The role of active buildings in the transition to a net-zero energy system

A white paper on behalf of the Active Building Centre Research Programme

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Executive summary

An active building is one that interacts with the local and whole-energy system. It, therefore, has intelligence and the facility to modulate load and export energy to networks. In its simplest form, it is either energy neutral or acts to minimise local energy imbalances to reduce congestion, defer network investment while improving resilient and maintaining system security. In its full form, it interacts with the GB whole-energy system providing services that the system needs. Using a range of innovative technologies, active buildings can offer both energy and flexibility to local and national network operators.

The Active Building Centre Research Programme aims to transform the construction industry to facilitate the UK's commitment to a transition to net-zero carbon emissions by 2050. The objective of this paper is to investigate the role and value of active building technologies in facilitating this transition.

First, we consider three key active building technologies: smart electric vehicle (EV) charging (and discharging); smart thermal energy storage (TES) and insulation of the building envelope. Using Imperial's Integrated Whole Energy System (IWES) model, we carried out illustrative studies quantifying the benefits of these technologies. The model balances local and national benefits, giving a holistic assessment of the value of the flexibility offered by foregoing active building technologies to the energy system considering different deployment levels for each technology in question. The aggregated electricity and heat demand was developed from the bottom-up modelling considering energy efficiency improvement. The IWES model optimises the energy system infrastructure and hourly operation of Great Britain (GB) future (2050) system considering spatial regional characteristics and interconnection with the EU. The study assumes an emission target of 30Mt CO_2e/year covering the emissions from electricity, heating, transport (all electrified), and hydrogen production. Future studies include studies on a system with zero emissions.

We find that using smart EV in active buildings as a source of flexibility can reduce the need for high-cost but firm low-carbon generation (e.g. nuclear) while, at the same time, increasing the ability to integrate more renewable energy sources (RES). Although nuclear generation can provide low-carbon energy continuously (not intermittent), it is relatively expensive and lacks flexibility, so it is economical if its presence can be minimised. The required total installed capacity of gas-fired generation decreases as flexibility from this source is displaced by active building flexibility. The modelling shows that smart EV can reduce total system costs by between £3 billion and £8 billion per year. Smart TES can also provide flexibility to the system by storing electricity as thermal energy and releasing it when required. Results indicate that smart TES can save total system costs by £1 billion to £2 billion per year. Building energy efficiency improvements were also modelled, and system savings of £6 billion to £7 billion per year were found for a high level of insulation. Savings improve for stricter carbon targets.

The aforementioned evolution in active buildings as a strategic player of the holistic approach to energy, reveals that there is an urgent need to prepare low-voltage distribution grids (LVDGs) for hosting millions of active buildings and mobile EVs. In this white paper, the main challenges of the LVDGs when faced with the increased penetration of active buildings are identified and discussed, to facilitate their inclusion and leverage the benefits of active buildings in supporting the UK decarbonisation strategy. These challenges include planning and reinforcement challenges, voltage and line flow issues and operational limits, and also market and economic challenges. These challenges are analysed in detail, and the important directions of the future of this field have been charted.

Recommendations

The current regulatory framework is not fully aligned with the net-zero agenda. Our illustrative modelling shows that active buildings have the potential to offer a very significant amount of flexibility through the key technologies of smart EV and smart TES, but there is no adequate mechanism to reward this flexibility. We suggest several options to solve this problem: access to markets for ancillary services via aggregators; a carbon credit scheme and a carbon price on the heat for fossil-based heating systems. The current electricity market design is also not ready for hosting small-scale participation of active buildings on LVDGs. Therefore, the participation of active buildings (directly or via aggregators) should be considered at the local as well as national level, i.e. in local as well as national markets. Also, incentive mechanisms need to be set to increase the benefits of active buildings in the planning and operation of LVDGs and more importantly, in moving toward a zero-carbon economy.

Whole system modelling also shows that total system costs are reduced significantly when active buildings have a high level of insulation. If active building heating is electric (by heat pump), incentives need to be found for this form of heating. Previous work by Imperial has shown that heating by a combination of gas[1] and electric heating is likely to be cheaper, so these options should not be disregarded.

With the use of information and communication technologies, smart metering and control devices, and also with the help of cloud/edge computing and block-chain technologies, active buildings could manage and organise a large number of devices in a manner not previously possible to provide services (e.g. Demand Side Response (DSR)) to the LVDGs. This is of great value due to the increased penetration of intermittent Renewable Energy Systems (RESs) into the energy networks, which can be supported through flexibilities in demand. According to an analysis done by Newcastle University on a real-world educational building, it was identified that 40% of electrical loads could be available for DSR events.

Last but not least, considering the large number of stakeholders who are active in this evolving area, a high-level strategy should be designed for the way forward that consider the market development and technology readiness level required for LVDGs to accommodate active buildings and their linked elements, e.g. EVs, PVs, storage devices, among others.

Key conclusion

Whole-system modelling has shown that significant savings in total system cost are achievable by an extensive rollout of active building technologies in the low carbon future. Their combined flexibility can allow a higher proportion of electricity production from renewables and simultaneously reduce the reliance on firm low carbon generation, such as nuclear power. Studies also showed that total system costs decline as building energy efficiency improves and that this trend is enhanced as carbon targets tighten.

Using whole-system modelling allows us to inform the selection and sizing of the technologies that go into active buildings. These assessments will be carried out as the Active Building Centre Research Programme identifies new active building technologies.

Due to the increasing share of active buildings in the energy systems, LVDGs would be affected and therefore cannot be considered as a passive network in future. Network modelling at the local level

[1] Natural gas, biogas or hydrogen.

helps us to understand the local constraints on active building implementation. Suitable policy regulation, market mechanisms, incentives and services need to be designed for active buildings to harness and unlock the full potentials of active buildings in LVDGs, suitable policy regulation, market mechanisms, incentives and services need to be designed for active buildings.

Introduction

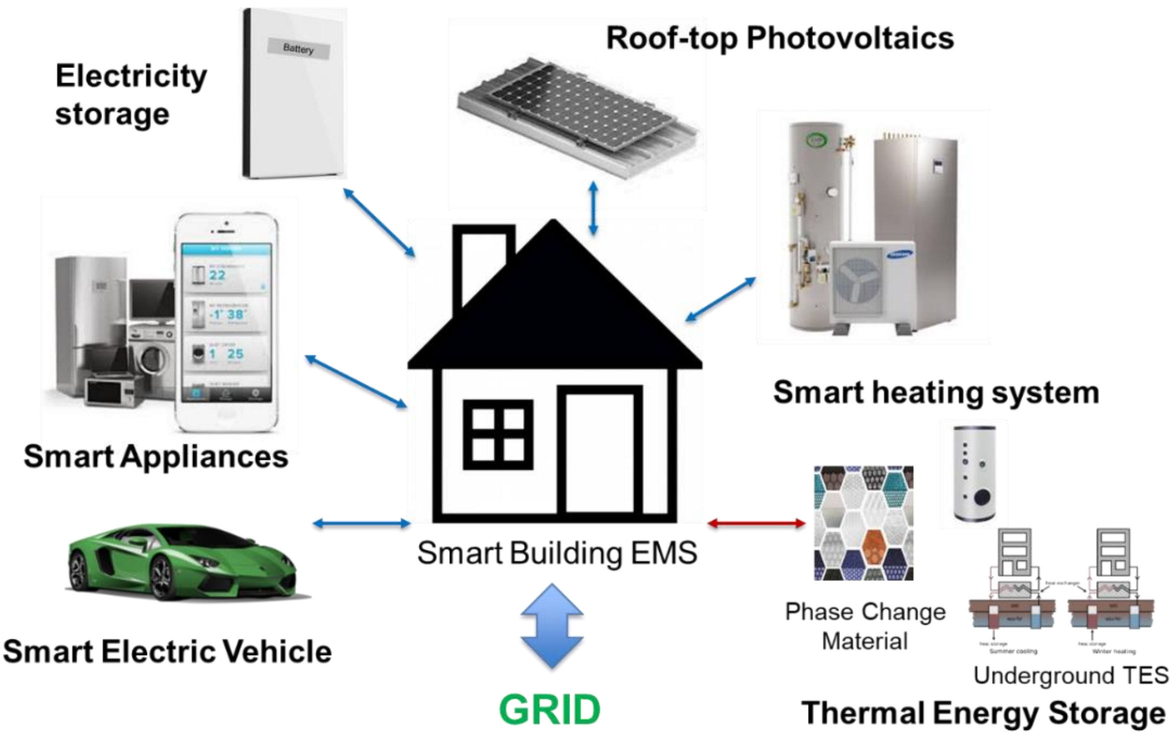

Figure 1: The active building concept

An active building is one that interacts with the local and whole-energy system. It, therefore, has intelligence and the facility to modulate load and export energy to networks. In its simplest form, it is either energy neutral or acts to minimise local energy imbalances to reduce congestion, defer network investment[2] while improving resilient and maintaining system security. In its full form, it interacts with the GB whole-energy system providing services that the system needs. Using a range of innovative technologies, active buildings can offer both energy and flexibility to local and national network operators. Figure 1 illustrates the active building concept.

