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Battery Storage Systems in Smart Grid Optimised Buildings

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Abstract

The building sector is responsible for a significant proportion of the consumed energy and the consequent carbon emissions. Currently, electricity and natural gas are the most popular fuels used in the UK Services sector and the industry. Furthermore, buildings constitute a key component of the power network, in both its current conventional form and its evolution, the smart grid. The smart grid is expected to integrate energy storage, distributed generation and buildings into the network. This paper introduces the concept of Smart Grid Optimised Buildings (SGOBs), recognising the importance of energy storage to establish a dynamic interaction between the building and the smart grid. SGOBs are expected to be fully electric, make the best use of the available resources and utilise their embedded battery storage systems to respond to notifications issued by the smart grid and to dynamic electricity prices. Assuming that buildings have access to the day-ahead electricity market, initial results show that battery storage can be successfully used to change a building's electricity profile and perform load-shifting (arbitrage) and peak-shaving while the excess electricity is exported back to grid to take advantage of the price difference and relieve pressure on the infrastructure.

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Keywords: energy storage; battery storage; energy arbitrage; smart grid; smart buildings; smart grid optimised buildings

1. Introduction to the Building Sector

It is a common practice for most agencies and organisations to classify the final energy consumption into three categories and more specifically industry, transport and 'other'. The third category is vaguely defined and usually incorporates several sectors and subsectors. According to the International Energy Agency (IEA), this broad definition

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includes residential & commercial buildings, public services, agriculture, fishing and energy consumption which is not specified. However, it is recognised that all building types contribute to a significant proportion of the consumed energy worldwide and the third category, mentioned above [1]. Breaking down the sector to its individual components, Eurostat defines non-residential buildings as buildings other than dwellings that include a variety of structures, including hotels, hospitals, schools and in general industrial, commercial, public, health and educational buildings. A common or widely accepted definition for non-residential buildings has not been found as the building sector and its associated typologies have a broad variety of uses [2].

The Government of the United Kingdom (UK) and the Department for Business, Energy & Industrial Strategy (DBEIS) separate buildings into the Domestic Sector, Industry and Services. The domestic sector includes residential buildings and the respective households, industry refers to any industrial energy consumption, while services constitute a complicated sector as several subsectors such as offices, retail, hospitality, health and education are included. Regarding their contribution to the UK final energy consumption in 2016, the domestic sector was responsible for the 29%, with the industry accounting for 17% and services for 14%. Assuming that industry refers to industrial buildings and their activities, the non-domestic sector contributes to the combined percentage of 31% [3].

Figure 1 was compiled using the data provided by DBEIS and shows the fluctuation of the final energy consumption in the UK Services Sector, between 1970 and 2016. Regarding the underlying trend, a relative stability can be observed since 1970 and consumption in 2016 was 6.9% higher than in 1970. Furthermore, the total floor area used by the sector also increased. In particular, from 2000 to 2015, the retail floor area increased by 9.6% and the office space area by 13%. As the UK shifted away from the industry to a more services-based economy, additional pressure was put on the services sector which successfully managed to improve its energy intensity [3]. Additionally, natural gas and electricity significantly increased their share throughout the years, constituting the two most important fuels of the services sector since the middle 1980s, when petroleum's popularity started declining remarkably. The industrial sector followed a different course but reached the same destination, regarding its most used fuel types. In the future, heating and domestic hot water are expected to be increasingly electrified, with heat pumps supplying the majority of the energy demand, in the UK building sector. Different electrification percentages can be found in the literature depending on the scenario used but the Department for Energy and Climate Change estimated 80% of the residential space and water heating and 90% of non-residential heating to be delivered by heat pumps, by 2050 [4].

Regarding the sector's impact on the environment, buildings accounted for 33% (152.1 $MtCO_2e$) of the UK's total greenhouse gases (GHG) emissions, in 2016. For the same year, non-residential buildings, consisting of the business and the public sector, were responsible for 15% of the overall GHG emissions [5].

