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Evaluation of Flexibility Impacts of Thermal Electric Storage Using an Integrated Building-to-Grid Model

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***Abstract*—Demand Side Management (DSM) using Thermal Electric Storage (TES) presents a promising opportunity for enhancing the system flexibility, resulting in reliable and economic operation of future low-carbon power systems. System-wide analysis of the flexibility potential of TES necessitates representation of dynamic thermal models in large-scale power systems models. Therefore, this study presents a novel Building-to-Grid (B2G) model integrating buildings' thermal dynamics and end-use constraints with a security-constrained unit commitment model for energy and reserve scheduling. The behaviour of residential thermal demand is represented through linear state space (RC-equivalent) models for different residential archetypes. The B2G model is subsequently used to evaluate the energy arbitrage and reserve provision potential of TES for a test system and various sensitivity analyses for wind penetration levels and presence of other flexibility options have been conducted. The optimisation results highlight the significant value of TES in terms of annual generation cost savings, reserve provision, peak load reduction and utilization of wind energy. The findings also emphasize the importance of co-optimising energy arbitrage and reserve provision from TES devices vis-a-vis system performance and household energy consumption scheduling.**

***Index Terms*—Ancillary Services, Demand Side Management, Electric Heating, Energy Arbitrage, Smart Thermal Storage.**

I. Introduction

Space and water heating demand represents approximately 80% of the final energy consumption in domestic buildings in Europe [1]. Therefore, environmental and energy security targets set by the European Climate Foundation have encouraged heating electrification in the residential sector [2]. Thermal Electric Storage (TES) has emerged as a promising electricity-to-heat technology with the potential of enabling the participation of thermal demand in active Demand Side Management (DSM). By virtue of decoupling the scheduling of electric power demand from the time of thermal energy end-use without compromising consumer thermal comfort, TES devices can enhance power system flexibility.

Previous studies which have evaluated the system-wide benefits of thermal demand usually implement simplistic representation of demand. In [3], the authors integrate a price responsive shiftable demand model in a Security Constrained Unit Commitment (SCUC) model to assess the value of demand bidding in both the energy and reserve markets. Representation of large, spatially-distributed populations of heat pumps, electric vehicles, and electrolyzers in Security Constrained Economic Dispatch (SCED) using a Virtual Generator Model has been presented in [4]. Representation of thermal demand constraints for different building archetypes using a temporal profile of power draw values in a SCUC model has been implemented in [5]. These studies highlight the significant energy arbitrage and reserve provision potential of TES devices. However, the simplified representation of thermal demand in the aforementioned studies fails to take into account the load dynamics and therefore, the impact of demand response on the consumers and also does not guarantee fulfilment of consumers' thermal comfort constraints.

On the other hand of the spectrum are studies focusing on the impact of demand response on individual consumers. These studies implement detailed thermal demand models but have a simplistic representation of the supply side, usually using price signals. The economic value of Heat Pumps (HP) and Electric Boilers (EB) is assessed based on a two-stage stochastic programming model in [6]. The model is employed to optimize the operation of HP and EB using price signals in the context of a heat market in Denmark. In [7], the authors optimize the control of partial storage electric space heating to minimize the total energy cost of customers based on fixed electricity price profiles. However, using exogenous price signals to evaluate the performance of responsive demand has the limitation of not considering the feedback impact of the change in demand on the electricity price [8]. Therefore, such models cannot provide technically valid estimates of the flexibility potential of a large fleet of TES devices.

Studies which integrate detailed building thermal models with conventional power systems models are scarce, with the exception of a few recent studies. An integrated model for representation of residential thermal demand in a power system unit commitment model has been presented in [9]. The authors compare the integrated model with the simplified models to highlight the superiority of integrated modeling in terms of in terms of representing the impacts of load shifting on the consumers and also on the supply mix and electricity prices. Similarly, authors in [10] evaluate the energy arbitrage capability of smart TES devices by integrating building thermal models for different residential archetypes in a power systems economic dispatch model. However, these integrated models only consider the energy arbitrage potential of flexible thermal demand without considering simultaneous participation in ancillary service provision. Additionally, these

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studies have been conducted in the absence of other competing flexible technologies such as large scale pumped storage, interconnection, battery storage etc. Therefore, the performance of TES determined in these studies may not be representative of realistic current and future scenarios.