The Active Building Centre Research Programme aims to transform the construction industry to facilitate the UK's commitment in a transition to net-zero carbon emissions by 2050. The objective of this paper is to investigate the role and value of active building technologies in facilitating this transition.

System flexibility is the ability to adjust generation or consumption in the presence of network constraints to maintain a secure system operation while giving reliable service to consumers. Due to the intermittency of the cheapest sources of renewable energy (wind and PV), an increasing level of

[2] Investment costs for the distribution (local) network operator (DNO) are influenced mainly by peak flows in the local network. Accommodating increased peak flows requires investment to reinforce the network (higher capacity cables, transformers and so on). Active buildings have the potential to limit these increases in peak flow.

low carbon flexibility will be required in the system if we are to reach net-zero for minimum cost. There are three core active building technologies capable of offering this kind of flexibility:

- Smart EV (different forms of smart electric vehicle charging including arbitrage, frequency response, vehicle to building (V2B) and vehicle to grid (V2G))[3]
- Smart thermal energy storage
- Energy efficiency[4]

Using a multi-vector whole energy system model developed at Imperial, we present illustrative studies investigating the potential of these technologies in reducing the cost of the transition to net-zero. Since energy consumed in buildings accounts for one-third of total annual energy consumption in the UK and heating contributes to the majority of this, we expect this potential to be very significant. For this initial study, we focus on understanding the system and cost implications of deploying different foregoing flexibility technologies. As current legislation requires all new buildings to have no connection to the gas grid from 2025, we focus on electric heating in this work. However, the option to replace natural gas with hydrogen for heating, using the current gas grid to transport it should not be ignored. Hydrogen heating and hybrid systems (combining electric and gas-based heating appliances) will be considered in future work.

We also consider the role of active buildings from a different perspective: their impact on the low voltage distribution grids (LVDGs). Adding a large number of active buildings to the local networks presents planning and operational problems for the network operators. There are some questions to discuss, including:

- What challenges in the planning and reinforcement of LDVG will a rollout of active buildings present?
- How will active buildings change the operation of the LVDGs?
- Whether the current market frameworks are suitable for active buildings, and if not, what are the appropriate new market mechanisms that need to be developed to facilitate active buildings?
- What services can be offered to LVDGs by active buildings?

This discussion points the way forward for the Active Building Centre Research Programme, where the local grid is concerned.

The rest of the paper is arranged as follows. In Section 2, we look at the role and value of active buildings in the transition to a low carbon system. We consider the three key technologies described above and discuss results from our whole-system modelling. In Section 3, we turn to the LVDGs and discuss the impact of active buildings at a local level. We give an overview of LVDG operation and planning in the presence of active buildings, discuss the impact of active buildings on the LVDGs and finally look at the economic and market challenges. In Section 4, we present recommendations arising from our work. Finally, in Section 5, we present our conclusions.

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[3] Arbitrage is storing energy when it is cheap and discharging it when it is more valuable. Frequency response involves changing the demand on an electricity system to return the system frequency to close to its nominal value (50Hz in the UK). In this way total demand and generation can be balanced. V2B is using an EV battery to import or export power to an active building, in order to reduce building energy costs. V2G involves injecting power from an EV into the electricity grid.

[4] Although building energy efficiency typically comes from passive measures (mainly insulating the building envelope), we consider it as an active building technology because (as demonstrated in this paper) it has a large influence on system costs.

1 The role and value of active buildings in supporting a cost-effective transition to a low carbon energy system

Since energy systems need to be planned so that they can cope at times of system peaks, uncertainty in the amount of capacity in the system will lead to the procurement of unnecessary excess installed capacity. Also, in the running of energy systems peak demand is typically supplied from the most expensive generation. For these reasons, knowing the contribution that active buildings can make to the energy system will reduce uncertainty and therefore significantly reduce system costs.

1.1 The integrated whole energy system model

The Integrated Whole Energy System (IWES) model incorporates the modelling of various technologies and captures the interaction across different energy carriers. This is illustrated in Figure 2. For example: where actions in the heating system (such as retaining hot water stores) can complement measures in the electricity system, the model can use these as opportunities to minimise the overall energy system costs. The IWES model also optimises the energy supply, transmission and distribution infrastructure requirements and the additional system services (e.g. balancing) required in each of the above scenarios. In summary, the IWES model minimises the total cost of long-term infrastructure investment and short-term operating cost, while considering the flexibility provided by different technologies and advanced demand control, and meeting carbon targets. The IWES model includes electricity, gas, hydrogen, transport and heat systems, simultaneously considering both short-term operation and long-term investment decisions, covering both local district and national/international level energy infrastructure. It also includes carbon emissions and security constraints. The spatial and temporal resolutions of IWES are illustrated in Figure 3 and Figure 4, respectively.

Through the IWES model, opportunities for flexibility provision through active buildings in providing support to short-term and long-term balancing in the power system are analysed across different vectors.

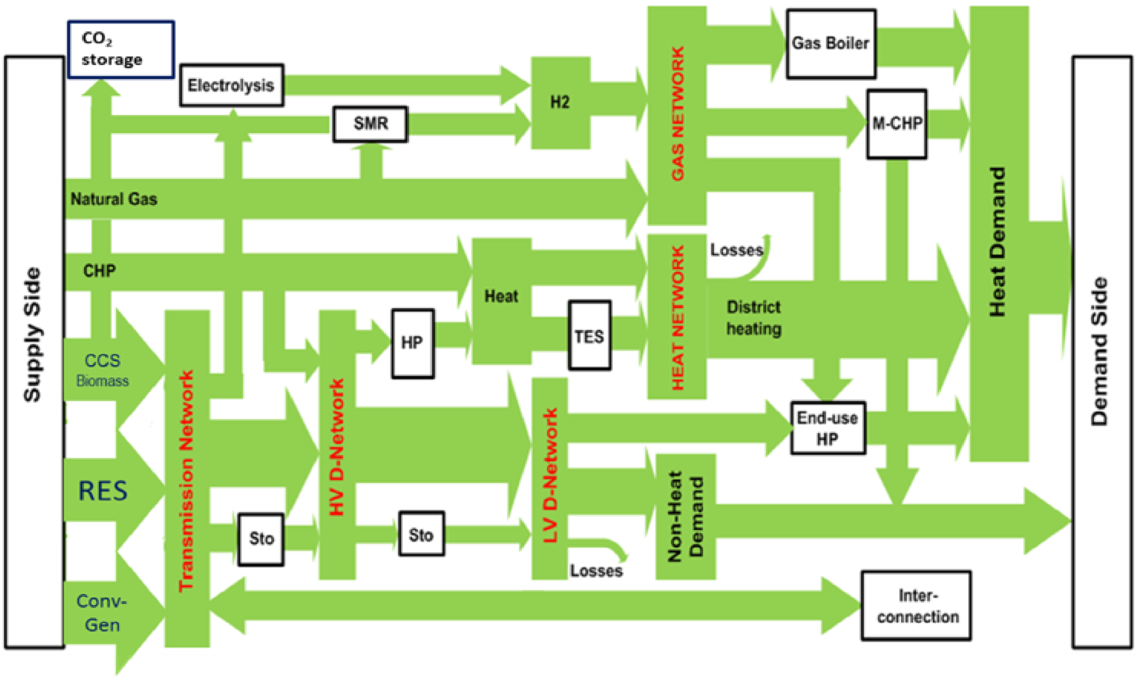
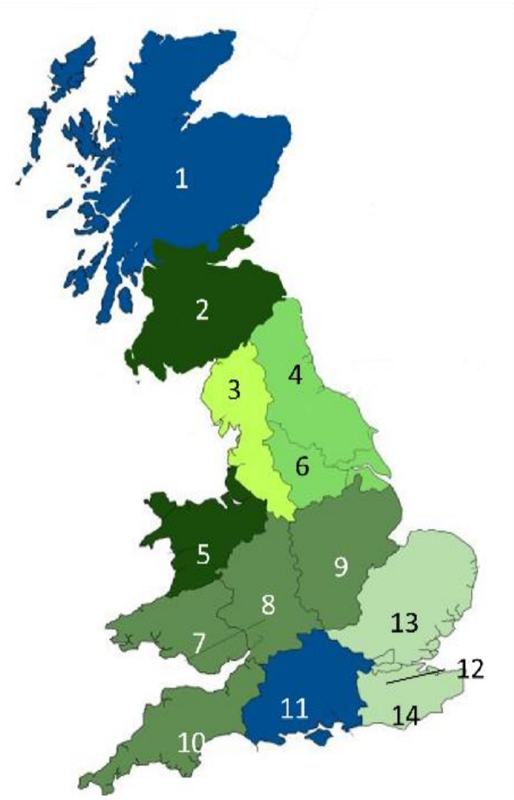


Figure 2: Modelling of technologies



Region	Region name
1	North Scotland
2	South Scotland
3	North West England
4	North East England
5	North Wales, Merseyside and Cheshire
6	Yorkshire
7	South Wales
8	West Midlands
9	East Midlands
10	South West England
11	Southern England
12	London
13	East England
14	South East England