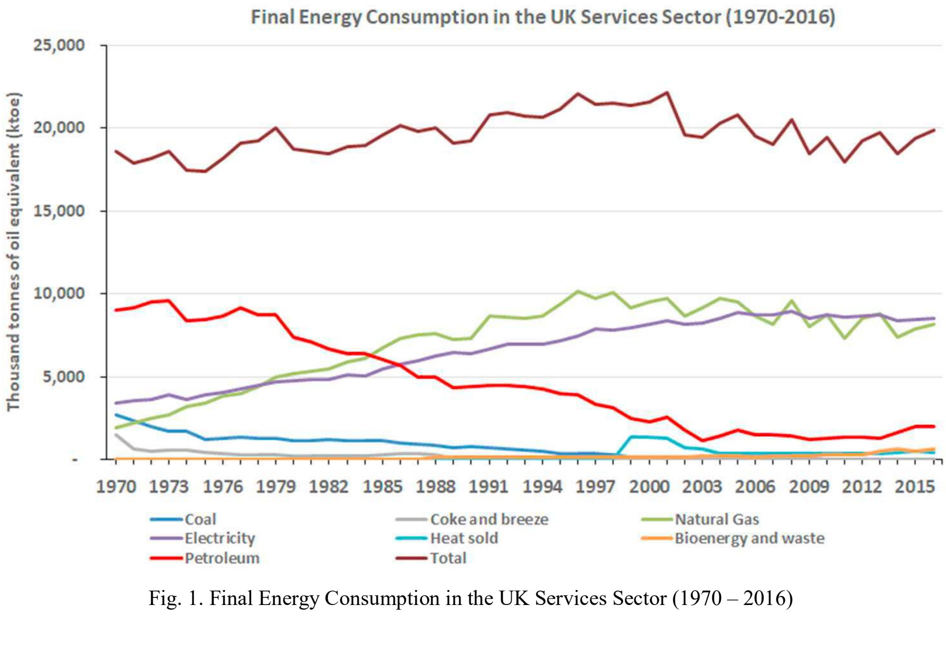

Fig. 1. Final Energy Consumption in the UK Services Sector (1970 – 2016)

2. Buildings as a component of the Smart Grid

Looking at the sector from a global perspective, IEA points out that buildings are responsible for 80% of the total final energy use. Consequently, a transformation of the sector will bring additional benefits for other sectors as well, considering that half of the electricity used is consumed by buildings. Electrical savings will be of fundamental importance for the power sector as expanding the electrical capacity can be avoided, with reduced expansion needs for the transmission and distribution network. IEA also highlights the fact that the building sector is a key part of the energy system and will play a major role in the decarbonisation of the power network [6].

The present power network has adopted a conventional architecture which is expected to be replaced in the future by the so called Smart Grid. The Smart Grid incorporates interactive real-time infrastructure of dynamic nature, is more resilient and more efficient. Controls, automation and IT technology are used to enable a two-way communication between the customers and the grid operator. In this way, all the technologies combined make the Smart Grid components able to adapt and respond digitally to the continuously changing energy demand of the end users. Additionally, the Smart Grid can successfully integrate renewable energy sources (RES), energy storage systems (ESS), the building sector and distributed generation into the network, promoting an efficient and reliable delivery of power through demand response. Also, consumers have the opportunity to participate in the electricity market and control their electricity consumption. Therefore, the Smart Grid has the capacity to “create a revolution in the building sector” and more specifically with Smart Buildings [7].

Buckman et al. [8] reviewed the academic and industrial literature to define Smart Buildings. The authors concluded that energy and efficiency, longevity, comfort and satisfaction are the four drivers for building progression that smart buildings must meet. This is feasible only when they integrate four elements as one adaptable building system: intelligence, enterprise, control and materials and construction. In addition, Smart Buildings can achieve adaptability through an increased amount of information from different sources. Their strong relationship with the Smart Grid is also mentioned, with Smart Buildings being self-aware and grid-aware, prioritising real-time demand side response.

