Towards net-zero carbon performance: using demand side management and a low carbon grid to reduce operational carbon emissions in a UK public office

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Abstract. This paper investigates the performance of an office building that has achieved a low carbon performance in practice thanks to a performance contract and Soft Landings approach. The findings show the potential of this building for further de-carbonisation as a result of electrification of heating and load shifting to take advantage of a low carbon electricity grid. Whilst retrospective modelling based on the past carbon intensity data shows the effectiveness of demand-side management, assessment of the existing smart readiness of the building revealed that the building services and control strategy are not fully equipped with the data analytics and carbon or price signal responsiveness required to facilitate grid integration. The environmental strategy and procurement method used for this building combined with an effective grid integration strategy can serve as a prototype for low carbon design to achieve the ever stringent carbon emissions objectives set out for the non-domestic buildings.

1. Introduction

The recast of the Energy Performance of Buildings Directive (EPBD) called for the EU member states to draw up national plans to facilitate transition to nearly zero-energy buildings [1]. It was envisaged that such high performance buildings will adopt passive environmental measures to reduce the demand for energy in the first place, will use the most efficient building services, and will also use renewables to supply energy to the buildings. The UK Green Building Council introduced a framework definition for net-zero carbon buildings [2]. This framework recommended the adoption of 'time of use' emission factors for all carbon calculations. Net-zero carbon for operational efficiency is achieved when all carbon impacts are balanced by all carbon credits. Dynamic carbon emission factors associated with electricity grid can play an important role in achieving net-zero carbon. Energy flexibility and potential for energy storage and load shifting has also been identified as a key component of the smart readiness indicator for buildings developed under the auspices of the European Commission. This has led to an increasing interest in the benefits of energy flexibility [3-5].

The carbon intensity of the national grid in the United Kingdom has significantly come down in the last decade thanks to the increasing contribution of renewable and low carbon sources such as offshore wind turbines, PV systems and biomass, in addition to replacing coal with gas power stations and other incremental efficiency improvements. However, the net reduction in the carbon intensity of the grid and also the variation in carbon factors have not been fully transposed to the building regulations and energy certification schemes. This can potentially delay the transition from fossil thermal fuels to low carbon electricity.

At the same time, voluntary and industry led campaigns such as the RIBA Climate Challenge and London Energy Transformation Initiatives (LETI) have set out ambitious targets for domestic and non-domestic buildings. For example, RIBA calls for all new non-domestic buildings to achieve a net energy use intensity lower than 55 kWh/m²/annum equivalent to an operational rating of DEC A by 2030. These operational targets are set to be consistent with an energy supply projected for a low carbon grid according to the current trajectories [6]. Very few buildings have currently achieved these operational targets. This paper sets to investigate how a good practice low-energy non-domestic building that currently has an operational rating of DEC B, with in-built facility to transit from natural gas to heat pumps, could be fine-tuned to approach net-zero carbon performance. This can be a proof of concept of how these targets could be achieved based on a review of a case study that has already achieved a good level of performance in practice. Given the fluctuations in the carbon intensity of the grid, it is also important to investigate the implications of time of use emission factors and tariffs to further decarbonise energy use of buildings and also provide opportunities for better load balance and capacity management for utility suppliers. Figure 1 shows the fuel mix for production of electricity from 2010 to 2019 and the average hourly carbon intensity factors for 2019 in the UK. There is approximately 40% variation between the peak and minimum carbon intensity reported in Figure 1. This could be even higher at regional level and thus can have important consequences for building control strategies and net carbon emissions.