In view of the aforementioned literature review, the Building-to-Grid (B2G) model developed in this study extends the state of the art through the following novel contributions:

1) The proposed B2G model integrates the thermal dynamics for different residential archetypes with a SCUC model. Therefore, the model facilitates the evaluation of TES load's participation in energy arbitrage and different categories of contingency reserve provision while maintaining end-user thermal comfort.
2) The impact assessment of increasing renewable generation penetration levels and the presence of other competing technologies (pumped hydro storage and interconnection) on the flexibility potential of TES devices using various sensitivity analyses is performed.

The B2G model is implemented on the All Island Power System (AIPS) of Ireland to conduct an annual analysis of the flexibility potential of TES in terms of generation cost savings, peak load reduction and utilisation of wind generation.

II. Methodology

A. Space and Hot Water Demand Modelling

Space heating requirements for different residential archetypes are modelled using calibrated thermal network (RC-equivalent) state space models as discussed in detail in the authors' previous work [10]. The resulting state vector $x_n^j = \begin{bmatrix} T^j_{n,w_1} & T^j_{n,w_2i} & T^j_{n,r} & T^j_{n,int} & T^j_{n,hall} \end{bmatrix}$ models the temperature evolution for different nodes of the RC model for each archetype. The analytical domestic hot water (DHW) demand profiles for the different archetypes are developed using an occupant focused approach based on Time-of-Use Survey (TUS) data. Building Performance Simulations (BPS) of these archetypes are then modeled by integrating high space and time resolution operational data. Subsequently, activity specific DHW volume draw profiles are obtained using the bottom-up approach developed by Neu et al. [10], [11], which is based on the application of Markov Chain Monte Carlo techniques to TUS data [12].

B. Building-to-Grid Model

The Building-to-Grid (B2G) model is fundamentally a SCUC tool with integration of the building thermal dynamics to co-optimise generation scheduling with power consumption scheduling of the TES devices. The objective function of the B2G model (1) minimises the system operating cost which consists of generation fuel costs ($\pi_{g,i}$), carbon prices ($pi_{c,i}$) and start-up costs ($\pi_{su,i}$):

$$min \sum_{j=1}^{J}\sum_{i=1}^{I} C^j_{g,i}\left(g^j_i, \pi_{g,i}, \pi_{su,i}, \pi_{c,i}\right) \tag{1}$$

The cost minimisation, performed over the horizon J with resolution Δj, is subject to the standard SCUC constraints in addition to the constraints unique to this piece of work which are the thermal demand constraints for domestic space and water heating. System level constraints include the power balance constraint, System Non-Synchronous Penetration (SNSP) limit, N-1 contingency reserve constraints, interconnection (IC) limits, and stability related constraints, etc. The power balance balance constraint ensures that the total electricity generation equals the sum of total demand (inflexible baseline demand (D^j_{base}) plus the flexible heating demand (P^j_{heat})) and the net exports at all times. The SNSP limit defined below constrains the ratio of non-synchronous generation (wind (w^j) and HVDC imports (μ^j_{im})) to demand plus HVDC exports (μ^j_{ex}) to a specified limit [13].

$$\frac{w^j + \mu^j_{im}}{P^j_{heat} + D^j_{base} + \mu^j_{ex}} \le snsp_{lim}, \quad \forall j \in [1, J] \tag{2}$$

The N-1 contingency reserve requirements are defined for different categories of reserves while restricting maximum participation in reserve provision from static reserve sources (e.g. HVDC IC, pumped storage in pumping mode and demand side reserves). Stability related constraints require that a minimum number of high inertia units must be kept online for dynamic stability. Constraints on individual generation units include minimum and maximum generation levels, ramping limits, minimum up and down time requirements in addition to each unit's ability to provide different categories of reserve. The full representation of these standard SCUC constraints can be found in [14], which has a similar implementation.