However, different definitions and suggestions can be found in the literature for the future of the building sector. Active Buildings are expected to incorporate several smart grid features and use innovative technologies, especially on-site RES and energy storage, to become active participants of the energy network, instead of passive energy consumers. They should have the capacity to respond to real-time electricity prices and change their energy demand through a two-way dynamic interaction with the grid. There is no commonly accepted definition of Active buildings; however, their unique and robust relationship with the grid is highlighted and recognised [9].

Other building definitions focus on the amount of the consumed energy and carbon emissions. Kylili et al. [10] defined Zero Energy Buildings (ZEBs) as buildings with zero carbon emissions on an annual basis. The utilisation of RES and other suitable technologies is critical in order for ZEBs to meet their objective while smart energy management is only possible by using smart appliances, smart metering, smart demand response and advanced ESS. The authors support that the ZEB definition is open to many different interpretations as zero energy could refer to net zero site energy use, net zero source energy use, net zero energy emissions and net zero costs. Buildings must work in synergy with the grid to relieve pressure on the infrastructure. By using electricity storage, they will be capable of shifting their electrical loads effectively, becoming distributed energy storages themselves and providing balancing services to the grid and assistance under specific circumstances should power imbalances take place, for example [7].

3. The concept of Smart Grid Optimised Buildings

It is clear that numerous definitions exist regarding the future of buildings, as described in the previous section. The aim of the current paper is to present the concept of Smart Grid Optimised Buildings (SGOBs), a novel concept first presented in [11] that builds on the description and characteristics of both smart and active buildings, and demonstrate the operation of a specific building design. A SGOB makes use of its embedded energy systems to respond to any notifications issued by the smart grid, by adjusting its energy demand, accordingly. However, demand response as an operation is not sufficient to define the innovative nature of this building type. SGOBs make the best use of the available resources, meet their obligations to their occupants and are actively engaged with the energy network by responding to the dynamic nature of electricity prices.

ESS should be utilised by SGOBs in order for them to be fully engaged in a bidirectional exchange of power with the smart grid and have the capacity to provide balancing services. It is also hypothesised that by configuring their building design and the ESS specifications and operational strategy, SGOBs can be techno-economically optimised for the needs of the smart grid. Therefore, they are anticipated to have specific design and ESS characteristics, constituting a building type that significantly differs from zero energy or low carbon buildings [11]. It should be highlighted that the balancing services market was worth £1 billion in 2014 [12], indicating the potential financial opportunities for SGOBs as energy storage vectors in the energy market. Nevertheless, this will only be possible by establishing a proper regulatory framework with specific financial motives and rewards for the participating buildings.

The current paper presents the first results from a simulated non-residential building, capable of shifting its daily energy demand and therefore adapting its daily electricity profile, by using its battery storage system (BSS) to respond to real-time electricity prices. Concerning its loads, the building is assumed to be fully electric, enabling in this way the potential for a full interaction amongst the building, the BSS and the power network. In this context, the continuously increasing usage of electricity as the primary fuel, in the commercial and services sector, and the expected electrification of heating and hot water through heat pumps should also be taken into serious consideration.

4. Methodology

The methodology of the current research consists of three main components, already mentioned as the major elements of SGOBs: building design, real-time electricity pricing and battery storage. The software used, the dispatch strategy adopted, the assumptions considered as well as obtaining the necessary data are described in this section.

4.1 Building Modelling

For the needs of the energy simulation, the commercial software DesignBuilder and its integrated EnergyPlus engine were used to model a heavyweight square non-residential building, 30% glazed and located in Birmingham, England, United Kingdom. Guidelines and standards from both the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Chartered Institution of Building Services Engineers (CIBSE) were used and applied in every aspect of the building design, activity, equipment, lighting and the heating, ventilation and air-conditioning (HVAC) system. The ASHRAE 55.1 standard was used to assess the thermal comfort of the building's occupants and the operative temperature was employed for temperature control, using the HVAC set-points.

