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EVALUATION OF AN EVOLVING HOUSING STOCK: SCENARIOS TOWARDS ITS DECARBONISATION

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ABSTRACT

Whilst the application of housing stock energy models has allowed us to rigorously model both energy use and indoor comfort, their usability is still being questioned by their restricted, or even null, ability to represent the impacts of trade-offs that households make between energy bills, indoor comfort and health, as well as changes on the composition of houses and householders over a number of years. This work describes a complement to EnHub, a platform that dynamically simulates the energy demands and carbon emissions of the English housing stock, by deploying scenarios that reflect multiple changes in the (future) composition of it. The aim here is to highlight the potential for improvement of the housing stock energy performance, and to improve the evidence base of future housing decarbonisation policy.

INTRODUCTION

The English housing stock is expected to grow by 24% in 2050 (Office for National Statistics 2018; Department for Communities and Local Government (DCLG) 2016). In a perhaps idealistic scenario, the energy demand of the more than 6 million new dwellings will be limited to levels below 25 kW/m^2. Although in principle such an intensity seems relatively low—note that current estimations range between 175 and 200 kW/m^2, and complies with Building Regulations; when compared to the national energy demand, the energy contribution translates into about 5 mtoe (with respect to the current energy mix). For this reason, it is essential to characterise and evaluate an evolving housing stock, and to represent the series of changes and stimuli that may affect its accumulated energy demand. In this regard, more evidence is needed to better design policies that account for this, and to successfully intervene the housing stock in the future.

The formulation of energy policies in the residential sector has been commonly supported by deploying Housing Stock Energy Models (HSEMs) (Sousa et al. 2017), albeit employing steady-state deterministic algorithms to estimate thermal demand. Essentially, HSEMs evaluate a selection of archetypes provided in a survey, or generated from a national census reference, and then scale the results based on the statistical representation of each archetype within its corresponding database (i.e. the application of statistical weights). This approach facilitates the evaluation of substitutions or improvements to the envelope, and also to the technology of systems and appliances. However, due to the generalisation of variables needed for this approach, it is common to under- and over-estimate results, affecting in consequence the trustworthiness of their predictions. Besides, this approach ignores the processes of occupant decision-making (to invest in technology or to adopt better practices) that take place in practice, and the series of responses and adaptations that occur over time. This latter represents one of the facets of rebound effects that, some argue (Druckman et al. 2011; Summerfield et al. 2013), are essential for the successful execution of energy-related policies and consequential decarbonisation of the domestic sector.

In addition to these responses and adaptations, it is worth noting that the housing stock is a techno-social system that evolves in different dimensions, and suffers transformation. For example, new constructions and demolitions alter the typological composition of the housing stock; household fragmentation contributes to housing stock growth; as a result of social policies and/or development schemes—perhaps by influencing migration to/from cities, tenure composition and urban connectedness can influence the development of a certain typology; and finally, both availability and affordability of heating systems and household appliances may significantly may boost the adoption of technologies and specific fuels across the stock. This can be reflected at regional scale, for example by investing in district heating; or at individual scale, for example by increasing the ownership of household appliances. All this in addition to the series of improvements that have been proven to be effective, such as better insulation of the envelope, efficient glazing, and draught proofing. If HSEMs are unable to characterise and process the aforementioned transformations, it is likely that their outcomes propagate uncertainties, negatively impacting the effectiveness of polices informed by them, and in turn limiting the stimuli required to decarbonise the housing stock in the future.

In the UK, formal records of energy use and carbon emissions began in the 1960s. Later in the 1990s, these records were more refined and the contribution of the domestic sector was further considered (Department for Business 2019)—incidentally, including (and calibrating) the results from prior HSEMs. In the 1990s, the UK reduced its carbon footprint by replacing coal with natural gas. While this immediately improved the energy mix, although primarily impacting power plants, it prolonged the country's dependency on fossil fuels. This shift im-