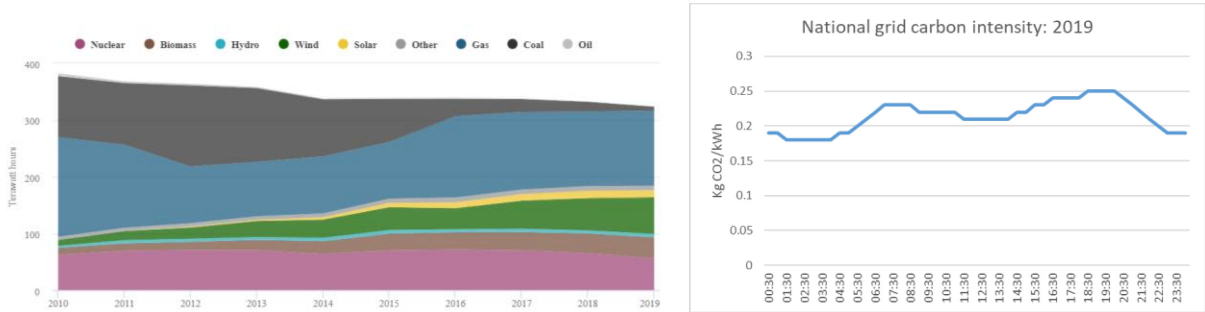

Figure 1. Annual electricity generation in the UK by fuel [7], and hourly averaged carbon intensity factors for electricity in 2019 derived from the National Grid dataset.

2. Method

There have been attempts to define a roadmap and proof-of-concept prototypes for net-zero carbon buildings in the UK [8-9]. This paper expands on the extensive work carried out to evaluate the operational performance of a low carbon non-domestic building [10], to assess the potential benefits of full transition to electrical building services and opportunities for demand side management and grid integration. The procurement process adopted for this building entailed achieving the highest operational energy rating grade and makes this building a good example to explore how energy flexibility can help further decarbonise building performance.

The following tasks were fulfilled to enable such an analysis. The reference for electricity carbon factors used is the daily average factors illustrated in Figure 1, derived from the National Grid dataset. Regional variations of carbon intensity are even higher than the national average figures, and therefore this analysis will yield conservative estimates of the savings that could potentially be achieved:

1. The baseline performance for the case study was established following the outcomes of the building performance evaluation.
2. A computer model was developed for the building using DesignBuilder software which provides an interface to EnergyPlus simulation engine. This model was calibrated with the

actual energy performance of the building in accordance with ASHRAE Guideline 14 [11] monthly calibration criteria. The coefficient of variation of the root mean square error (CVRMSE) and the normalised mean bias error (NMBE) were 12% and 3% respectively for gas use & 7% and 3% for electricity against the limiting values of 15% and 5% set out in Guideline 14. The calibration also covered independent variables such as operative temperatures to ensure the model is a reasonable representation of the actual performance. The calibration process of this building and its outcomes are covered in detail by Jain et al. [12].

3. Using this calibrated model, the following scenarios were investigated to determine the CO_2 emissions associated with the energy required for heating and the potential effects on indoor operative temperatures:

    3.1. Using water-to-water heat pumps for heating supplemented by gas-fired boilers and normal heating schedules,
    3.2. Investigating the capacity of the installed water-to-water heat pumps and the existing thermal buffer vessel (1,000 litres capacity) for load shifting with a preheating schedule (5:00-7:00) and a top-up around noon (11:30-14:00). The heating system was turned off outside these schedules. This scenario reflects the potential capacity of the existing buffer vessel and the building's thermal mass for load shifting.
    3.3. Investigating the effect of increasing the capacity of the thermal buffer vessel to a practical maximum (equivalent to 4×5 m³ storage vessels), determined by spatial constraints, with a heating schedule coincident with the minimum carbon intensity for electricity (1:30-4:00) and a top-up around noon only when necessary (11:30-14:00).

4. Analysis of these strategies using the carbon intensity factors reported by the National Grid in 2019 is a retrospective investigation in modelling environment. In practice, enacting demand side management for heating can be facilitated and automated by system intelligence and smart measures to revise the operating schedules based on the forecast available for the carbon intensity of the grid (currently, the UK National Grid releases the carbon intensity forecasts for the next 48 hours). It is therefore necessary to evaluate the smart readiness of the building for such strategies. To this end, the framework and toolkit developed to define a Smart Readiness Indicator (SRI) for buildings in the EU was used to evaluate this case study. The SRI scheme is designed to evaluate the capacity of buildings to improve energy efficiency, energy flexibility and user comfort with smart measures. Seven impact categories are defined under this scheme along with a catalogue of several smart measures for technical building systems. The 'detailed assessment method' defined for this scheme that covers 54 smart services across nine domains was used to evaluate the building and compare its readiness for energy flexibility against other impact criteria [3].