Regarding the building's loads, equipment has a 11 W/m^2 power density, LED lighting 12 W/m^2 with an occupation density of 12 m^2/person. The auxiliary energy that includes fans, pumps and controls is considered constant throughout the year and equal to 7 kWh/m^2. The building is mechanically ventilated to provide fresh air at 10 L/(s·person). A heat pump is used for both heating and cooling purposes, with seasonal coefficients of performance (SCoP) 3.5 and 5, respectively. The building's envelope meets all the relevant UK Part L Regulations, having insulation similar to the Notional Building [13]. More specifically, the thermal transmittance values of its envelope, external walls have a U-value of 0.26, the ground floor 0.22 and the flat roof 0.18 W/(m^{2}K). The air-tightness of the building is excellent with an air infiltration of 2 m^3/(m^2·hour) at 50 Pa. Regarding its size, there is one ground level and three storeys above it; hence 4 storeys in total. Each floor has a 625 m^2 area that consists of the main office area (589 m^2) and a small lift/stairway area, located at its center (36 m^2). Finally, the building is assumed to keep the same working hours for all weekdays (8 am – 6 pm) while it is closed on weekends and the UK bank holidays.

4.2 Real-Time Pricing Data

Nord Pool is the largest electrical energy market in Europe, having been appointed Nominated Electricity Market Operator (NEMO) in 15 European countries. Customers are able to trade in power spot markets, day-ahead and intraday power auctions. In order to be able to engage in bidirectional power exchanges, it is assumed that buildings in general and SGOBs have access to the Nord Pool energy market, and more specifically to the day-ahead market, which constitutes the main arena for trading power [14]. In this way, SGOBs and their integrated BSS know in advance the hourly real-time prices of the following day (£/MWh) and can optimise their operational-dispatch strategy on a daily basis, considering the set of the 24 hourly prices and the respective building loads.

As the day-ahead pricing represents only the wholesale cost of electricity, additional charges must be applied in order to calculate a realistic final price for the end user, the building. According to Ofgem [15] and the consolidated segmental statements released annually by the power companies, the wholesale costs are responsible for 36.3% of the total electricity bill, which includes network costs, operating costs, VAT, environmental and social obligation costs, as well as the supplier pre-tax margin. For modelling purposes, the historical day-ahead hourly electricity prices for the calendar year 2017 were provided by Nord Pool and the wholesale cost of electricity was assumed to be 36% of the total final cost. This percentage was used to calculate the retail cost of electricity (£/kWh).

4.3 Energy Storage Modelling & Operational Strategy

A battery storage model was created in MATLAB that receives the building energy loads generated in DesignBuilder and the Nord Pool real-time prices as an input. Regarding the energy storage methodology, an arbitrage optimisation algorithm for large scale energy storage, such as pumped hydro, was used after implementing a number of important changes and constraints in order to adapt it to the building scale BSS. The description and operation of the original algorithm can be found in detail in [16], [17] and [18]. The original algorithm uses as an input year-ahead hourly electricity prices, trying to optimise the charge-discharge pairs so that the ESS can charge at the cheapest prices (pump operation) and discharge when electricity reaches its most expensive values (turbine operation). Two efficiencies are considered in total, one for charging and one for discharging, to investigate whether it's financially cost-effective for the ESS to operate. The algorithm ends when all the hours of the year have been examined. Operational bottlenecks apply to avoid exceeding the maximum state of charge (SOC) and to make sure the energy added or removed from the ESS are in accordance with the system's charging and discharging capacities.

Changes were implemented in order to make the transition from a pump/turbine system and year-ahead arbitrage to a BSS and day-ahead building arbitrage. The BSS consists of a lithium-ion battery and a bidirectional converter (rectifier & inverter) that converts the current when needed, as the battery uses direct current (DC) and the electrical grid alternate current (AC). Four efficiencies are used, one for charging and one for discharging, along with the rectifier/inverter efficiencies to calculate the marginal cost of production, compare it with the maximum electricity price and evaluate if the BSS should operate. Regarding structural differences, instead of one annual arbitrage optimisation that takes place in the original algorithm, the BSS building algorithm performs one optimisation per day to determine the daily optimal BSS operation. Further operational bottlenecks were added to ensure the energy exchanges between the battery and the grid do not violate its minimum and maximum SOC requirements.