Figure 3: Spatial resolution, considering both local & national level infrastructure

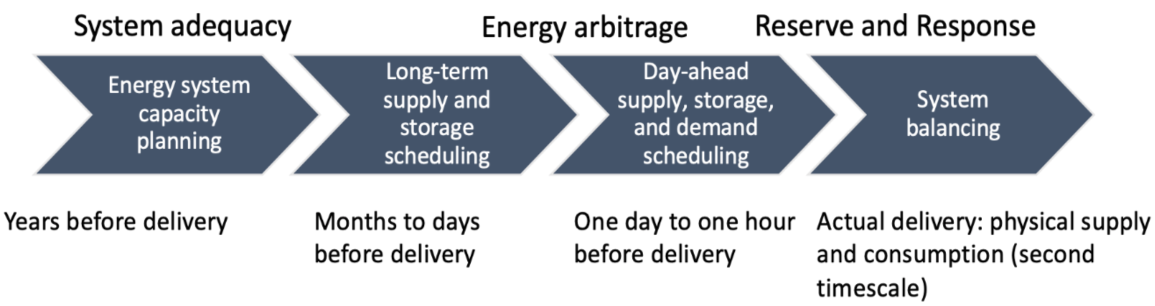


Figure 4: Temporal resolution of IWES

Due to various interactions between different levels of assets, the investment strategy for infrastructure at one level can influence investment at the other levels. For instance, the electrification of heat systems on the end-use side will drive:

- substantial investment in the electricity generation and network reinforcement particularly at the distribution network
- deployment of distributed flexibility such as demand-side response, and higher investment in energy storage particularly thermal storage
- the retirement of gas distribution and more conversion of gas appliances to electricity

Therefore, it is imperative to incorporate the whole-system perspective when designing active buildings and integrating them into energy systems. In this way, synergies between investment and operation of different technologies and local and national system objectives can be maximised.

To further demonstrate the significance of taking into account the synergies of local and national objectives, Figure 5 compares the cost savings delivered by adopting the whole system approach with those from the local distribution-centric approach. It can be observed that although the distribution-centric approach maximises the local savings, the investment decision is suboptimal from the whole energy system perspective. In the whole-system approach, cost savings in the distribution networks are like those for the local approach. However, savings from reduced OPEX (principally, the cost of burning gas in generators) are much greater, and savings in interconnection and transmission investment are also greater. This is because of the high value of utilising local end-user flexibility to displace the flexibility from flexible thermal generation (such as the combined-cycle gas turbines currently used to produce nearly 40% of our electricity and interconnection). Overall, cost savings are approximately doubled when a whole-system approach is taken.

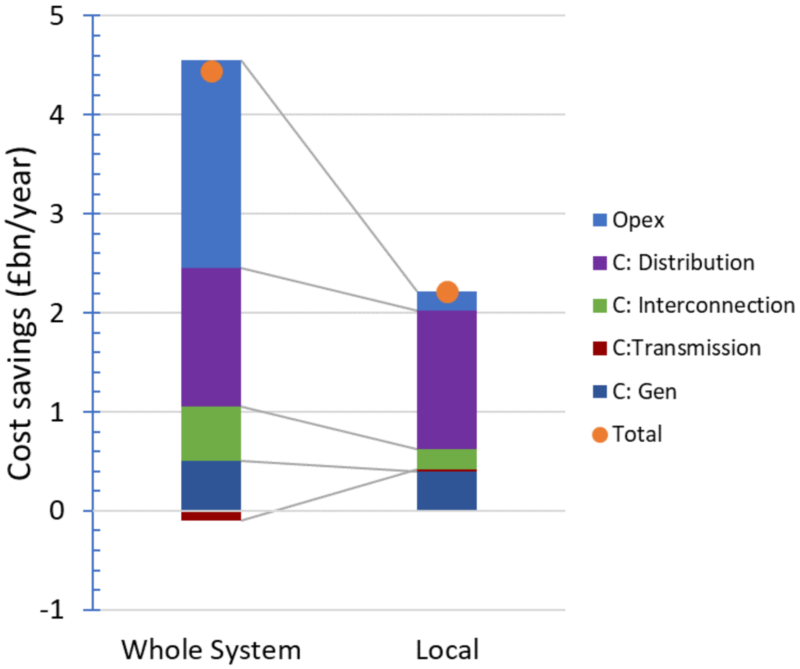


Figure 5. Whole system vs local control for maximising the value of end-user' flexibility

1.2 Whole-system benefits of active buildings

In this section, we present results from our preliminary studies of the value of active building technologies under the whole-system perspective. Our analyses are focused on the core active building technologies: integration of smart Electric Vehicle (EV) and smart Thermal Energy Storage (TES) into active buildings and building energy efficiency. For reasons given in the introduction, we consider only electric heating here.

1.2.1 Whole-system benefits of integrating smart electric vehicles into active buildings

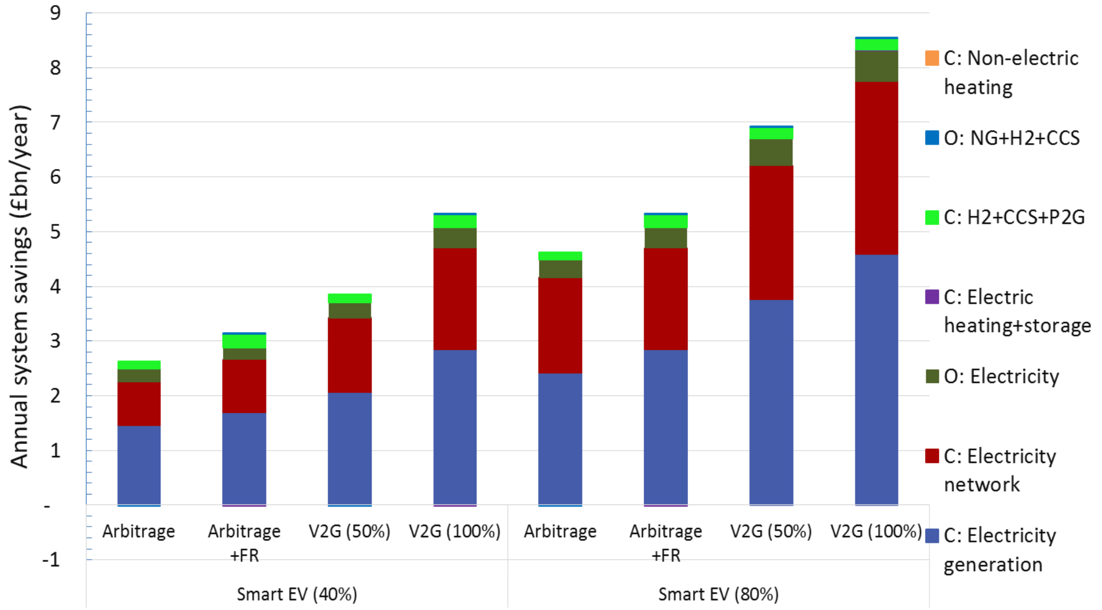


Figure 6. The Value of Smart EV Charging

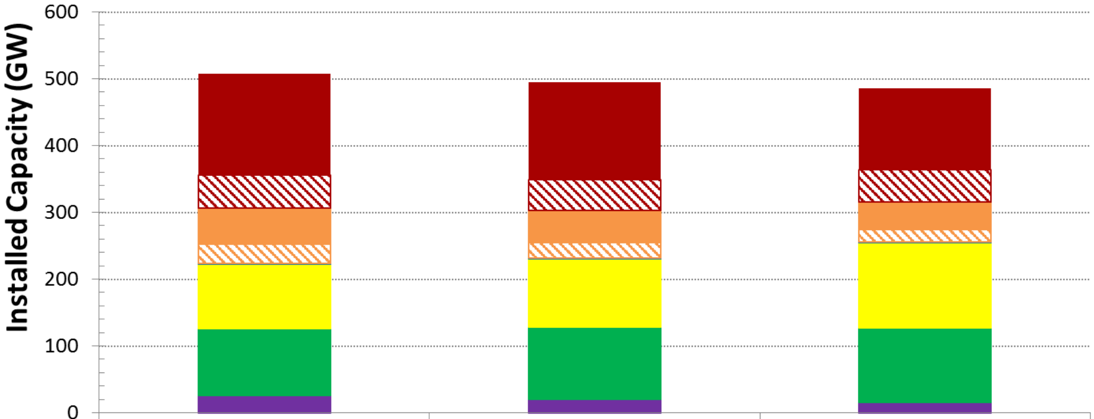
Our definition of smart EV here assumes that the flexibility available from smartly charging EVs can be utilised to varying degrees by the national grid, through the mechanisms of arbitrage, frequency response and Vehicle-to-Grid (V2G).[5]

We have applied our IWES model to estimate the value of smart EV to the energy system. All our scenarios assume that, in 2050, we have a fully electrified heat and transport system (light vehicles only) and a low-carbon target. The modelling is based on an emission level of 30Mt CO_2/year in 2050, covering the emissions from electricity, heat, gas, and transport (electrified). The results are compared with the counterfactual that no active buildings are adopted in the energy system, which is characterised by low flexibility. In Figure 6, the annual savings (in £billion/year) compared to the no active building counterfactual are plotted for various scenarios. Specifically, smart EV penetration levels of 40% and 80% are compared. Within these categories, four different versions of smart EV implementation are shown: arbitrage; arbitrage with frequency response; V2G at the penetration of 50% and V2G at the penetration of 100%. There is an evident trend that system savings increase as the flexibility from smart EV is increased. For comparison, in [1] a similar pathway, with all electric heating, was estimated to have an annual system cost of close to £90billion/year, so smart EV has the potential to reduce this cost by up to 10%. In fact, most of the value of smart EV is in reducing capital expenditure (CAPEX) in the electricity system (generation and networks). This implies that proper market frameworks are needed if the value of smart EV is to be fully realised.

