The participation in the STOR window is not significantly affected by constraints (20) and more by constraint (12). Indeed, in the case that there is no STOR call, the STOR minimal power will make the system almost over heat. Thus, one can conclude that even if a less conservative approach to modelling the uncertainty related to the STOR call was considered, such as for a stochastic case, this would not influence a lot the obtained STOR optimal power. However, the bivalent system considered here with the non-electric based heating enhances the STOR capacity as it gives more flexibility to the optimizer in the equation (20). The MPC problem and reserve commitment is then simulated. Some random reserve calls are also simulated and the system never violates any constraints.

It can be noticed that the advantage of the robust approach means that, first, no restoration period is needed and straight after a call, a new reserve call could be provided. It also means that the building can be called as many times as needed with no limit on the weekly and seasonal utilization. This advantage will make the building's bid in the STOR markets more competitive and will enhance the chances of its bids to get accepted by the NG. However, the disadvantage of this approach is the provision for the STOR window would waste a little bit less energy. Also, it could increase the maximal feasible STOR bid for a system with no auxiliary heating system.

Finally, the implementation of the reserves increases the energy consumption and the costs remain similar to the economic MPC with no reserves.

V. CONCLUSIONS

A scheduling problem was formulated, where the optimal STOR bids were computed in a single optimization with perfect disturbance and electricity price knowledge for a week ahead. Real STOR economic bids were used and the results concluded that the only the morning windows were economical. In the real-time simulation problem, using an MPC formulation, the optimal participation in the STOR reserves provides a marginal reduction of the energy bill of the CB.

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