The most important change came with the addition of two qualitative constraints in order for the BSS to consider the hourly building loads before deciding the operational strategy for each hour of the day. The battery is not allowed to discharge if the building's energy activity is minimal (below a specific power threshold, e.g. 5 kW) as this would mean that there are no significant building loads to meet. Similarly, the battery will not charge if the building loads are higher than the same threshold as this would make the battery charge during the day and working hours, resulting in higher peak loads. For modelling purposes, this threshold is calculated as the average load of the first calendar day when the building's activity is minimal. The BSS operation is instructed to discharge its entire capacity during the most expensive hour(s) of the day. If the discharged energy is more than the energy required for the building, the excess electricity is exported to the grid and a feed-in tariff equal to the real-time retail price of the hour is assumed as a revenue. Finally, a lithium-ion battery of 120 kWh was considered along with an inverter/rectifier capacity of 70 kW and 40 kW, respectively. The minimum battery SOC was set at 10%, resulting in a usable capacity of 108 kWh. Charging, discharging and the rectifier efficiencies were assumed to be constant at 96%, while the inverter's performance was set as a function of the ratio between rated and hourly power.

5. Results & Discussion

5.1 Building Energy loads

The results from the Building simulation are shown in Figure 2 where the monthly electricity demand can be seen per building sector. The majority of the loads originate from the building's equipment, followed by lighting loads and the auxiliary energy used. It can be observed that the heating loads are minimal due to the insulation and the low U-values applied for the building's envelope. Cooling is insignificant and present only during the summer months, as an economiser is deployed to provide free cooling when the outdoor temperature is lower than the indoor temperature. The breakdown of the annual energy consumption per sector is equipment (45%), lighting (32.4%), auxiliary energy (14.3%), heating (5.5%), cooling (1%) and domestic hot water (1.8%). It should be noticed that the monthly values for certain sectors can be different for each month, despite the power consumption being constant throughout the year, as the value of the total energy is dependent on the total number of weekdays included. The building's total annual energy demand is 122,642 kWh or 49.1 kWh/m^2. The most demanding month of the year is January due to the additional heating loads required, with a total energy consumption of 13,469 kWh or 5.39 kWh/m^2. Finally, there were only 48 discomfort hours for the entire year which correspond to 1.8% of the total working hours of the building.