3. Case study

3.1. The context
The case study is a four-storey public sector office building with 6,400 m² useful floor area located in West England (Somerset) and constructed in 2014. Figure 2 shows external and internal views of this building. The client decided to opt for an operational energy performance rating of A instead of environmental credentials based on design measures. This performance target was embedded into a Design and Build contract and the Soft Landings framework [13] was used to help achieve this target after the second year of operation.

Design and construction was primarily driven by the fabric first approach. The U-values specified for the building fabric are generally lower than the regulatory limits in England. The air permeability of the building is 4.7 m³/h/m² at 50 Pa pressure difference confirmed by the pressure test after building completion. The structural system of the building is based on an exposed cross-laminated timber (CLT) frame that helps reduce the building's embodied carbon. Precast concrete panels constitute around 50% of the ceilings, whilst the rest of the ceilings have acoustic panels to strike a balance between exposed thermal mass and acoustic performance.

The building's services strategy relies on advanced natural ventilation facilitated by manually operable vents and automated vents that were designed to respond to temperature and CO_2 levels. The inter-cuts between the floors facilitate stack ventilation in addition to opportunities for single-sided and cross ventilation. Water-to-water heat pumps were designed primarily to meet the server room cooling load, and the heat dissipated from the server room to provide free heat to the low temperature hot water loop supplemented by gas-fired condensing boilers. Underfloor heating and perimeter trench heaters provide heating to internal spaces and acoustically perforated radiant aluminium cooling sails are installed in meeting rooms. The roof is oriented for optimal solar gain and is paved with 1,150 m² of photovoltaic panels (230 kW_P nominal capacity) to decarbonise part of the energy use of the building.

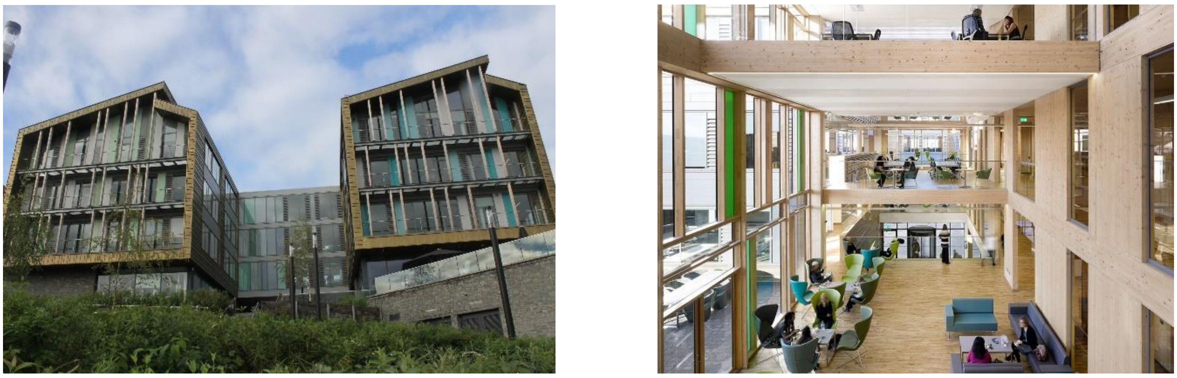

Figure 2. External view (north-east orientation) and an internal view of the case study.

3.2. The baseline performance

Following the fine-tuning of the building in the first couple of years post completion, the building achieved an operational energy rating of B (DEC B/36). Although the energy rating target defined in the contract was not met, the building's performance is among the top 10% of public offices according to the data available for offices through the Display Energy Certification scheme in the UK [14]. This was the first public sector office building that targeted an operational rating in the UK at design stage.

Figure 3 compares the as-designed performance of the building against the steady performance after the second year of operation and also presents an excerpt from the latest display energy certificate for the building.