Figure 7 and Figure 8 show how the UK electricity generation portfolio and generation mixes evolve as the level of smart EV flexibility increases. The same range of scenarios described above is compared

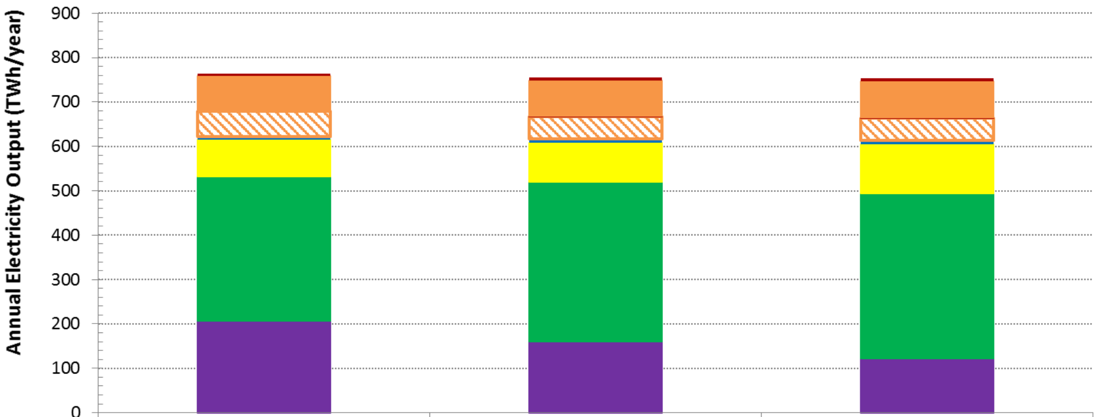
[5] 'Arbitrage' is storing energy when it is cheap and discharging it when it is more valuable. Frequency response involves changing the demand on an electricity system to return the system frequency to close to its nominal value (50Hz in the UK). In this way total demand and generation can be balanced. V2G involves injecting power from an EV into the electricity grid.

with a scenario with no smart EV. The required installed capacity of gas-fired generation (CCGT and OCGT) decreases as flexibility from this source is displaced by smart EV flexibility.



	No EV	Smart EV 40% with V2G 50%	Smart EV 80% with V2G 100%
OCGT	151	145	121
H2 OCGT	50	47	49
CCGT	54	48	41
H2 CCGT	28	23	18
Hydro	1	1	1
PV	96	101	127
Wind	100	108	112
Nuclear	26	20	16

Figure 7. Changes in the optimal electricity generation portfolio due to smart EV



	No EV	Smart EV 40% with V2G 50%	Smart EV 80% with V2G 100%
OCGT	7	7	7
CCGT	78	79	81
H2 OCGT	2	2	2
H2 CCGT	56	51	51
Hydro	8	8	8
PV	83	88	111
Wind	324.49	360	372
Nuclear	207	160	122

Figure 8. Annual electricity production by generation type

The figure shows that the integration of smart EV into active buildings as a source of flexibility can reduce the need for nuclear as a firm low-carbon generation technology while increasing the ability to integrate more renewable energy sources (RES). This effectively reduces the annual system costs due to the lower levelised cost of electricity (LCOE)[6] of RES compared with nuclear power. Moreover, increased flexibility from smart EV also reduces the security-driven requirement for firm capacity.

1.2.2 Whole-system benefits of integrating smart thermal energy storage into active buildings

Currently, natural gas boilers are the primary source of heating in the UK. In order to reduce emissions from the heating sector, it is essential to adopt low carbon heating technologies to replace natural gas boilers. There are two main options to achieve this: electric heating and hydrogen. Since heating by hydrogen would require connection of active buildings to the gas grid, which is against the government policy that no new build homes have such a connection from 2025, we only consider electric heating for active buildings.

Space and water heating is the largest contributor to domestic energy consumption. In the scenario where the heating is fully electrified, Thermal Energy Storage (TES) can significantly reduce CO_2 emissions by charging a thermal energy store when the carbon intensity of electricity is low and discharging it when it is high. More details of the analysis are given below.

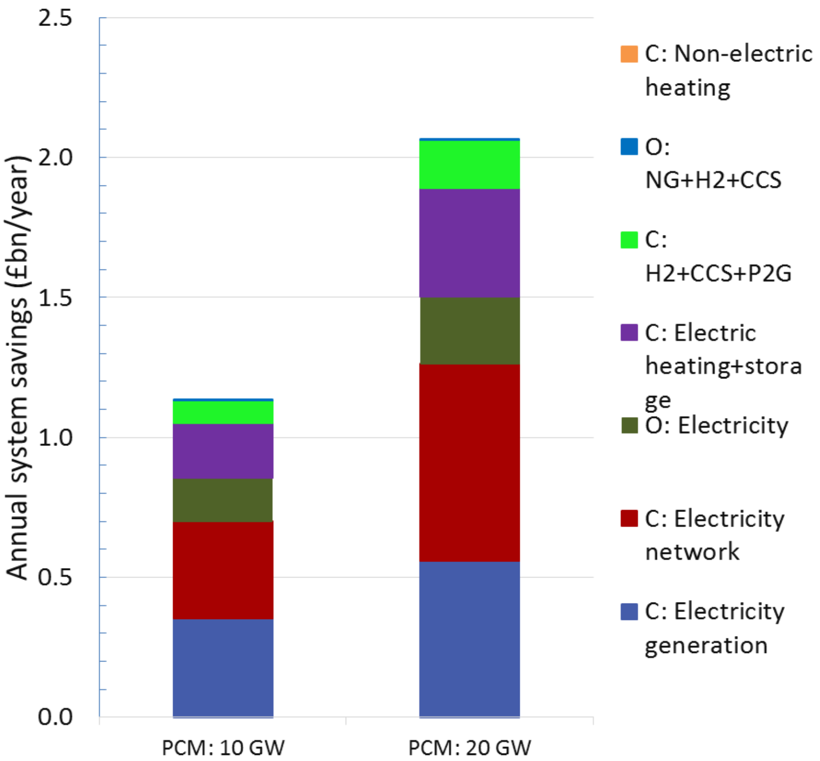


Figure 9. Annual system savings from thermal energy storage

There are two promising TES technologies being considered in the Active Building Centre Research Programme: Phase Change Materials (PCM) and thermochemical storage. There is no degradation in energy stored with time for either material. Although thermochemical materials have the potential of much higher volume energy density than PCMs, PCM is a well-established technology and is commercially available today, so our initial study will be focused on PCM-based TES.

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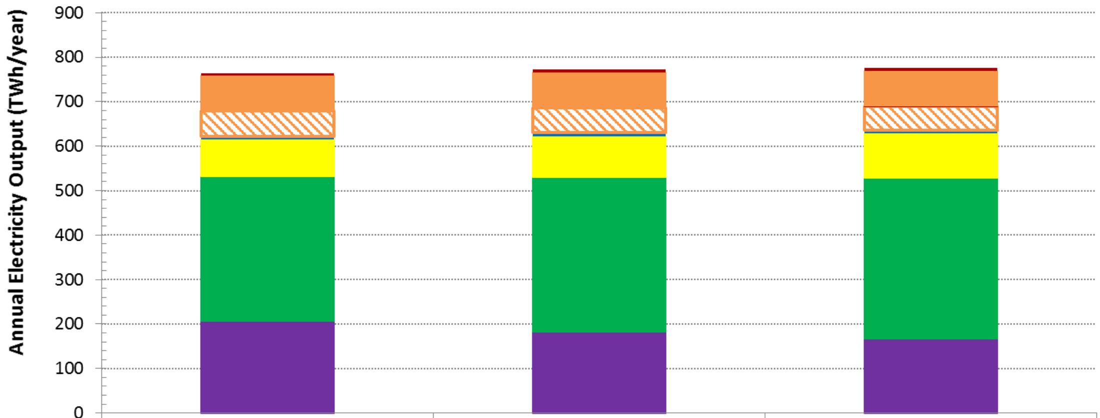
[6] The levelised cost of electricity (LCOE) is a measure that allows comparison of different methods of electricity generation on a consistent basis.