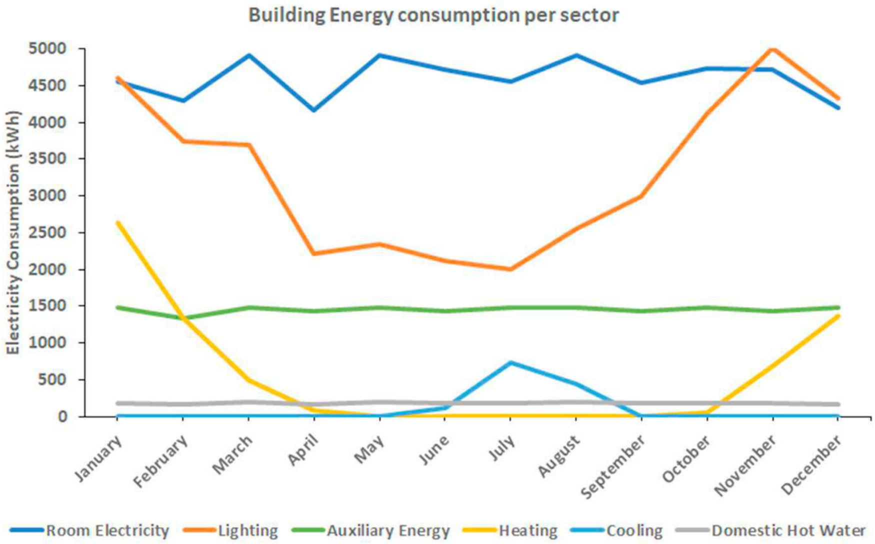

Fig. 2. Building Energy Consumption per sector

5.2 Real Time Pricing Data

The Nord Pool wholesale pricing data were converted from their original form to the total retail cost, following the methodology described in section 4.2. There is a significant fluctuation throughout every 24-hour period while it can be noticed that the difference between the daily maximum and minimum price can be substantial, in terms of energy costs. Spikes can be observed to have taken place from time to time and it is worth noting the minimum and the maximum retail prices of the year were £0.038 and £0.3657, respectively. Given these fluctuations, battery storage can be introduced to take advantage of the pricing differences and make the building responsive and adaptable.

5.3 Day-ahead arbitrage & Battery Storage Results

Both the original loads of the building and the loads using battery storage are shown in Figure 4, for five weekdays of July (Monday to Friday, from left to right) and a Saturday which is a non-working day. The loads can be compared by looking at the black solid and the black dash-dotted lines, noting that there is an overlap for the hours of the day during which the BSS does not operate. At the beginning of each 24-hour period, the MATLAB model identifies the daily cheapest hours that usually belong to the early hours of the day in order to charge the battery at its full capacity. Later, the most expensive hours of the day are also identified and provided there is building activity and active building loads, the battery discharges the previously purchased energy to take advantage of the price difference.

Utilising the BSS results in peak shaving and load shifting as a significant number of loads are moved temporally from peak to off-peak hours and either the duration (20/7 & 21/7) or the value (17/7 & 19/7) of the highest daily peak load is reduced. The impact of the battery operation is highly dependent on the distribution of the real-time prices and

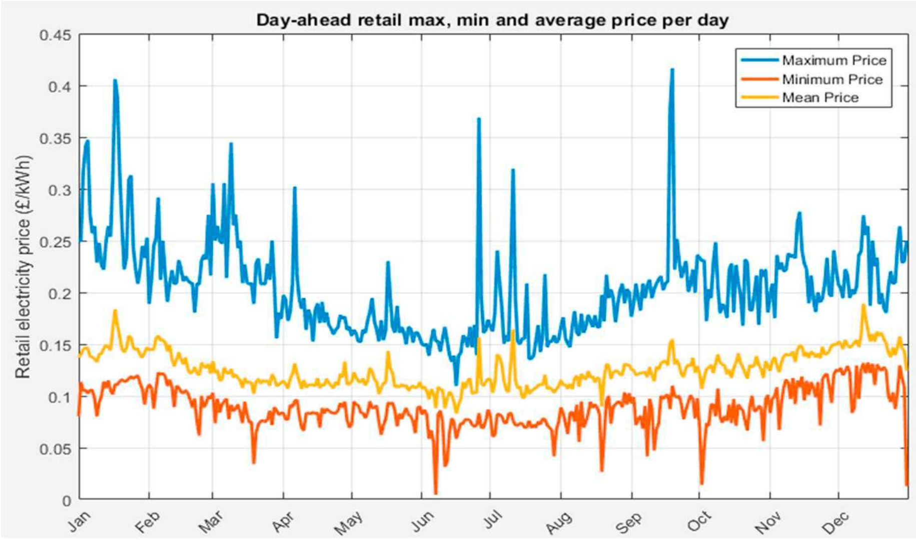

Fig. 3. Maximum, minimum and mean retail electricity prices per day (2017)

the building's energy demand and working hours; therefore, the exact battery impact varies per day. Additionally, when the energy discharged by the battery is higher than the building's demand, the remaining energy is exported back to the grid. The exports take place during all the days presented as for the month in question the size of the inverter exceeds the peak load value per day. This occurs as the BSS is designed to discharge the entire battery content at the most expensive electricity prices to profit without examining how the inverter's capacity compares with the building loads of the hour. Also, the difference between the loads with storage and the battery charging loads are attributed to the charging & rectifier losses. Finally, it can be seen that during weekends, the battery dispatch strategy is simpler as the building's activity is not considered and all the discharged energy is exported back to the grid.