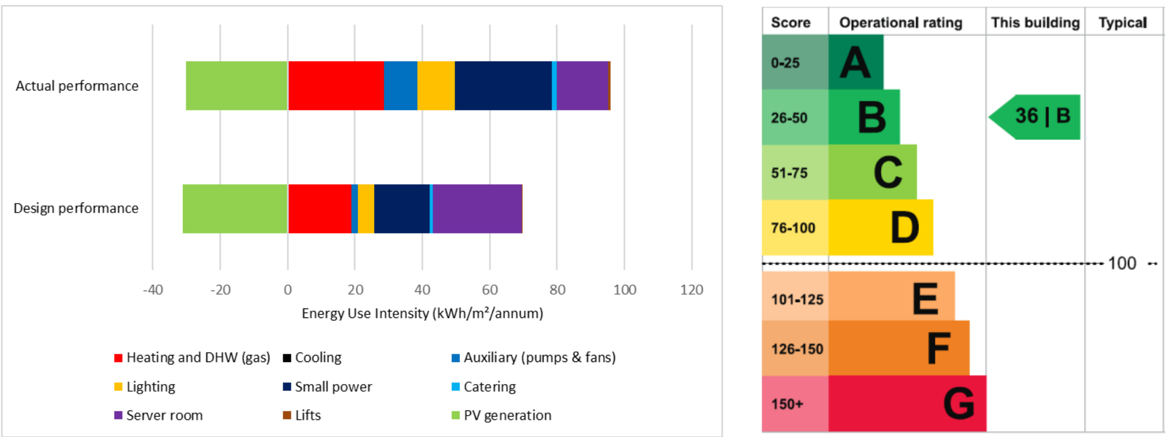

Figure 3. Actual against design performance and the operational rating for the case study.

Figure 4 shows the net half-hourly electrical demand curves for the building based on the data provided by the utility supplier for 2019 (i.e. last year of steady performance before the Covid-19 pandemic). The graphs show the baseload electrical demand, and the effect of PV generation in shaving off the peak during weekdays which also explains the dip in demand during weekends when the building is not occupied.

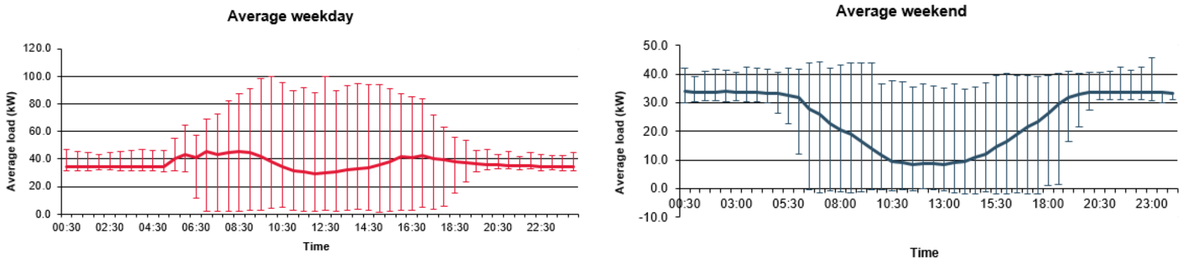

Figure 4. Half-hourly net electrical demand curves for the case study.

One of the key problems identified in the building after completion that compromised the performance in-use was that the heat pumps were effectively not used as a result of problems at the control interface between the heat pumps and boilers in hot water buffer vessel, in addition to the higher than anticipated heating demand of the building that led to an increase in hot water flow temperatures from the heating plant. This issue was compounded by the fact that the waste heat available from the server room was in practice lower than predicted as the server room's actual loads had been overestimated at design stage.

4. Results

The following sub-sections report the results of the respective scenarios outlined in the methodology section and assessment of the smart readiness of the case study.

4.1. Water-to-water heat pumps supplemented by gas-fired boilers for heating

If the control issues at the interface between heating systems are addressed, by replacing the existing heat exchanger in the buffer vessel and heating flow temperature re-set, the CO_2 emissions associated with heating will reduce by 56% assuming both heat pumps (each with 41.1 kW output and seasonal COP of 2.89) will act as the lead system for heating. This means that if the carbon conversion factors used in the DEC scheme are updated to reflect the current annual average emissions (i.e. from 0.55 set in 2008, to 0.21 kg CO_2/kWh for 2019), fine tuning the building to fully utilise heat pumps will achieve operational rating of DEC A.