In the base scenario, we consider an energy system with the following 2050 targets: 30 Mt CO2/year; full electrification of heat and transport (light vehicles); large energy storage capacity; highly efficient TES (99%). This scenario is compared with the counterfactual with no active buildings, equivalent to a system with low flexibility.

In Figure 9, we demonstrate the annual system savings given by 10GW and 20GW of PCM TES (compared to the counterfactual). Given that the heating system is fully electrified, smart TES can provide flexibility to the electricity system by storing electricity as thermal energy and releasing it on demand. The gross system value of smart TES (excluding the capital cost of TES) is estimated at £103-£113/kW per year. As can be seen in Figure 12, 10GW/20GW of smart PCM TES can reduce annual system costs by £1.13/£2.08 billion per year. Savings are delivered across different sectors of the energy system, involving a reduction in both investment costs and operational costs. In order to realise these savings, proper market frameworks to recognise the value of smart TES would be required.

To further illustrate the impact of TES on the electricity system, we investigated how optimal electricity generation evolves with the increase in capacity of PCM TES, as shown in Figure 10. Scenarios with no PCM-based TES, 10GW of PCM and 20GW of PCM were simulated. It can be observed that TES can facilitate the integration of more RES with reduced dependence on nuclear power, especially in the context of a highly electrified heat system where TES enables stronger coupling between the heat and electricity sectors.



	No PCM	PCM: 10 GW	PCM: 20 GW
OCGT	7	7	7
CCGT	78	79	79
H2 OCGT	2	2	2
H2 CCGT	56	55	53
Hydro	8	8	8
PV	83	93	100
Wind	324.49	347	361
Nuclear	207	183	168

Figure 10. optimal electricity generation due to PCM-based TES

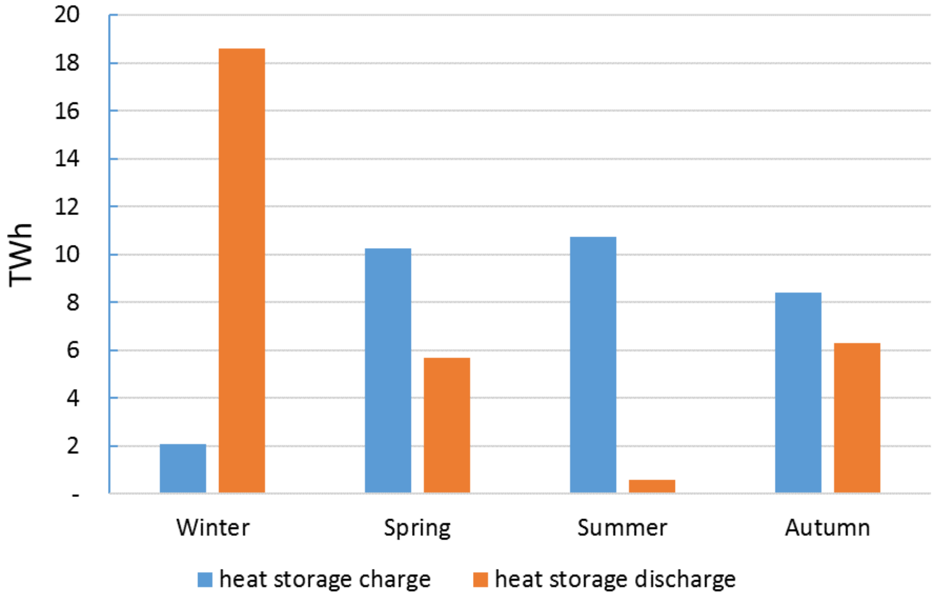


Figure 11. Charging vs discharging pattern for PCM-based TES

Figure 11 shows the charging and discharging pattern for the scenario with 20 GW of long duration TES. Overall, heat is stored, especially in summer, to be released in winter. Over 18 TWh of the stored heat is discharged over winter, compared with a total annual electricity output of approximately 760 TWh. In these preliminary studies, we have assumed that seasonal storage of this type is practical. This is likely to be the case, though it would require further development of thermochemical storage.

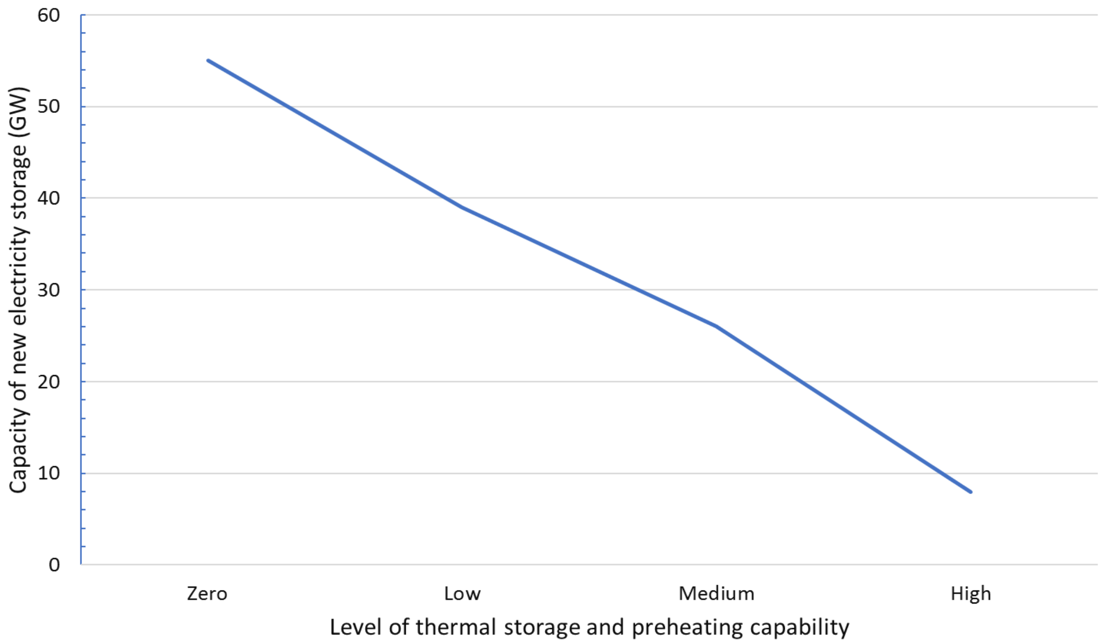


Figure 12. comparison of thermal and electrical energy storage

In Figure 12, we compare thermal energy storage with electricity storage. The graph shows an inverse proportionality between the two. This shows that there is a coupling of the two forms of storage, creating competition for flexibility resources across energy sectors.

1.2.3 Whole-system benefits of active building energy efficiency

The energy efficiency of a building is largely determined by the insulation of its fabric. The level of this insulation has a significant impact on the building's heat demand level. Improving building energy efficiency provides an alternative way to contribute to the cost-effective decarbonisation of the energy system. As insulation is improved, thermal energy consumption for space heating decreases linearly, driving savings across different sectors.

Figure 13 demonstrates the relationship between the level of building energy efficiency and the decomposed system costs. Here we look at the optimal heating technology portfolio under different carbon targets. For each carbon target, three scenarios with improved building energy efficiency (e.g., Low, Medium and High) are tested. It can be observed that when the building energy efficiency improves, the total system cost decreases. Specifically, the investment in district-heating technologies is gradually shifted to distributed-heating (end-use, such as air-source heat pumps) technologies, while large savings are achieved in the total investment in the heat sector.

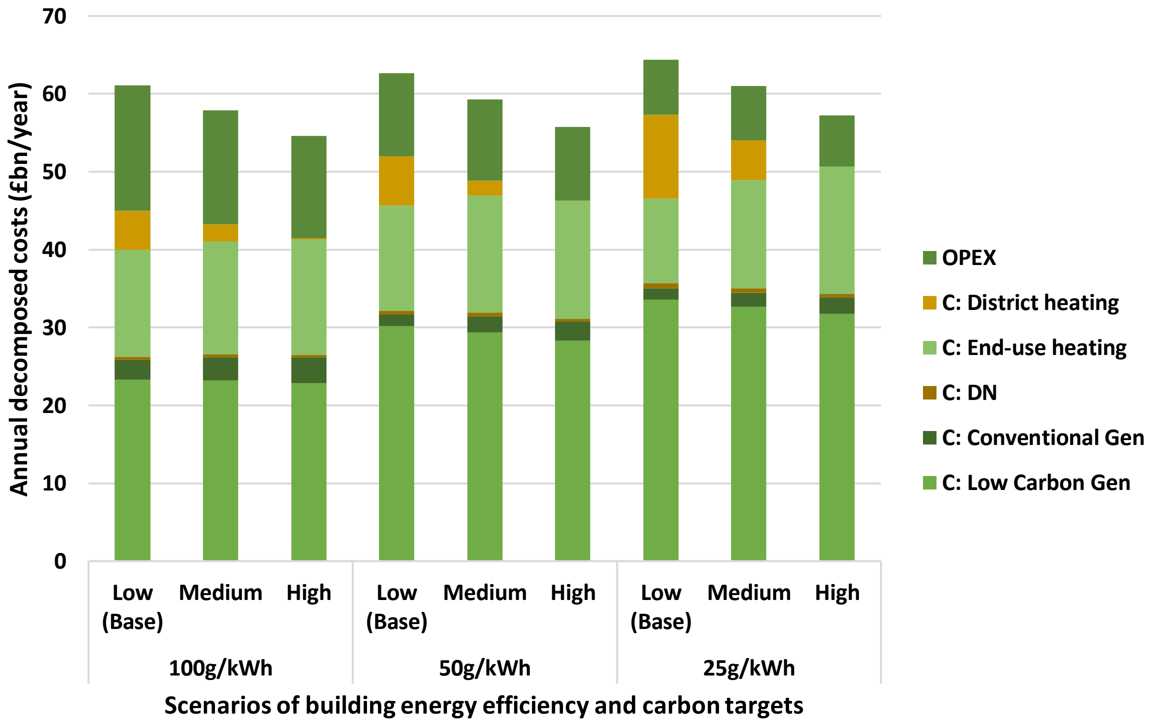


Figure 13. Impact of building energy efficiency on the system cost under different carbon targets