In conclusion, the building, behaving as a SGOB, is able to adapt its energy demand profile and relieve pressure on the grid by utilising its integrated energy systems and responding to dynamic electricity prices.

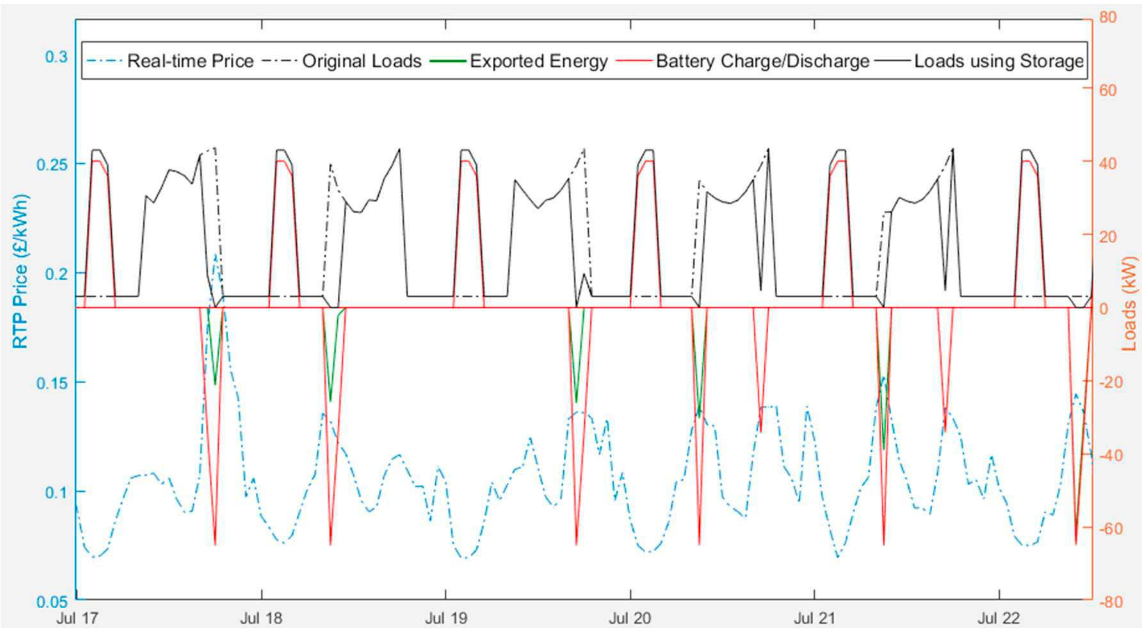

Fig. 4. Battery Storage altering the original building's electricity demand

6. Conclusions & Future Work

The building sector constitutes a significant component of the current power network and the future smart grid. In this direction, the concept and the theoretical background of SGOBs have been presented and initial modeling results have demonstrated the operation of SGOBs with battery storage. It has been shown that buildings can become energy storage vectors and provide balancing services to the grid, adapting their loads and responding to real-time electricity prices. However, a proper regulatory framework and financial motives are needed for SGOBs in order to construct a feasible and cost-effective scheme as the BSS capital costs can be significant. Regarding future work, additional operational strategies will be applied (e.g. load leveling) while multiple building designs and techno-economic optimisation around the battery storage and converter sizing are essential towards defining the optimal design and energy system characteristics of SGOBs.

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References

[1] Allouhi A., Y. El Fouih, T. Kousksou, A. Jamil, Y. Zeraouli, and Y. Mourad. "Energy consumption and efficiency in buildings: Current status and future trends." *Journal of Cleaner Production* 109 (2015): 118–130, doi:10.1016/j.jclepro.2015.05.139.