4.2. Re-scheduling the heating system

The capacity of the existing buffer vessel for load shifting is limited. Thermal mass of the building can also be used to store heating energy. However, simulation revealed that any attempt to utilise thermal mass to save heating energy will have to be as part of the pre-heating schedule. Therefore, it was not possible to produce heating energy at the lowest carbon intensity. Nonetheless, the pre-heating schedule set up (05:00-7:00) and the top-up schedule around noon (11:30-14:00) reflect periods with comparatively low carbon intensity (Figure 1). Re-scheduling the heating system to store energy in the existing buffer vessel, provision of space heating to the building during these periods, and turning the system off outside these periods will reduce the CO_2 emissions by around 25% compared to 4.1. Figure 5 compares histograms of annual operative temperatures in a typical zone of the office in the baseline scenario (existing building) against what could be expected with re-scheduling and rationing the heating system. It shows that the success of such an operating strategy in further reducing CO_2 emissions relies on behavioural strategies that may justify operative temperatures lower than the baseline scenario, but still largely within the acceptable comfort range in heating season (i.e. above 18 °C).

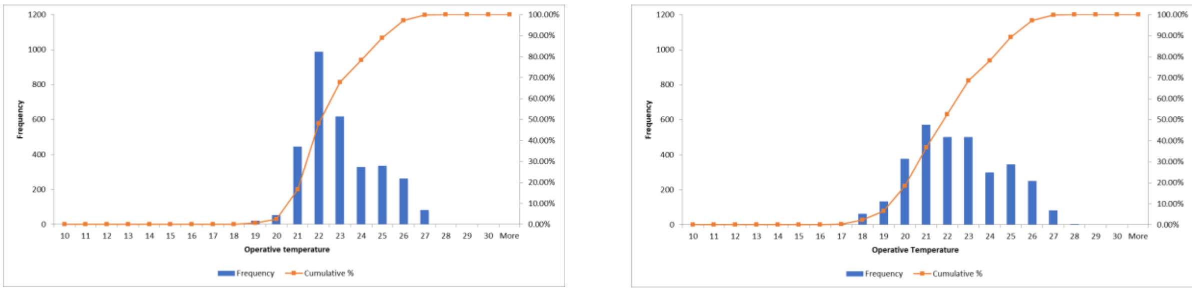

Figure 5. Histogram of operative temperatures in the baseline scenario (left) and when the heating system is re-scheduled (second floor open plan office).

4.3. Load shifting scenario facilitated by refurbishment

This scenario projects the savings in CO_2 emissions, if the existing plant room and heating strategy is refurbished for load shifting. It is assumed that new thermal storage tanks and heat pumps with sufficient capacity, and COP identical to the existing units, will be installed for load shifting. The storage tanks can store 20,000 litres water in total assuming a thermal storage density of 35 kWh/m^3 [15], equivalent to the average daily demand for heating in the case study in winter. Table 1 compares the CO_2 emissions associated with heating energy in this scenario against the previous scenarios.

Table 1. CO_2 emissions associated with heating energy: scenario analysis.

Performance metric	**Baseline scenario (existing building: gas boilers only)**	**Heat pumps as lead heating system (gas boiler top-up)**	**Optimisation (re-scheduling of heating system)**	**Refurbishment (load shifting)**
Carbon emissions related to heating energy (kg CO_2 / yr.)	35,264 (reference point)	15,543 (56% improvement)	11,598 (67% improvement)	7,412 (79% improvement)

Figure 6 shows that the operative temperatures achieved in the load shifting scenario are close to the baseline scenario and savings achieved in carbon emissions will not change the operative temperatures and thermal comfort conditions significantly.