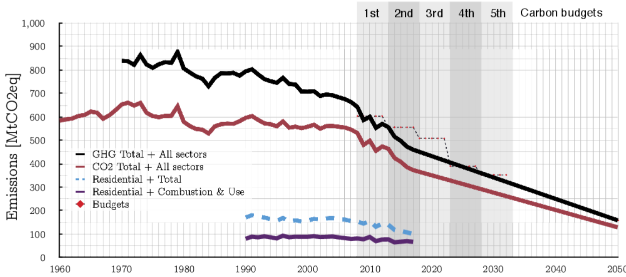


Figure 1: Accumulated national emissions 1960-2050 (historical and projection)

pacted the residential sector in the same way, although the end-use energy demand has just been marginally improved. In fact, it can be argued that the adoption of gas as the main fuel supply in the country increased the affordability of gas technologies (i.e. a typical example of supply and demand). Today, more than three quarters of the domestic sector use gas for heating, where heating represents about 80% of the total energy demand (Palmer and Cooper 2012). It is due to this contribution that the representation of heating systems has thus been at the core of all UK-focussed HSEMs (Palmer and Cooper 2012; Sousa et al. 2017).

Over this recorded period (see Figure 1), the residential sector has in general become more efficient, although at a significantly slow pace, especially when compared with the carbon reduction targets for 2050 (Committee on Climate Change 2008; Committee on Climate Change 2019). On the one hand, it can be said that: the fabric of houses has improved; heating systems are more energy efficient (i.e. more heat at lower cost); and, broadly speaking, the idea about a more responsible use of energy has been diffused across the population, although with a rather speculative application. On the other hand, as mentioned earlier, occupants' decisions—often without even noticing it—have intensified the use of energy, and have in turn balanced the achievements caused due to technological improvements. Acknowledging that in some cases occupants are deliberately responsible for increased heat demand or excessive use of electricity (Summerfield et al. 2013).

The work described in this document aims to assess possible changes in the housing stock, considering national projections in its composition; and to quantify how the adoption of different practices (to regulate indoor conditions) impact on energy usage intensity. These changes are also complemented—perhaps optimistically—with a series of potential adoptions of more efficient heating systems. Yet in practice it would be possible to evaluate more constrained scenarios, as well as a larger catalogue of rebound effect scenarios.

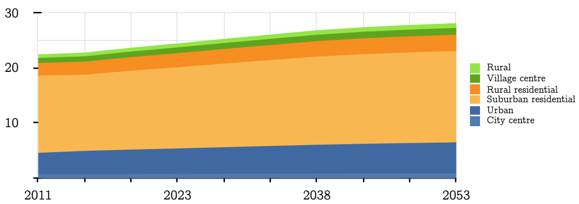
Table 1: Differences between EnHub and prior HSEMs

Improvements	**Previous features**
✓dynamic simulation with selectable time resolution and range	– simplified energy balance model
✓representation of adjacency and form: explicit thermal flow	– thermo-physical values in function of surface area
✓hierarchical management of survey data	– direct conversion of survey data
✓flexible data pre- and post-processing capabilities	– single data source dependency
✓modular and scalable architecture for occupancy properties	– simplified occupancy properties

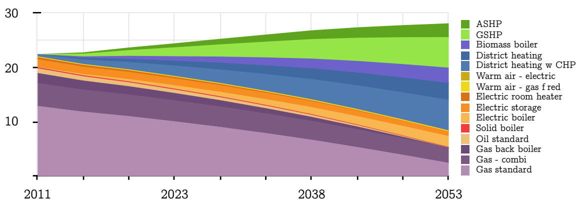
METHOD

As described earlier, HSEMs scale the evaluation of (a snapshot of) the population in a given period, typically a year, although carrying with a range of biases and miscalculations, due to their modelling approach. Dynamic simulation has been proved to be a suitable and flexible candidate to overcome these issues, and so to reduce inaccuracy in estimates (also known as energy performance gap). The housing stock Energy Hub (EnHub) (Sousa et al. 2018) systematically performs dynamic simulation of survey archetypes, coupling `R`–a statistical software (R Core Team 2016), and `EnergyPlus`–a building energy simulation software (Strand et al. 2000); and it has thus been employed to evaluate the housing stock. Table 1 summarises the series of improvements to the attributes offered by previous HSEMs, particularly the Cambridge Housing Model (CHM), which has been identified as the most flexible and powerful of them, and that has thus been employed to inform official statistics. In sum, EnHub is an open and modular platform that extracts survey data, generates volumetric archetypes (enabling also the representation of multiple thermal zones within a house), represents heating systems in detail (allocating heat emitters for each thermal zone), performs dynamic simulation (representing thermal flow conditions over a given period), and explores the potential impacts of policies and strategies to decarbonise national housing stocks, based not only on aggregates of fuel demand, but also on spatio-temporal indicators. The modularity of EnHub helps to replace and, whenever applicable, incorporate more appropriate algorithms, processes (or functionalities) and data sources; improving in turn the utility of the analyses.