It is interesting to observe that a significant decrease in the investment in district heating occurs as building energy efficiency improves, while the increase in the investment in distributed heating is minor. This is because the district heat network (DHN) CAPEX mainly depends on the length of the pipeline. When the layout of consumers in a district has been determined, the potential capital cost of DHN in that district is also determined and will not be influenced by the variation in heat demand. Therefore, the lower the heat demand (kW), the higher the unit investment (£/kW) in DHN. Consequently, the optimal penetration level of DHNs decreases with improvement in building energy efficiency. In contrast, the optimal level of investment in distributed-heating technologies is influenced by two factors: first the penetration, which increases to compensate for the decrease in DHN penetration; and second the heat demand (kW) per household, which decreases with improvement in building energy efficiency. Therefore, the change in investment in distributed-heating technologies is minor across different building energy efficiency scenarios, due to these contributions largely cancelling out. This result indicates that the competitiveness of DHNs reduces when building energy efficiency improves.

Additionally, it is noticeable that the investment in low carbon generation (including nuclear and RES) decreases with improved building energy efficiency. The impact of the carbon target on the value of building energy efficiency improvement is demonstrated in Figure 14.

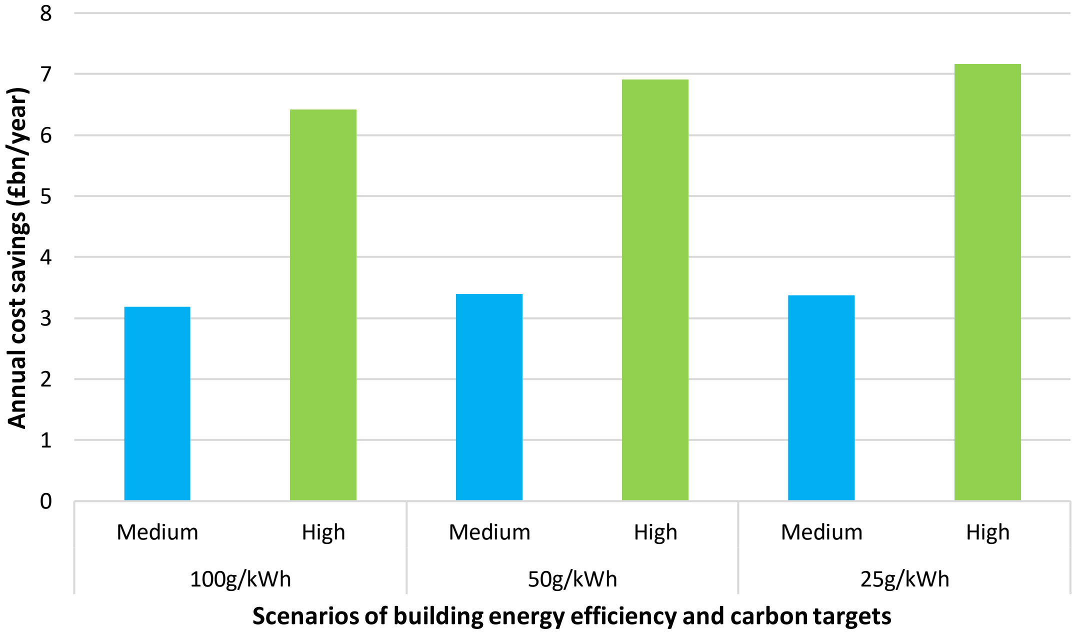


Figure 14. Savings through improved energy efficiency under different carbon targets

The key observation here is that the more demanding the carbon target, the more savings can be achieved through improved building energy efficiency. This result is more apparent in the “High” energy efficiency scenario, where we see cost savings of £6bn to £7bn per annum.

1.3 Challenges in whole-system modelling

One of the main challenges for the Active Building Centre Research Programme is the selection and sizing of technologies to place in active buildings. These questions can be addressed at the building level or the whole system level. The benefit of the IWES approach is that it quantifies the possible benefits for the whole system, given specific scenarios. It can, therefore, prevent the large-scale adoption of unsuitable technologies. There are, however, challenges in performing this type of analysis. There are many types of active building to consider and suitable archetypes need to be found to represent each of these. It is also necessary to consider geographical differences: thermal storage is of lower value in Cornwall than in Scotland, for example. Finally, appropriate scenarios need to be chosen.

1.4 Further work

Going forward, these results will be refined as more data comes in from Active Building Centre Research Programme demonstrators and will also be extended as we further develop our scenarios, and more active building technologies are considered. Moreover, we will consider different building types through a set of archetypes, and the effects of geographical differences will be further analysed.

As stated in the introduction, current legislation requires all new buildings to have no connection to the gas grid from 2025. However, the option to replace natural gas with hydrogen for heating, using the current gas grid to transport it, is a very attractive one. Previous work has indicated that this, or hybrid systems (combining electric and gas-based heating appliances), maybe the cheaper option [1]. These alternatives will be analysed in future work.

2 Impact of active buildings on the low voltage distribution grids

In this part of the white paper, we discuss the low voltage distribution grids that active buildings connect to directly. This contrasts with the whole-system approach above, that takes into account all three levels of the grid: Low Voltage (LV); High Voltage (HV) and Extra High Voltage (EHV). We identify the specific challenges to the LVDG operators in maximising the benefits of active buildings at the local level and supporting the transition to low carbon energy.

There are a number of questions to address:

- How can a high penetration of active buildings be effectively integrated into the Low Voltage Distribution Grids (LVDGs)?
- What is the best possible operation strategy for future LVDG operators, to improve network performance whilst considering the requirements and constraints of active buildings and the comfort of the residents?
- How will these active buildings be able to be energy-positive and participate in the provision of flexibility services (or any other possible/required services) for the LVDG?
- What might be an appropriate electricity market design to enable active buildings to participate in better operation of the LVDGs?
- What are the most appropriate incentive mechanisms for leveraging the potential of active buildings in enhancing LVDG operation?
- What will future LVDG energy management systems look like?
- What is the vision of the future of distribution network operation and planning, taking active buildings into consideration?

2.1 An overview of the LVDGs operation and planning in the presence of active buildings

According to UK standards, an LVDG is defined as a network with a maximum voltage level of 1,000 V [2]. Also, based on the international standard recommendation of the International Electricity Commission IEC-60038, the voltage level of three-phase, four-wire LVDGs is defined as 230/400 V [3]. It is the last stage of the power network, that directly connects to the end-users (including consumers, produces and prosumers). Hence, there are a very large number of nodes spread across the network. A comprehensive literature survey on the operation and planning of the LVDGs is presented in [3,4].

There are different challenges in the operation and planning of the LVDGs when considering active buildings. These are summarised in the following sections.

2.1.1 Challenges in the planning/reinforcement of LVDGs

Reinforcement of the LVDGs is necessitated when a new load area is created or when the existing LVDG can no longer respond adequately to operational problems. These may be violations in current or voltage limits caused by a change in the load level of the customers or the penetration of new intermittent energy resources like photovoltaic panels (PVs). The conventional solution for reinforcement of the LVDGs is expansion planning, but due to the development of the smart grid, there are some new alternatives to expansion planning, such as the use of demand side response (DSR) resources.

2.1.1.1 Reinforcement of the LVDGs via Expansion Planning

Just as in bulk power systems planning, the planning of LVDGs needs to take economic, technical and environmental factors into account. Economic factors include investment and operation costs, technical factors include reliability and/or voltage improvement, and environmental factors include CO2 emission reduction. Planners need to find an optimal solution taking all these factors into account. The traditional approach to LVDG planning is based on a deterministic strategy, but in the active distribution networks, many uncertainties need to be considered. While there is a substantial body of literature considering these uncertainties for DGs (both renewable and non-renewable), loads and EVs, there are specific uncertainties related to active buildings that need to be considered in planning studies. Here are some of the questions that need to be addressed in future planning studies:

- Considering the evolution in the penetration of technologies that use Direct Current (DC), is Alternating Current (AC) still the best choice for the design and operation of power networks, especially in LVDGs? For example, photovoltaics, EVs and batteries would all be more efficient if the inversion or rectification stage could be removed
- Considering the development in different building-level generation and storage devices, are the LVDGs a necessity? Is it an optimal solution?
- What is the vision of the future of distribution operation and planning, considering active buildings?