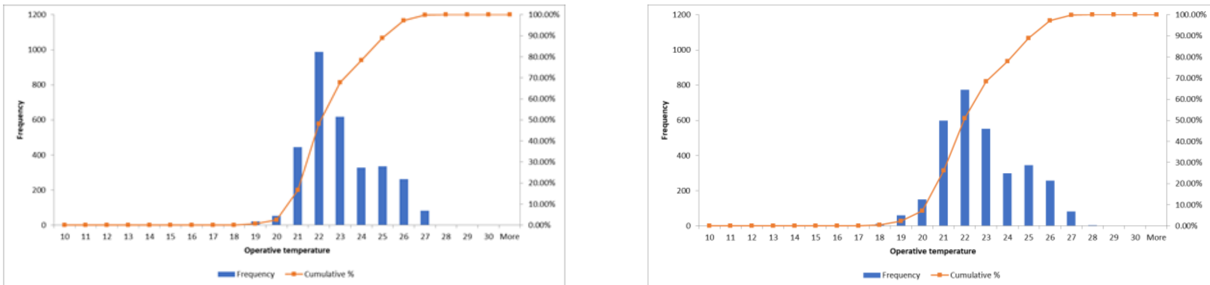

Figure 6. Histogram of operative temperatures in the baseline (left) and the load shifting scenario.

4.4. Smart readiness of the case study

Figure 7 shows the results of the assessment of the case study for smart readiness for each impact criterion covered in the SRI scheme. It shows that the existing capacity of the building for energy flexibility and interaction with the grid is rather limited and is considerably lower than other impact criteria. The key services that should be provided to improve the smart readiness of the building in heating domain are: provision of thermal storage capacity, capability of heating system for flexible control through grid signals, and optimisation of control strategy based on local predictions and grid signal (e.g. through model predictive control).

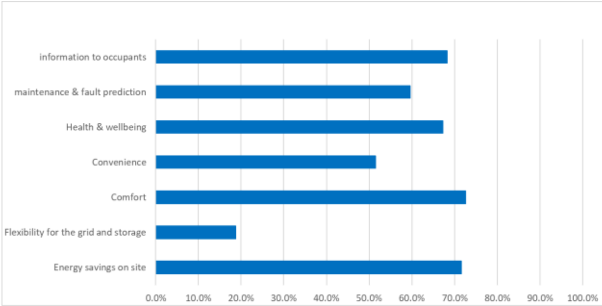

Figure 7. Scores for different impact criteria covered by the SRI scheme.

5. Discussion

The scenarios investigated for the case study clearly demonstrate the value of addressing the control issues at the interface between the installed heat pumps and supplementary gas-fired boilers, re-scheduling the heating system combined with behavioural strategies and campaigns to achieve more moderate but still acceptable thermal comfort conditions, and finally planning to further facilitate opportunities for load shifting as the national electricity grid is increasingly decarbonised. However, the results of the evaluation of the smart readiness for the case study show that opportunities for interaction with the grid and the potential for energy storage and load shifting in this building are currently limited. Although this building was completed in 2014 and one would expect to see further consideration for energy flexibility and grid integration in newer buildings, the findings in this case study point to other potential issues that need to be addressed to facilitate opportunities for better grid integration. Achieving an operational rating of A was clearly an important target for this building and yet the carbon factor used for electricity in the DEC scheme has not been changed after its introduction in 2008 meaning that the carbon intensity assumed for electricity in this scheme (0.55 $kgCO_2/kWh$) is far greater than the current carbon intensity of the grid (average of 0.21 $kgCO_2/kWh$, in 2019). This can hardly be an incentive for building operators to address any issue with electrical building services and use electricity as the main heating fuel where there is the potential of using back-up fossil thermal systems. Dynamic tariffs offered by the suppliers can also encourage a more environmentally friendly operation at building level, whilst providing the suppliers with the opportunity for better load management. However, the tariffs defined in the current utility contract for the case study follow the conventional pattern of off-peak(night)/peak(day) fixed unit rates based on pre-determined hours. It is important to tackle these issues to achieve a better integration between decarbonisation policies at upstream and building performance downstream. This can provide a win-win situation for utility suppliers with better opportunities for load management, and for building operators to further decarbonise their buildings' performance and take full advantage of an increasingly low carbon grid. This case study is an exemplar public office building that can achieve operational energy rating of A subject to minor and cost-effective measures with potential for further improvements. It serves as a prototype of how a low carbon non-domestic building can be procured. More attention to demand-side management and energy flexibility can reduce operational emissions even further and help achieve the ever stringent operational carbon emissions expected from buildings.