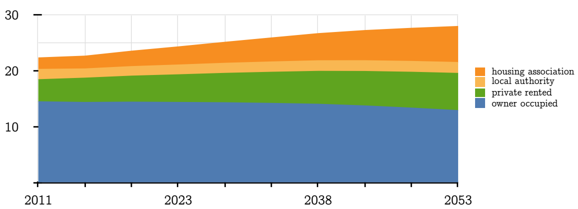
The method used in this work integrates two main subprocesses: (a) projection of changes in the composition of the housing stock, and (b) size reduction with respect to a referential data source: the English Housing Survey (EHS) (Department for Communities and Local Government (DCLG) 2011). The first sub-process: *projection of changes*, collects and processes data from Office for National Statistics (ONS) (via NOMIS - Official Labour Market Statistics), Department for Business, En-



(a) Urbanity composition



(b) Space-heating system



(c) Tenure composition

Figure 2: Projected changes on stock composition

ergy and Industrial Strategy (BEIS) and Digest of UK Energy Statistics (DUKES). Here, the main selection of summaries and projections includes: tenure structure, household composition, urbanity, type of construction, epoch of construction (as a combination of demolition rates for pre-2002 constructions, and construction rate for post-2002), and thermal insulation (see Figure 2, which outlines three of these projections). In addition, a series of projections related to substitution of heating systems are included here; particularly, the replacement of, or preference for, heat pumps and district heating technologies over traditional gas-, coal- and oil-fuelled systems. It must be noted that, at this stage, we are not modelling the way stimuli accumulate to influence such a substitution at both power sector and end-use; however, data permitting, this module is planned to be included in future research. The second sub-process: *stock reduction*, picks the most representative typologies to represent a diverse but encompassing representation of the housing stock. In previous analyses (Sousa et al. 2018), this sub-process was only applied as a preliminary step in preparation for scenario analysis. Now, the reduction is applied iteratively after each projection. Figure 3 outlines the flowchart for the method employed in this work.

The projection of changes, i.e. sub-process (a), consists in reflecting estimates provided by national statistics. (Incidentally, some of the values provided by national statistics

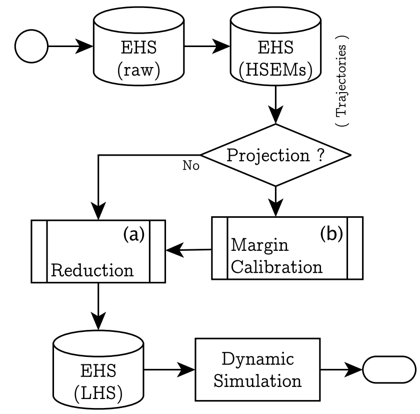


Figure 3: Main workflow for the evaluation of an evolving housing stock

result from previous evaluations of the EHS). For each new period, a margin calibration method (Deville and Särndal 1992; Rebecq 2016) is applied. The method alters the weights initially assigned to the database, and applies the rate of change with respect to the available projections. By way of demonstration, if only one variable were available, the adjustment would be directly achieved by multiplying each weight, within each group, by the rate of change provided in the summaries. However, because more variables are available—as expected, a process of iteration is needed where each group repeatedly adjusts its weights, with respect to the summaries (or margins), until each group matches the projections. Now, if these changes are abrupt (e.g., if all gas systems are fully removed from one period to the other), the iteration may never converge, and so the proportion within each group will never match. A similar condition may also occur if the number of reference variables (or new proportions) is considerably large. In that case, it might be easier to generate a new reference survey data.

Once the calibration succeeds, the reduction module, i.e. sub-process (b), is applied to the newly calibrated dataset. This order (calibration first, reduction later) is preferred because the available projections contain socially-related data and, although their values provide essential information for determining a degree of uniqueness of the stock—and hence are used during the sub-processes, these are not essential for the simulation of heat flow at this stage and may add redundancy in the EnHub results.