The following equations and constraints pertaining to the flexible domestic space and water heating demand have been integrated in the SCUC tool described above:

$$P^j_{heat} = \alpha_n\left(S^j_n + H^j_n\right), \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{3}$$

$$T^{min}_{n,r}.O^j_n \le T^j_{n,r}.O^j_n \le T^{max}_{n,r}.O^j_n, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{4}$$

$$E^{j+1}_n = E^j_n + S^j_n.\Delta j - Q^j_n - Q^j_{n,loss}, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{5}$$

$$Q^j_{n,loss} = (1 - \eta_n).E^j_n, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{6}$$

$$Q^j_{n,heat} = Q^j_n + Q^j_{n,loss}, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{7}$$

$$0 \le Q^j_n \le Q^{max}_n, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{8}$$

$$0 \le S^j_n \le S^{max}_n, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{9}$$

$$0 \le E^j_n \le E^{max}_n, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{10}$$

$$\rho c_p V_{n,t}\frac{T^{j+1}_{n,t} - T^j_{n,t}}{\Delta j} = H^j_n - UA_n.(T^j_{n,t} - T^j_{n,r}) - \rho c_p V^j_{dem,n}.(T^j_{n,t} - T^j_{n,in}), \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{11}$$

$$T^{min}_{n,t} \le T^j_{n,t} \le T^{max}_{n,t}, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{12}$$

$$0 \le H^j_n \le H^{max}_n, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{13}$$

$$R^j_{POR\uparrow,n} \le S^j_n + H^j_n, \quad \forall j \in [1, J] \quad \forall n \in [1, N] \tag{14}$$

$$R^j_{POR\downarrow,n} \le S^{max}_n + H^{max}_n - S^j_n - H^j_n, \forall j \in [1, J] \forall n \in [1, N] \tag{15}$$

$$E_n^{j-1} + S_n^j - \beta . S_{TOR,n}^j \geq Q_{n,heat}^j, \forall j \in [1,J] \forall n \in [1,N] \quad (16)$$

$$S_{TOR,n}^j \leq S_n^j, \quad \forall j \in [1,J] \quad \forall n \in [1,N] \quad (17)$$

$$\rho c_p V_{n,t} \frac{T_{TOR,n,t}^{j+1} - T_{n,t}^j}{\Delta j} = H_n^j - \beta . H_{TOR,n}^j - UA_n . (T_{n,t}^j - T_{n,r}^j) - \rho c_p V_{dem,n}^j . (T_{n,t}^j - T_{n,in}^j), \quad \forall j \in [1,J] \quad \forall n \in [1,N] \quad (18)$$

$$T_{TOR,n,t}^j \geq T_{n,t}^{min}, \quad \forall j \in [1,J] \quad \forall n \in [1,N] \quad (19)$$

$$H_{TOR,n}^j \leq H_n^j, \quad \forall j \in [1,J] \quad \forall n \in [1,N] \quad (20)$$

$$R_{TOR,n}^j \leq S_{TOR,n}^j + H_{TOR,n}^j, \quad \forall j \in [1,J] \quad \forall n \in [1,N] \quad (21)$$