[2] D'Agostino D., B. Cuniberti, and P. Bertoldi. "Energy consumption and efficiency technology measures in European non-residential buildings." *Energy and Buildings* 153 (2017): 72–86, doi:10.1016/j.enbuild.2017.07.062.

[3] Department for Business Energy and Industrial Strategy. *Energy Consumption in the UK*. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/633503/ECUK_2017.pdf [Accessed 10th June 2018].

[4] Fawcett T., R. Layberry, and N. Eyre. *Electrification of heating: the role of heat pumps*. BIEE Conference, Oxford, United Kingdom, 2014.

[5] Department for Business Energy and Industrial Strategy. *2016 UK Greenhouse Gas Emissions, Provisional Figures*. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/604408/2016_Provisional_Emissions_statistics.pdf [Accessed 24th January 2018].

[6] International Energy Agency. *Transition to Sustainable Buildings*. 2013. Paris: IEA Publications. Available from: https://www.iea.org/publications/freepublications/publication/Building2013_free.pdf [Accessed 23th February 2017].

[7] Kolokotsa D. "The role of smart grids in the building sector." *Energy and Buildings* 116 (2016): 703-708, doi:10.1016/j.enbuild.2015.12.033.

[8] Buckman A.H., M. Mayfield, and S.B.M. Beck. "What is a Smart Building?" *Smart and Sustainable Built Environment* 3(2): 92–109, doi:10.1108/SASBE-01-2014-0003.

[9] Bulut M.B., M. Odlare, P. Stigson, F. Wallin, and I. Vassileva. "Active buildings in smart grids - Exploring the views of the Swedish energy and buildings sectors." *Energy and Buildings* 117 (2016): 185-198, doi:10.1016/j.enbuild.2016.02.017.

[10] Kylili A., and P.A. Fokaides. "European smart cities: The role of zero energy buildings." Sustainable Cities and Society 15(2015): 86–95, doi:10.1016/j.scs.2014.12.003.

[11] Georgakarakos A.D., M. Mayfield, A.H. Buckman, S.A. Jubb, and C. Wootton. "What are Smart Grid Optimised Buildings?". In: Young M. (ed.) *Living and Sustainability: An Environmental Critique of Design and Building Practices, Locally and Globally, AMPS Conference 9, 08 – 09 February 2017, London, United Kingdom*: AMPS Publication Series 8; 2018, p. 21–36.

[12] National Audit Office. *Electricity Balancing Services*. Available from: https://www.nao.org.uk/wp-content/uploads/2014/05/Electricity-Balancing-Services.pdf [Accessed 19th August 2016].

[13] Communities & Local Government. *National Calculation Methodology (NCM) modelling guide (for buildings other than dwellings in England and Wales)*. Available from: https://www.uk-ncm.org.uk/filelibrary/NCM_Modelling_Guide_2013_Edition_20November2017.pdf [Accessed 10th January 2018].

[14] Nord Pool. *The Nord Pool Energy Market*. Available from: https://www.nordpoolgroup.com/ [Accessed 22th May 2018].

[15] Ofgem. *Breakdown of an electricity bill*. Available from: https://www.ofgem.gov.uk/data-portal/breakdown-electricity-bill [Accessed 10th July 2018].

[16] Barbour E., G. Wilson., P. Hall, and J. Radcliffe. "Can negative electricity prices encourage inefficient electrical energy storage devices?" *International Journal of Environmental Studies* 71(6) (2014): 862–876, doi:10.1080/00207233.2014.966968.

[17] Staffell I., and M. Rustomji. "Maximising the value of electricity storage." *Journal of Energy Storage* 8 (2016): 212–225, doi:10.1016/j.est.2016.08.010.

[18] Connolly D., H. Lund, P. Finn, B.V. Mathiesen, and M. Leahy. "Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage." *Energy Policy* 39(2011): 4189-4196, doi:10.1016/j.enpol.2011.04.032.0