

A domestic operational rating for UK homes: Concept, formulation and application

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ABSTRACT

A Domestic Operational Rating (DOR) scheme is presented for assessing the energy performance of occupied dwellings. The DOR is complementary to the method used to generate the asset rating of UK dwellings: the Standard Assessment Procedure (SAP). The DOR is transparent, easy to calculate, based on readily available information, producible from daily smart meter data, calculable for any period on a rolling year basis and applicable across all UK homes.

The DOR method was developed using a new primary data set collected from 114 homes as part of the DEFACTo project. All were semi-detached, gas centrally heated, privately owned and internet connected properties, located in the English Midlands. The mean daily energy demands are analysed alongside information gathered through an energy survey and household questionnaires. These data are presented and analysed for the first time in this paper.

The DOR method, which is described in full, generates metrics that indicate the absolute and relative energy demands, greenhouse gas emissions and energy costs of homes. The DOR ratings for the D114 homes were stable from year to year. Comparing the DOR with homes' asset (SAP) ratings, indicates that the SAP rating poorly reflects the inter-home variation of households' actual energy demand. For the D114 homes, it was possible produce a reduced data Domestic Operational Rating, rdDOR, using the energy demands measured on only a few cold days.

Although developed in the UK context, the DOR is generally applicable to national, regional or local housing stocks in which daily energy demand is metered. Potential improvements to the DOR, and the need for trials using smart meter data from diverse homes and locations, are discussed.

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1. Introduction

The United Kingdom (UK) has the oldest housing stock of EU Member States, with nearly 38% of homes dating from before 1946 [5]. The energy use of this stock is currently 480.26 TWh pa,¹ which is 29% of all UK energy use [15,16]. The stock therefore represents, on the one hand, a major opportunity to reduce energy demands and greenhouse gas (GHG) emissions but on the other hand, a problem: a massive drain on energy resources, a major source of GHGs and a burden on the finances of UK households.

Yet energy demand reduction is essential if the UK is to meet its GHG emissions reduction targets [58].

Over the last 50 years there have been impressive improvements in the energy efficiency of the UK housing stock. GHG emissions resulting from energy use have fallen despite a 42% increase in the number of dwellings² and an increase in the internal winter-time temperatures. The real cost of energy to households is similar to that in 1970 (Fig. 1). This has been achieved by decarbonising the fuel used to heat homes, notably shifting from coal burning to

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¹ To convert from tonnes of oil equivalent (toe), the measure used in some UK government documents such as the Digest of UK Energy Statistics [15,16], a figure of 11,630 kWh per toe is used.

² Domestic building, and like terms, need to be treated with caution. In this paper domestic building is synonymous with dwelling, which means the physical object, the house, flat, bungalow etc. A home is an occupied dwelling, and a household, essentially, a group of individuals living together in the same dwelling. Throughout this paper an attempt has been made to use terms according to this system, but any errors will not affect the sense of the arguments.

Nomenclature

Uppercase

B	Benchmark
C	Linear equation constant coefficient
DD	Degree-days at dwelling/°C.days
DDS	Standard number of degree-days
DOR	Dwelling operational rating
DORB	Dwelling operational rating band
DY	Days
EC	Energy cost/£
ED	Energy demand/kWh
EER	Energy efficiency rating
EERB	Energy efficiency rating band
EIR	Environmental impact rating
EIRB	Environmental impact rating band
GG	Greenhouse gas emissions/kgCO _{2e}
GGF	Greenhouse gas emissions factor/kgCO _{2e} /kWh
M	Linear equation multiplication coefficient
P	Percentage/%
SC	Standing charge of fuel/£ per year
T	Mean daily ambient temperature
TFA	Total usable floor area/m ²
UC	Unit cost of fuel/£/kWh
WCF	Weather correction factor
WCW	Weather correction weighting

Lower case

e	Electricity
f	Fuel
g	Gas
h	Heat
o	Other purposes
s	Space heating
t	Total

Subscripts

a	Annual
d	Day
ddb	Degree-day base temperature
e	Estimated
h	Hour
n	Normalised by TFA
SAP	Standard assessment procedure
w	Weather corrected
Y1	Year 1
Y2	Year 2
5	When $4 < T < 6$ °C
<15.5	Ambient temperature below 15.5 °C
>15.5	Ambient temperature above 15.5 °C

the use of efficient gas central heating systems, and by decarbonising the electricity supply.