2.1.1.2 Reinforcement of the LVDGs via demand Side response

Use of DSR as a new source of flexibility is a promising method to defer investments in the LVDGs. This additional flexibility can assist the move to an energy system with more intermittent renewable generation. active buildings can be one of the important sources of DSR provision playing an important role in this area. Previous work by Newcastle University has identified the potential of DSR for an educational building which predominantly has an electrical load. The research showed that typically 40% of electrical load could be available for DSR events, see [5].

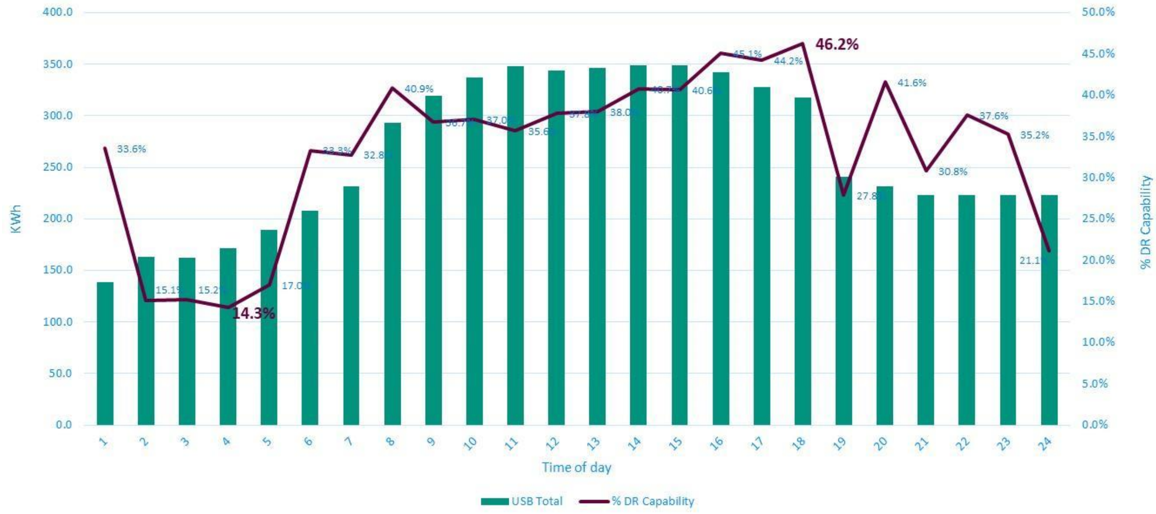


Figure 15. Urban Sciences Building - total electricity consumption, and percentage demand response capability, February 2018 average hourly results [5]

2.1.2 Voltage and current concerns in the LVDGs

Due to the intrinsic nature of the operation and planning of LVDGs, they are normally unbalanced and asymmetrical. In a 3-phase system, an unbalanced condition occurs when the magnitude of voltages and currents in the three phases are not equal and the phase shift angle between two adjacent phases is not precisely 120 degrees. The main reason for such imbalances is the uneven distribution of single-phase customers among the three phases and the consequential variation in loads. Moreover, with the recent evolution in the power networks, LVDGs are now hosting a high penetration of low-carbon technologies (such as wind, PV and EVs), which contribute further to the imbalances in the network. These voltage and current imbalances may cause inefficient use of LVDG assets, increase in neutral currents, thermal overloading and unacceptable stresses on assets. Various techniques have been employed to mitigate these effects, such as voltage and reactive power compensation and amended network reconfiguration.

The proliferation of active buildings is likely to affect LVDG performance greatly, so the effects of this should be considered when performing voltage and current imbalance mitigation. active buildings also have the potential to play an active role in mitigating these problems. This is an active field of research and development requiring further in-depth study.

2.1.3 Challenges in the operation of the LVDGs

In the operation of LVDGs, power quality and reliability (PQR) is a major issue that needs to be considered, alongside economic and environmental considerations. Operating procedures are designed to ensure adequate and secure conditions in the network. This is achieved using energy management systems that have the role of control and management of the LVDG. The presence of a large number of active buildings in the network would also affect the operating protocols of the LVDGs, so rethinking of current operating procedures (taking the effects of active building interaction with the network into consideration) is crucial.

Some of the important questions that need to be addressed in the area of operation are:

- What are the different types of service that can be performed by active buildings for the LVDG?
- What is the vision for LVDG-level energy management systems, taking active buildings into consideration?

2.2 Impact of active buildings on the LVDG

An active building can be viewed as a nano-scale energy grid which is able to intelligently integrate the actions of all users. These actions involve the operation of generation devices (mainly PV), storage devices and EVs, alongside electricity consumption. They need to efficiently deliver sustainable, affordable and secure energy supplies, while actively/proactively participating in services required by the upstream networks. To reach this objective, active buildings employ innovative devices and services together with intelligent monitoring, control and communication technologies.

As the penetration of such active buildings increases, it will become more important to consider their capabilities as active participants in the enhancement of LVDG performance. An active building can affect technical parameters of the network, such as the voltage of connected nodes and nodes close to them, loading of distribution lines and power losses. The degree of the impact will depend on the active building’s mode of operation and the behaviour of residents.

Also, the available energy resources inside an active building can provide a range of active and reactive power. This can be used internally or to provide a service for the other active buildings or the upstream network. Therefore, the optimal operation and scheduling strategy for an active building is subject to the potentially conflicting objectives of the involved stakeholders, including active building residents, the distribution system operator (DSO), neighbouring active buildings, energy suppliers, aggregators and regulatory bodies. Hence, the optimal operation of an active building and an LVDG are interrelated, and a techno-economic-environmental decision-making process is required to find the best possible operation strategy for an LVDG. This strategy should consider the requirements and constraints of active buildings and the comfort of occupants while improving network performance.

Active buildings would also be able to be energy-positive and participate in the provision of flexibility services or any other active/reactive services for the LVDGs. This is an interesting aspect of active buildings that makes them a viable option to assist in coping with the intermittent nature of renewables.

2.3 Economic and market challenges

In this section, the following two main questions regarding the economic and market challenges of active buildings are discussed:

- What might be the appropriate electricity market design to enable participation of Abs in better operation of the LVDGs?
- What are the most appropriate incentive mechanisms for leveraging the potential of active buildings in the enhancement of LVDG operation?

2.3.1 Market mechanisms that can be used at the active building level

Due to the relatively small scale of the energy transactions of active buildings, they would not be able to directly participate in the wholesale or even retail electricity markets. In this regard, they can contribute as a part of a portfolio of an aggregator, which may limit the potential of active buildings. However, due to the advent of peer-to-peer (P2P) electricity markets, active buildings are conceptually allowed to directly trade their electrical energy with the other peers within the market. These so-called P2P markets rely on a bottom-up perspective by allowing small scale energy providers like active buildings and EVs to freely choose the way they buy/sell their required energy. An overview of the motivation, challenges and market designs of these new P2P markets is presented in [6].

2.3.2 Overview of the different types of service that can be harvested from active buildings for the LVDGs

Participation of active buildings in electricity markets can mainly be divided into the demand side response and ancillary services:

2.3.2.1 Demand side response

According to the FERC[7] definition, demand side response is:

> *"changes in electric usage by demand-side resources from their normal consumption pattern in response to changes in the price of electricity over time or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardised."*

Integration of DSR is an important feature of active buildings that, according to the definition, can be managed in the forms presented in Figure 16. A comprehensive review of DSR tools in electricity markets is presented in [7].

[7] Federal Energy Regulatory Commission

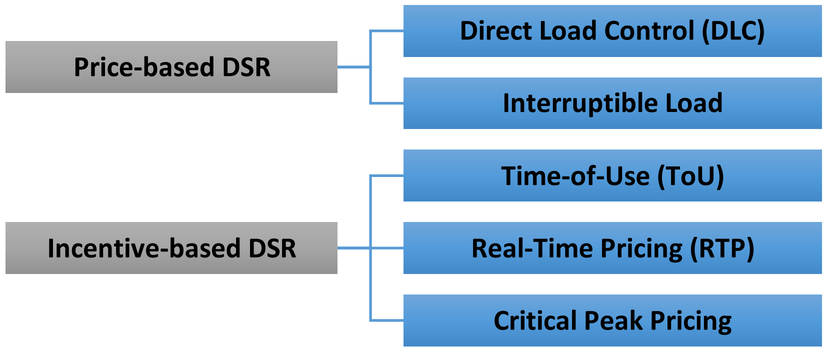


Figure 16. Potential DSR mechanisms.

The objective of DSR policies is to smooth the daily load of a system by shifting the load (including peak shaving and valley filling).