EnHub extracts information primarily form the EHS. First, the extraction follows a similar approach taken by the CHM (Hughes et al. 2012), although this time adding an extensive section about household-specific and contextual information (i.e. urbanity, street type, household composition, outdoor obstructions, socio-demographics), which is used to parse occupancy and usage patterns. To improve the generation of three-dimensional archetypes, as well as the processing of the EHS and the complementary data sources, EnHub converts these sources into dictionaries (a common practice in R and other programming languages; see also the recent addition of `*.json` objects in EnergyPlus). In this way, each dictionary can be manipulated independently or in tandem while running a workflow in EnHub. Likewise, a dictionary of global parameters is also editable and adjusted for each scenario. Once the datasets are processed and the archetypes generated, EnHub generates a catalogue of scenarios that can be then simulated at a a different time or using more efficient hardware, such as a High Performance Computing (HPC).

Scenarios

The application of the main workflow helps to create different scenarios. For this exercise, the population-related projections are fixed, and the adoption of more efficient technologies as well as investments on supply side are variable, based on (assumed) trends. It must be noted, however, that these later cases are at the moment either speculative or dependent on structural changes at governmental level. Either way, the main scenarios tested in this work include: substitution of gas systems with heat pumps and district heating; adoption (in-situ) of renewable sources of energy; adoption of higher heating set-points; and increase of Energy Usage Intensity (EUI) of household appliances. With respect to supply side, or power generation, here is assumed a reduction of 80% in Greenhouse Gases (GHG) by 2050. The extent to which this target is achievable or not lies beyond the scope of this work. In the definition of scenarios, the corresponding contributions for supply and demand side are considered independently. In practice, it is expected that as one of them is significantly improved, then the other is directly affected in turn. Also, it is also worth noting that in case more parameters are needed (or available), additional margins can be added at any step (or year) of the iteration. Therefore, under these circumstances, the combination of these parameters defines 3 main trajectories of study:

1. Business as usual (BaU), with lack of investment on the supply side;
2. BaU, with assumed 80% decarbonisation of the supply side; and
3. better practices, with assumed 80% decarbonisation of the supply side.

There are some assumptions taken—that should be amended in the future—for the BaU trajectory. First, rates of household fragmentation, which also contribute to the population growth, are expected to reduce the average household size to nearly 2.0 by 2050. This not only increases the number of dwellings (perhaps also explaining an increase in suburban residential properties outlined in Figure 2), but also potentially contributes to higher EUIs. (Incidentally, the intensification of low-powered devices has in turn affected the distribution of EUIs in homes and even the frequency of presence (of occupants) in rooms, or for the case of modelling: thermal zones). This is due to a base energy-demand level that each dwelling reaches in average. Second, it is expected that a large-scale refurbishment of heating systems takes place over the next years, and that new constructions only install high-efficient or low-carbon technologies (e.g. district heating, heat pumps, solar hot-water, biogas/biomass sources). Moreover, although the efficiency of current heating system technologies (in cost and thermal energy) is expected to improve, there is evidence suggesting that the adopted indoor set-points will also increase. In practice, it is expected that if any of the aforementioned alternative heating systems is installed, then the adopted heating set-point may expectedly be more responsive and probably be lowered. For example, when a Ground Source Heat Pump (GSHP) is installed, a) either underfloor heating or larger radiators are installed in tandem, and b) the set-point is typically shifted down 0.5 °C; otherwise, the electric backup might as a result increase overall energy demand. Third, it is expected that all existing houses will insulate their façades and, together with new constructions, will comply with their corresponding Building Regulations. These insulations include optimally improved thermal transmittance of walls, roofs, lofts, floors, and windows, as well as draught proofing; yet in practice, there is evidence suggesting that not all the recorded insulations have been fully implemented, which propagates input bias into the stock evaluations. And finally, fourth, it is assumed that household appliances will be more efficient, their ownership will increase linearly, and their EUIs will be relatively maintained. This in practice is unlikely to be predicted accurately, given that both ownership and usage of appliances may transform drastically as it has happened in the past.