The total electric heating demand is defined in (3) as the scaled up summation of the electricity consumption for space heating (S_n^j) and DHW (H_n^j) of individual dwellings, where the scaling factor (α_n) is the total number of dwellings belonging to archetype n. The room temperature ($T_{n,r}^j$), obtained using RC-equivalent state space models, is constrained to be within the thermal comfort limits during active occupancy periods using (4), where O_n^j is 1 for active and 0 for inactive occupancy periods. The evolution of the storage level (E_n^j) and the corresponding storage heat losses ($Q_{n,loss}^j$) of TES for space heating are modelled in (5) and (6), respectively. The total space heating input to the building ($Q_{n,heat}^j$) is the summation of active heat output (Q_n^j) of the TES and the storage heat losses as shown in (7). Eqs. (8)-(10) constrain the active heat output, electric power input and storage level of the TES space heaters to be within their respective rated values. The temperature evolution of the DHW storage tank ($T_{n,t}^j$) is represented in (11) as a state space model. A simple one node perfectly stirred water tank model is considered. The first term on the right side of the equation represents the DHW input power (H_n^j), the second term represents the heat losses from the tank to the surroundings using the tank's heat transfer coefficient (UA_n), while the third term models the heat loss in the event of hot water draw, during which the cold water at the inlet ($T_{n,in}^j$) replaces an equivalent volume of water. The volume of water draw ($V_{dem,n}^j$) is obtained using the methodology described in Section II-A, and ρ and c_p represent the density and specific heat capacity of water, respectively. Eq. (12) constrains the DHW tank temperature to be within the prescribed operation limits and (13) limits the DHW input power to be within the rated values.

In addition to load shifting, TES devices can also participate in provision of different categories of contingency reserves. In this study, provision of upward and downward primary and tertiary operating reserves from TES devices is considered. To participate in upward reserve provision, power consumption of TES devices needs to be interrupted in case of a contingency. In contrast, participation in downward reserve would require the TES devices to consume additional power in case of an over-frequency event. TES participation is upward primary operating reserves ($R_{POR\uparrow,n}^j$) is constrained in (14) to be within the TES electricity consumption for space and water heating. As primary reserves are to be maintained for a very short period of time (typically a few seconds), it is assumed that TES participation in POR will not affect the thermal comfort of the consumers, therefore all the power consumption is available for upward POR. Similarly, TES participation in downward POR ($R_{POR\downarrow,n}^j$) is modelled in (15). In this study, TES participation in Tertiary Operating Reserves ($R_{TOR,n}^j$) is specifically modelled because these reserves are typically maintained for several minutes and hence could potentially impact consumer thermal comfort. Therefore, Eqs. (16) - (21) are implemented to determine TES TOR potential without violating thermal comfort. TES space heating load's participation in TOR ($S_{TOR,n}^j$) is constrained in (16) and (17) to ensure that the TES storage level even after the interrupted energy consumption ($\beta . S_{TOR,n}^j$) should be able to meet the dwelling's heating requirement and that ($S_{TOR,n}^j$) should be within TES space heating power consumption. The scaling factor β is implemented to convert TOR power interruption values to energy values based on the duration for which TOR provision is to be maintained. Similarly, DHW tank temperature evolution in case of TOR participation ($T_{TOR,n,t}^j$) is modelled in (18) to account for the drop in tank temperature after interruption of power consumption ($H_{TOR,n}^j$). This dropped temperature should still be above DHW minimum temperature requirement (19). Finally, the total TOR participation is constrained by the sum of space and DHW TOR participation in (21).