6. Conclusions

The review of the procurement method used for this case study, the existing operational rating, and the potential for further decarbonisation set an example of how low carbon performance could be achieved in practice. However, the study identified key improvements that require actions from different actors to facilitate grid integration as the next step for achieving net-zero performance targets in the UK:

Policy makers: Using a constant carbon conversion factor for electricity was probably necessary to maintain the consistency of the DEC scheme for more than a decade after the implementation of the EPBD (2008- to date). However, it is now necessary to update this factor and reflect the significant reductions in the carbon intensity of the grid. Failure to do so can send the wrong message to building operators and delay the transition from fossil thermal sources to electricity as the main heating fuel.

Utility suppliers: Introduction of more dynamic tariffs representing the variations in the carbon intensity of the grid will enable electricity suppliers to shave the peaks and better manage the capacity of their network. This will also incentivise demand-side strategies downstream at building level.

Clients and building designers: It is necessary to improve the responsiveness of buildings to carbon or price signals from the grid. The new SRI scheme provides a framework that could be used to identify the smart measures required to improve energy flexibility.

Acknowledgements

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References

[1] The European Parliament and the Council of the European Union, 2010. Directive 2010/31/EU of the European Paliament and of the Council of 19 May 2019 on the energy performance of buildings (recast), Official Journal of the European Union, 18.6.2010, L 153/13.
[2] UKGBC, 2019. Net Zero Carbon Buildings: A Framework Definition, The UK Green Building Council, April 2019.
[3] Verbeke S, Aerts D, Reynders G, Ma Y and Waide P, 2020. Final Reprt on the Technical Support to the Development of a Smart Readiness Indicator for Buildings, Report prepared by VITO and Waide Strategic Efficiency Europe for the European Commission.
[4] Märzinger T and Österreicher D, 2019. Supporting the Smart Readiness Indicator – A Methodology to Integrate A Quantitative Assessment of the Load Shifting Potential of Smart Buildings. Energies 2019, 1955; doi:10.3390/en12101955.
[5] Pemetti R, Reynders G and Knotzer A, 2017. Position Paper of the IEA Energy in Buildings and Communities Program (EBC) Annex67 "Energy Flexible Buildings".
[6] RIBA, 2019. RIBA 2030 Climate Challenge, The Royal Institute of British Architects.
[7] BEIS, 2020. Energy trends – Quarterly publication which presents data on the supply and demand of all the major fuels in the United Kingdom, Department for Business, Energy & Industrial Strategy.
[8] UKGBC, 2020. Building the Case for Net Zero: A feasibility study into the design, delivery and cost of new net zero carbon buildings, The UK Green Building Council, September 2020.
[9] ARUP, 2020. The Road To Zero, Net Zero Carbon Buildings: Three Steps to Take Now.
[10] CIBSE, 2020. TM61 – Operational Performance of buildings, The Chartered Institute of Building Services Engineers, December 2020.
[11] ASHRAE, 2014. Measurement of energy, demand and water savings ASHRAE Guidelines 14, The American Society of Heating, Refrigerating and Air-Conditioning Engineers.
[12] Jain N, Burman E, Stamp S, Mumovic D and Davies M, 2020. Cross-sectoral assessment of the performance gap using calibrated building energy performance simulation. Energy and Buildings, 110271; doi:10.1016/j.enbuild.2020.110271.
[13] BSRIA, 2018. Soft Landings Framework 2018 (BG 54/2018), BSRIA.
[14] Armitage P, Godoy-Shimizu D, Steemers K and Chenvidyakarn T, 2015. Using Display Energy Certificates to quantify public sector office energy consumption, Building Research & Information, 43:6, 691-709; doi: 10.1080/09613218.2014.975416.
[15] Hutty T D, Patel N, Dong S and Brown S, 2020. Can thermal storage assist with the electrification of heat through peak shaving?, Energy Reports 6 (2020), 124-131.