Additional considerations regarding hard-to-treat properties, that at present impose a significant hurdle to the large-scale refurbishment of the residential stock, are yet to be methodologically implemented. This includes (Ministry of Housing and Government; 2017), for example: interventions to improve loft conditions, when this has already been used as storage room or attic; problematic or unfeasible access to the loft excessive complication and costs associated to scaffolding (building height); unsuitable installation of heat pumps constrained by highly narrowed cavity walls; and walls with a predominant or spe-

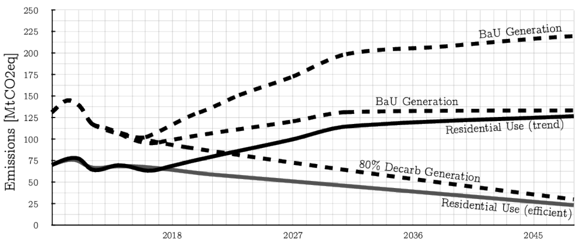


Figure 4: Projection of accumulated national emissions of residential sector

cialised finish. Their consideration is essential to determined whether additional stimuli is needed to intervene these properties.

The sequence of scenarios is developed with a span of 5-year margin calibration for each trajectory, and the simulations are run at hourly resolution, although some results are retrieved at daily resolution. Each simulation takes between 25 seconds (for smaller dwellings) and 150 seconds (for larger multi-storey dwellings) to complete, using a single core high-end computer. For this reason, a HPC facility is employed. In this way, not only the simulation process is detached, optimising memory resources, but also the simulation files may be allocated for parallel computation. The use of a (remote) HPC helps also to improve collaboration because users are able to monitor the simulations, to submit additional tasks, and to analyse data according to their own needs.

RESULTS

The simulation outcomes indicate that in absence of improvements in both supply- and demand-sides, the energy demand may even double by 2050. What seems striking, with respect to this increase, is that current practice is not substantially affected, i.e. household appliance ownership is not significantly intensified as compared to actual rate, nor is the uptake of fossil fuel systems increased. Correspondingly, an efficient scenario in both fronts reduces energy demand by more than three-quarters, and approximates to the 2050 decarbonisation target. A summary of these projections is outlined in Figure 4. Incidentally, it is worth highlight that in the past years, the contribution of end-use residential energy demand has been maintained in similar levels (shown in Figure 1). Thus, a purely statistical prediction might estimate residential use between trend and efficient lines in Figure 4.

The non-investment scheme depends exclusively on improvements in technology and best practices, and on the other end, an investment scheme that considers large-scale replacements such as renewable sources for power generation or low-carbon district heating. Note that, in principle, district heating reallocates the process of combustion that takes place in houses, and so the energy demand is

Table 2: Transition to a more efficient performance (carbon and temperature)

#	Typology	BASE → Eff
		Type
1	apartments	1,889 (19.2) → 475 (18.7)
2	bungalow	5,020 (18.9) → 514 (18.6)
3	detached	8,493 (17.7) → 2,677 (18.0)
4	semi-detached	6,301 (17.7) → 1,956 (18.0)
5	terraced	5,582 (17.7) → 960 (18.0)
		Epoch
1	pre-1919	6,210 (18.0) → 1,374 (18.0)
2	interwar	6,025 (17.9) → 914 (18.0)
3	postwar	5,338 (18.2) → 1,640 (18.0)
4	industrial	4,974 (18.3) → 108 (18.4)
5	modern	5,309 (18.3) → 442 (18.5)
6	post-2002	4,726 (18.4) → 2,163 (18.5)
		kgCO2.yr (Avg. In.Temp C)

not reduced at stock level per se. Because of the scale in which such a combustion, or conversion of energy, is performed, the overall efficiency of the system may be higher. Besides, district heating may also embed Combined Heat and Power (CHP) technology, increasing the efficiency of the whole system even more. For users, heat is available on-demand, which reduces waste during the warming process. It is in this way that energy demand can then be reduced as compared to an initial state.

Table 2 and Figure 5 compare efficient trajectories of improvement. The Table indicates the potential reduction of carbon emissions while marginally reducing the average indoor temperature for different typologies. The Figure shows a transition in terms of end-sue energy demand intensity by accumulated floor area, highlighting the presence of a certain space-heating configuration. As indicated previously, new technologies may be less intense, but may accumulate a significant contribution to energy use and corresponding carbon contributions, which depend on the quality and cleanliness of the future energy mix. The combined areas of the blocks in Figure 5 accumulate about 414 TWh on the upper side, and about 103 TWh on the lower one. Some of the average indoor temperatures are reduced, albeit in some cases the set-point was already above the reached levels and so is not impactful. Nevertheless, further investigation is required to determine whether real conditions are determined by the envelope or by household circumstances, as it has been identified in previous studies (Hamilton et al. 2017), and whether some values prioritise health over performance (Milner et al. 2014). Either way, this parameter may help to target future polices and may also help to better evaluate health and well-being.