C. Test System

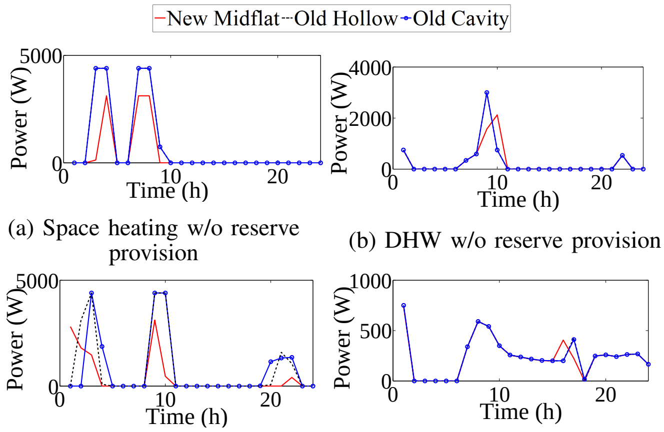
The developed B2G model has been used to conduct an annual analysis of the flexibility potential of TES for the AIPS. The set of system operational constraints pertaining to AIPS have been modelled according to [15]. Considering the requirement to maintain TOR for 20 minutes, β has been set to $1/3$. The conventional generation portfolio of the AIPS including the number of units, heat rates, ramping and reserve capabilities, and other important characteristics have been modeled according to [16]. The associated fuel costs of the various fuels are obtained from [17] and the fuel carbon intensities are based on [18]. In this study, three different Irish midflat archetypes based on periods and materials of construction are considered. The first two archetypes represent double glazed uninsulated apartments built before 1985. The first model features external hollow brick walls, whereas the second model features cavity walls. The third archetype is representative of recent constructions which feature energy efficiency measures. The thermal modelling assumptions, number of midflats and characteristics of the TES devices are detailed in [10]. Additionally, different penetration levels of TES devices in comparison to Direct Resistive Heaters (DRH) are studied. Participation of DRH in reserve provision is also considered.

The B2G model is solved at hourly resolution with a look-ahead horizon of 48 hours assuming perfect forecast. The results for the first 24 hours are stored, before rolling on to the next day of the year. The model is implemented in GAMS and MATLAB using the MATLAB-GAMS coupling as described in [19] keeping a MIP optimality gap of 0.25%.

III. Results and Discussion

A. Central Scenario

The central scenario evaluates the performance of TES devices in the absence of other flexibility options, keeping the



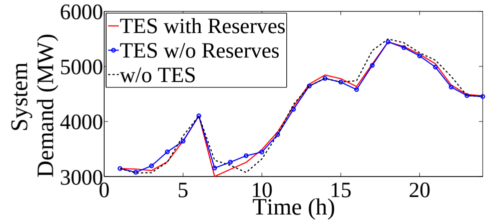
(a) Space heating w/o reserve provision

(b) DHW w/o reserve provision

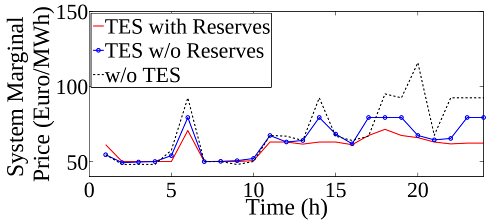
(c) Space heating with reserve provision

(d) DHW with reserve provision

Fig. 1. Typical daily charging of aggregated TES load



(a) System demand profile

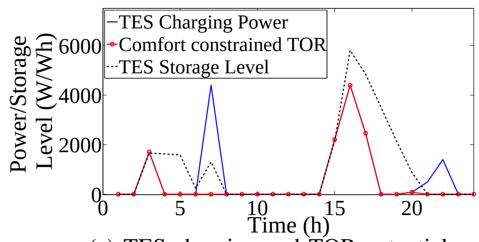


(b) System marginal price profile

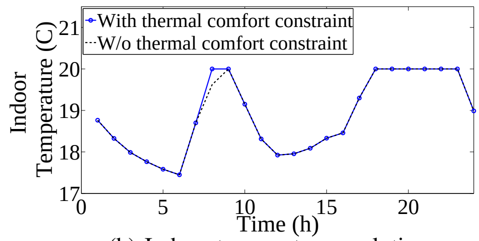
Fig. 2. Impact of TES on system demand and marginal price