2.3.2.2 Ancillary services

In power systems, some services are required by system operators to maintain the security of supply. These kinds of service include both mandatory services and services achieved via market-based mechanisms. Potential ancillary services that can be offered by active buildings are illustrated in Figure 17. They include:

- Voltage and reactive power support
- Constraint management
- Reduction in grid losses
- Power quality services (i.e. improvement in voltage dips and flicker, as well as harmonics compensation)
- Frequency response services

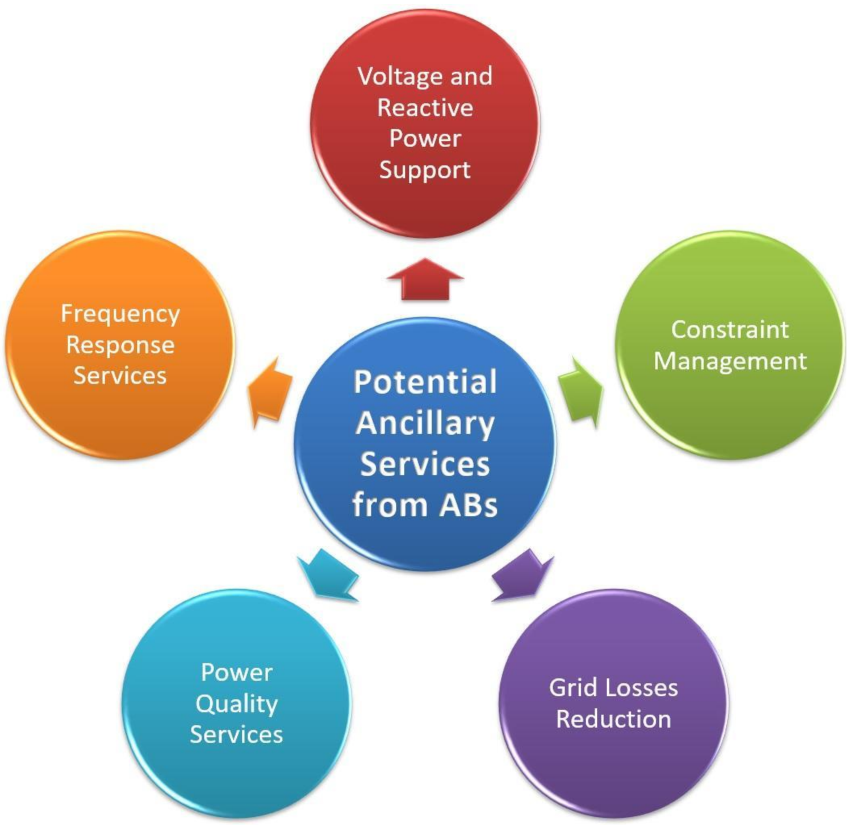


Figure 17. Potential ancillary services that can be offered by active buildings.

2.4 High-level strategy for the way forward in LVDG integration of active buildings

The following issues will be considered in the design of high-level strategies for the way forward:

- Analysis of the market development and technology readiness level required for LVDGs to accommodate active buildings
- Assessment of stakeholders: a very large number of stakeholders will be involved in this evolving area, including technology providers; academic and research institutions; finance and regulatory authorities; government and standardisation organisations

3 Recommendations

The key advantage of active buildings over conventional buildings is the ability to offer flexibility to the network operators. This applies both locally and nationally. Imperial's modelling for this paper shows clearly that active building flexibility from smart EV and smart TES can significantly reduce the need for nuclear as a firm low-carbon generation technology, while simultaneously increasing the ability to integrate more intermittent renewable energy sources (RES). Presently, market mechanisms do not adequately reward this kind of flexibility [8] and the current regulatory framework does not fully reflect the low carbon agenda. Hence, policy and regulation are needed to put new mechanisms in place. The guiding principle is that all market participants should face the costs and benefits of their actions equitably [9]. Projects that provide flexibility should be rewarded for the value that they provide; projects requiring flexibility should face penalties. Active buildings should also be able to participate on a level playing field with other participants.

One method of participation would be for active buildings to have access to markets for ancillary services. They would almost certainly do this through an aggregator, though it is possible that the DSO will take on this role. Another suggested mechanism is given in [10]: a carbon credit scheme operated by energy suppliers, rewarding consumers for occupying buildings with lower emissions. In [1] a carbon price on heat for fossil-based heating systems is proposed.

Our modelling also shows that total system cost reduces substantially as the standard of insulation in active buildings improves. Hence, the active building classification system[8] proposed in [11] should reflect this.

Active buildings will also be able to generate power (mostly through PV). Following the principle outlined above, policy should ensure that they have access to capacity and wholesale electricity markets. This could be through aggregators or feed-in-tariffs [12].

It is government policy that all new build from 2025 will have no connection to the gas grid. Heating in active buildings will be done by ASHPs or GSHPs. To facilitate investment in this form of heating, there is a further need to review and develop policy guidance and financial incentives for active building occupants. Despite current policy, previous work [1] indicates that further research is needed looking into hydrogen and hybrid (electric + gas) heating.

Investment decisions, especially when it comes to nuclear power, need to be made many years in advance. Since our analysis shows that active building technologies can have a very significant effect on the future generation portfolio, decisions need to be made early about the technologies to include in active buildings and the level of roll out.

[8] This is like the energy performance certificates (EPCs) currently given to all buildings. It provides a means of classifying a building as an active building and a rating of its flexibility and generation capacity.

Considering the wide large number of stakeholders will be involved in this evolving area, a high-level strategy should be designed for the way forward that consider the market development and technology readiness level required for LVDGs to accommodate active buildings.

Also, in the electricity market design for the future, the participation of active buildings should be considered and in parallel, the most appropriate incentive mechanisms for benefiting the potential of active buildings in operation and planning of LVDGs need to be considered.

4 Conclusion

The intention of the work described here is to inform debate on future policy and business cases for active buildings. Illustrative studies, using Imperial's Integrated Whole Energy System (IWES) model, show that active building technologies can certainly make a very significant contribution to the future energy system. Their combined flexibility can allow a higher proportion of electricity production from renewables and simultaneously reduce the reliance on nuclear power, while minimising system costs. Most of the savings come from reductions in capital expenditure and are influenced by the recent large fall in the cost of power from renewables. Cost savings increase as the flexibility available from smart EV and smart TES increases. We have considered the core active building technologies here (smart EV, smart TES and thermal insulation here), but other technologies may further increase the value of active buildings. However, these also need to be viewed in a quantitative way to avoid large-scale adoption of inappropriate technologies. Studies also showed that total system costs decline as building energy efficiency improves and that this trend is enhanced as carbon targets tighten. In the context of net zero, this highlights the importance of insulating the building envelope.

The IWES model balances local and national objectives. With the whole system approach, we see an annual total system saving of £4.5Bn per year: for the local distribution-centric approach we see a saving of only £2.2Bn per year. Hence, a whole-system approach should always be part of our thinking in developing the active building concept.

Currently, there is an increasing number of pilot projects across the world trialling buildings with active characteristics, connected to LDVGs. However, active buildings have not been widely deployed due to technological, market and regulatory issues. This is very likely to change soon, as the pace of change in the LVDGs increases. LVDGs are becoming less passive, smarter and are taking on an expanding role. Distribution network operators (DNOs) are becoming distribution system operators (DSOs). This is driven largely by the increasing presence of the distributed generation (e.g. PV) and storage (EVs, TES, Batteries, etc) at the local level, and active buildings are part of this.

In order to turn this potential into reality, suitable market mechanisms and policy regulation are needed to enable the operation of local markets (such as P2P markets) within a community of active buildings or even within an active building. With the use of information and communication technologies as well as smart metering and control devices, and also with the help of cloud/edge computing and block-chain technologies, active buildings will be able to organise a large number of devices in a manner not previously possible to provide the required services (e.g. DSR) to the LVDGs.

Considering a wide range of energy resources exist in active buildings, they have the potential to be a significant source of DSR provision to the network. This would facilitate more integration of renewables and as a result, make a smoother move toward the decarbonisation goals. According to the analysis done by Newcastle University on a real-world building, it was identified the great potential of DSR for an educational building which predominantly has an electrical load. The research showed that typically 40% of electrical load could be available for DSR events.

Acknowledgements

The Active Building Centre Research Programme

Funded as part of the UKRI Transforming Construction Challenge, the Active Building Centre Research Programme is delivering an evidence-based transformation of the UK's built environment.

Led by the team at Swansea University, the research programme brings together ten leading universities, businesses and service providers to develop and test innovative technologies and ideas that will ensure buildings of all scale contribute to a more stable power grid.

Our collaborative research framework is delivering valuable insight into novel heat storage, data gathering and analytics, building design and optimisation, software development and human interfacing, social science, and wellbeing.

Active Building Centre Research Programme activities are focused on enabling the construction industry to transform into a net zero emissions building sector within the next 30 years.

Transforming Construction Challenge

The Transforming Construction challenge is part of the Industrial Strategy Challenge Fund and brings together the UK's world-leading research with business to meet the major industrial and societal challenges of our time. It provides funding and support to UK businesses and researchers, aiming to transform productivity in the construction industry through the adoption of innovative technologies and the development of a more highly skilled workforce. part of the government's £4.7 billion increase in research and development over the next 4 years. It plays a central role in the Government's modern Industrial Strategy.

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