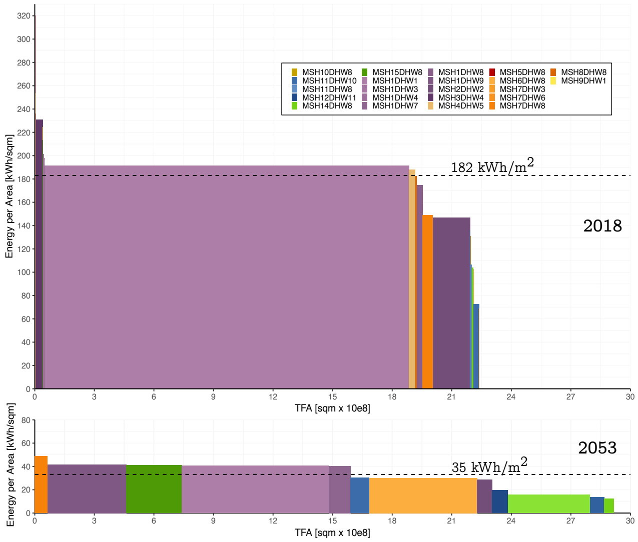


Figure 5: Energy intensity by accumulated floor area / 2018 and 2053 projection. Total floor area (→) x Energy intensity (↑) = Domestic sector energy demand (□). The colours are indicative of the main heating system; MSH1-3:gas, MSH4:oil, MSH5:solid, MSH6-8:electric, MSH9-10:air, MSH11-12:DH, MSH13:bio, MSH14:GSHP, MSH15:ASHP

CONCLUSION

The evaluation of improvements (all-things-equal) at stock level helps to identify the potential of large-scale investments in both supply- and demand-sides. Initially, such an evaluation may exclusively depend on a (generated or collected) snapshot of the population. However, although this practice seems succinct and it helps to prioritise future strategies, it also runs the risk of being quickly outdated, biased and potentially inappropriate over a short period of years. For this reason, it has been convenient to incorporate projections and potential changes to the structure of the stock and its performance, and whenever possible, to adapt new data. The challenges for representing a dynamic and evolving housing stock are vast. At the moment, this work applies margin calibration to initially represent a multi-dimensional stock transformation of the English housing stock. In future workflows, it is planned to include: climate change—including cooling demand; multi-stage evaluation of rebound effects; and a more refined representation of conditional uptakes (and trajectories) of energy-related measures.

The results of the evaluation also show that improvements to the efficiency of heating systems and household appliances may be shadowed if EUIs and higher set-points continue to grow; or more importantly, if the current dependence on fossil fuels to generate electricity and heat continues unabated in the coming years. Likewise, it is found that even though new constructions will significantly limit the accumulation of carbon at national level, large-scale refurbishments (of the existing stock) are needed to successfully achieve the 2050 decarbonisation targets. The results indicate also, however, that complementary empirical data is required to calibrate, rank and, if possible, validate our predictions. This includes a methodological interpretation of household circumstances; a comprehensive simulation of investment decision-making and adoption of better practices (with their corresponding counter-effects or rebounds); and a comprehensive emulation of the transition of the power sector to low-carbon.

To sum up, if housing stocks evolve and transform, then any policy or instrument used to forecast its energy demand, and carbon contribution, should be capable of reflecting such transformations, and of updating its estimations accordingly. This work helps to set-up some of these transformations; develops some (improvable) trajectories to reflect the impact of strategies exogenous and endogenous to the energy flow in houses, which may in the end shape their corresponding national carbon emissions; and contributes to improve the evidence base of future housing decarbonisation policy.

ABBREVIATIONS

BaU Business as usual

BEIS Department for Business, Energy and Industrial Strategy

CHM Cambridge Housing Model

CHP Combined Heat and Power

DUKES Digest of UK Energy Statistics

EHS English Housing Survey

EnHub housing stock Energy Hub

EUI Energy Usage Intensity

GHG Greenhouse Gases

GSHP Ground Source Heat Pump

HPC High Performance Computing

HSEM Housing Stock Energy Model

ONS Office for National Statistics

UK United Kingdom

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