SNSP limit at 50%. Fig. 1 depicts the charge scheduling of TES devices (at 50% penetration level) for a typical day in the heating season with and without reserve provision. It can be observed from Figs. 1a and 1b that when TES devices are not participating in reserve provision, these devices are typically charged in periods of low system demand and system marginal price (SMP) during 01:00-05:00 and 07:00-10:00 (see Fig. 2) in order to maximise the energy arbitrage benefits. However, when providing reserves (see Figs. 1c and 1d), TES devices shift some of the charging to evening and night times in order to enable provision of upward reserves during these periods of relatively higher system demand. It can also be noticed that the space heating requirements of the older uninsulated midflats are higher than that of the new insulated ones. The impact of TES on system demand and SMP in comparison to the case where all the considered dwellings are heated with DRH is shown in Fig. 2. It can be observed from Fig. 2a that without participation in reserve provision, TES loads are able to fill the valleys during periods of low system demand and consequently, reduce the evening peak during 17:00-19:00. Reduction of peak loads would mean that the expensive generating units do not need to be operated, which is translated into significant reduction of SMP during these periods as shown in Fig. 2b. Although TES participation in reserves reduces their valley filling capability, peak load reduction is still achieved. The importance of TES participation in reserves is evident from the SMP profile in Fig. 2b. By participating in reserves, TES devices avoid the need to keep extra units online for keeping the system N-1 secure throughout the day. Therefore, the SMP profile is flattened, resulting in lower prices as compared to the case where TES devices do not participate in reserves. These results signify the importance of evaluating the reserve provision potential of TES loads in addition to their load shifting capabilities not only in terms of their impact on system performance but also on the power consumption profiles of individual households.

Fig. 3 highlights the importance of considering consumer thermal comfort on TES participation in provision of tertiary operating reserves (TOR). It can be observed in Fig. 3a that when TES storage levels are low during periods of active occupancy (07:00 - 09:00 and 17:00 - 23:00), all of the TES charging power consumption is not available for TOR



(a) TES charging and TOR potential

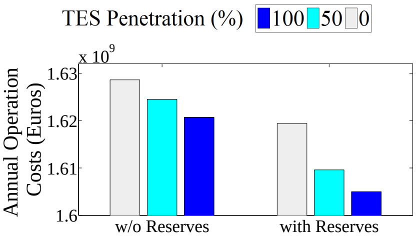


(b) Indoor temperature evolution

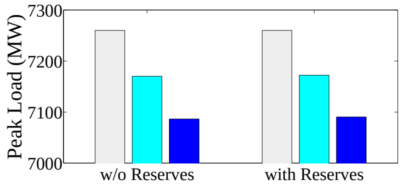
Fig. 3. Impact of thermal comfort constraint

provision. This is because constraint (16) ensures that the TES storage level after provision of TOR for 20 minutes should be able to meet the dwelling's heating requirement. The impact of provision of TOR on consumer thermal comfort is shown in Fig. 3b when reserve is called at 07:00. It can be seen that if the comfort constraint for space heating is not included, all of the TES power consumption would be interrupted to provide TOR, thereby causing thermal discomfort as the indoor temperature falls below the minimum required level of 20°C. Therefore, the integrated B2G model facilitates valid evaluation of the thermally constrained reserve potential of TES loads.

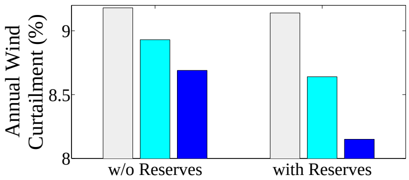
Fig. 4 shows the annual performance of TES for the central scenario. It can be observed from Fig. 4a that as the proportion of midflats heated with TES increases, there is a steady reduction in the annual electricity generation costs for the case where TES devices do not participate in reserve provision. However, a saturation effect in terms of cost reduction is observed with increasing penetration of TES devices when they participate in reserve provision. This can be attributed to the observation made in Fig. 2b which depicted that the



(a) Annual operation costs reduction



(b) Peak load reduction



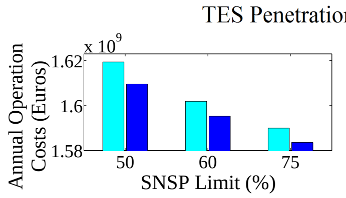
(c) Wind curtailment reduction

Fig. 4. Annual performance of TES

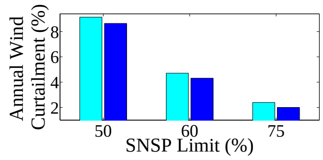
daily SMP profile is significantly flattened if reserves are provided with 50% penetration of TES. Therefore, increasing the number of dwellings with TES devices would not result in a proportionate decrease in operation costs if reserve provision from TES is considered. Additionally, it can also be inferred from Fig. 4a that the cost savings attributed to reserve provision are approximately of the same order of magnitude as those attributed to energy arbitrage. Fig. 4b highlights the peak shaving potential of TES devices. Indeed, circa 180 MW of peak load can be reduced if all the considered midflats are heated with TES devices. It can also be observed that reserve provision doesn't reduce the peak reduction potential of TES. Hence, TES can play an important role in reducing not only operational costs but also investment costs in generation and transmission infrastructure. Finally, the reduction in wind curtailment levels with increasing penetration of TES devices is shown in Fig. 4c. It can be seen that participation of TES in reserve provision results in greater utilisation of wind energy. However, the magnitude of curtailment reduction is not as significant as expected from load shifting resources. This can primarily be attributed to the small magnitude of the TES load and storage potential as compared to the total system inflexible load. Additionally, analysis of the wind curtailment events throughout the year indicated that these events can often last for long periods of time. Consequently, the benefit of the TES to shift demand during the day becomes redundant when compared to DRH during these curtailment events, as DRH too can benefit from the free wind energy.

B. Sensitivity Analyses

1) Increasing renewable generation: The annual cost savings and wind curtailment reduction capability of TES while participating in reserve provision for various SNSP levels is presented in Fig. 5. Increasing levels of SNSP result in increasing penetration of non-synchronous renewable resources in the power system. The Irish power system has been operating at 50% SNSP since a few years, and currently the system performance at 60% SNSP is being tested. By 2020, system operation at SNSP limit of 75% is being forecasted. It can be observed in Fig. 5a that although the total system costs fall with increasing SNSP, the magnitude of the cost savings attributed to TES remains approximately the same across all SNSP limits. This shows that TES devices have robust arbitrage potential even under low cost high renewables future power systems. Fig. 5b shows that although increasing penetration of TES devices reduces wind curtailment levels for all SNSP limits, however, the magnitude of this reduction falls as SNSP limits increase. This can be attributed to the fact that curtailment levels are already circa 2% at 75% SNSP limit and DRH can also benefit from increase in wind energy as discussed earlier.



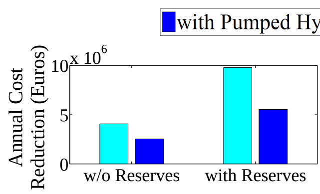
(a) Annual costs reduction



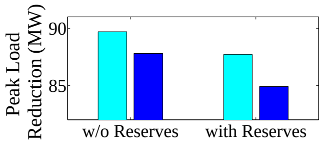
(b) Wind curtailment reduction

Fig. 5. Performance of TES at various SNSP levels

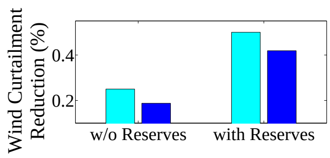
2) Presence of Flexibility Competitors: Large-scale storage units e.g. pumped hydro (PH) and interconnection (IC) are flexibility competitors for TES devices as they too can potentially smooth the net load profiles and participate in reserve provision. It is therefore important to analyse the flexibility potential of TES devices in the presence of these competing technologies. Figs. 6 and 7 depict the performance of TES when a large-scale PH unit and IC with Great Britain (GB) is included in the B2G model, respectively. The presented results show the difference in performance between 0% and 50% TES penetration levels. The PH unit is modelled according to the existing Turlough Hill PH facility in the Irish system [20]. The IC scenario is implemented by including the 2 existing Irish HVDC interconnectors to GB rated at 500 MW each. The GB system is modelled as a single gas unit with time-dependent heat rates and assumes that gas-fired generation is the marginal



(a) Annual costs reduction

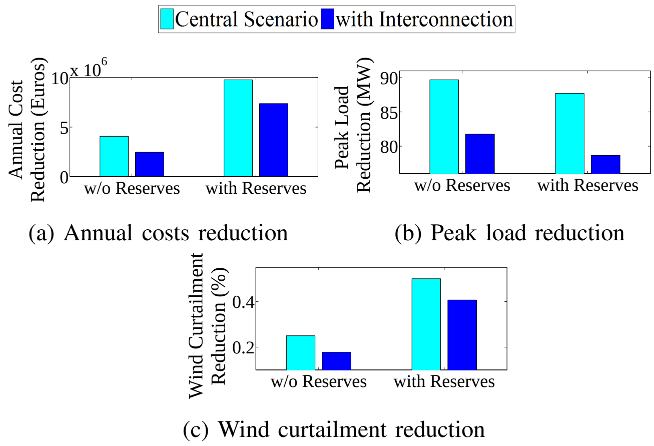


(b) Peak load reduction



(c) Wind curtailment reduction

Fig. 6. Performance of TES in the presence of pumped hydro



(a) Annual costs reduction

(b) Peak load reduction

(c) Wind curtailment reduction

Fig. 7. Performance of TES in the presence of interconnection

plant in the GB system as in [20].

It can be observed in Fig. 6a that presence of PH noticeably reduces the TES cost reduction potential (difference between 0% and 50% TES penetration levels) as expected. It is also evident from the decreased difference between cost reduction with and without reserves, that the savings attributed to TES reserve provision are also significantly diminished. Additionally, TES capability to reduce the peak load (see Fig. 6b) is deteriorated. This is because presence of PH can sufficiently reduce the SMP during peak hours to allow for some TES charging during this period. Finally, Fig. 6c shows that there is a negligible impact of PH on wind curtailment reduction potential of TES, owing to the fact that even in the central scenario, TES devices have a small impact on wind curtailment levels. IC with GB also has similar impacts on the flexibility potential of TES devices in terms of cost savings, peak load reduction and wind utilization as depicted in Fig. 7. However, it is interesting to note that the difference between the cost reduction with and without reserves even in the presence of IC remains approximately unchanged (see Fig. 7a). This implies that, in contrast to PH, IC does not reduce the reserve provision potential of TES devices. This finding can primarily be explained by the increased reserve provision requirement introduced due to the large magnitude of HVDC imports from GB, thereby complimenting the reserve provision potential of TES. Additionally, as PH can provide dynamic spinning reserves in generating mode as compared to the static reserve provided by TES and the HVDC IC, there is greater substitution of TES reserves by the reserves provided by PH. These results highlight the importance of analysing the performance of TES in the presence of different flexibility competitors and, thus, facilitate realistic and technically valid evaluation of TES flexibility.

IV. Conclusions

This paper presented the evaluation of TES flexibility using an integrated B2G model. The B2G model co-optimises the generation scheduling with TES charge scheduling for residential space and water heating demand to enable energy arbitrage and reserve provision. The model is implemented for the AIPS considering three midflat archetypes. The results highlight the importance of considering reserve provision of TES in addition to the energy arbitrage potential of TES in terms of significant generation cost savings, greater utilization of wind generation and reduction in peak load. Additionally, the integration of building thermal dynamics allows the B2G to determine the comfort constrained service provision levels of TES devices and also the impact of reserve provision on consumer comfort. Finally, TES performance under various scenarios emphasize the significance of including the presence of other flexible technologies to obtain realistic estimates of TES flexibility.

Future work will incorporate other residential archetypes, different occupancy profiles and other flexible domestic appliances in the B2G model to estimate the total flexibility potential of domestic loads. It would also be interesting to determine the cost optimum portfolio of flexible domestic demand based on investment planning studies.

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TABLE I. AUTHORS' BACKGROUND

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