Incremental improvements to the energy efficiency of new dwellings, driven by the gradual tightening of the Building Regulations, together with initiatives to improve the energy efficiency of the existing housing stock have, since the turn of the millennium, begun to drive down the absolute energy demand of the stock. These improvements have been hard won and the opportunities for further efficiencies to the fabric and heating system of UK homes are diminishing.

The UK Committee on Climate Change (CCC)³ sees improvement in the transparency of, and ability to manage domestic energy demand as crucial to achieving the required step-change in GHG emissions [8]; this is enabled by the introduction of so-called smart meters. Such meters enable more transparent energy billing and more versatile fuel tariffs, but they also pave the way for stakeholders, from the central government through to the individual households, to better understand how much energy is used, when it is used, and how the use is changing over time.

Across Europe, some 80 million such meters have already been installed, representing 30% of homes, and over 200 million are expected by 2020 [33]. Smart meter data have been used to give insights into energy usage in the domestic sector e.g.: estimating temperature set-points and fabric thermal efficiency in housing stocks in Denmark [34]; estimating the potential of demand response for air conditioning in California [25]; consumption pattern analysis in China [61]; and attempts at non-intrusive load disaggregation in Australia [40].

In the UK the ambition is that every homes and business will have been offered a smart meter by the end of 2020 [51]⁴. The UK smart meters will record at 30 min intervals and these data will be collected and stored centrally by the Data and Communications Company [51]. There is however, tremendous sensitivity around smart meter data (e.g. [60]). The intention, therefore, is that UK householders will control what data is collected, at what time intervals and who can use it [13]. 'Energy services' might be provided in return for data access, for example, by providing an In-Home Display (IHD) which shows the current and past energy use, and how this compared with the energy use of other households. Making the fuel used by households more transparent could incentivise more energy efficient behaviours.

This paper proposes, for the first time, a Domestic Operational Rating (DOR) for the UK that capitalises on the availability of smart meter data. The intention is that the DOR will complement the existing UK asset rating scheme (Section 2) but quantify the actual, in-use energy demand (DORED), GHG emissions (DORGG) and energy costs (DOREC) of every UK home. It will account for all fuel use, the physical form of the dwelling, the heating system installed, the behaviour of the occupants and the effects of ambient temperature.

A fully functioning DOR could also facilitate the achievement of the CCC's call for a strengthening of the energy use in buildings 'compliance and enforcement framework so that it is 'outcomes-based' [8], i.e. based on the actual 'energy efficiency' of dwellings rather than the calculated/predicted carbon emissions; a move supported by others in the industry [12].

The DOR is developed using a new primary data set gathered from homes in the English Midlands, as part of the Digital Energy Feedback and Control Technology Optimisation (DEFACTO) project [45]. All the homes were owner-occupied and semi-detached with gas fired central heating, which represents the most commonly occurring occupant/house/system combination in the UK [17]. The DEFACTO project and data set collected is described in Section 3, but more fully in Haines et al. [35].

Every effort is made to document the proposed DOR scheme thoroughly (Section 4). Supporting data needed by the DOR scheme is taken from authoritative, primary sources: the composition of the English and UK housing stock [14],[46],[47]; national level energy-use data from the digest of UK energy statistics⁵ [15],

³ The CCC produces the five yearly carbon budgets and advice reports to the UK government to help keep GHG emissions reductions on track to achieve at least 80% reduction by 2050 compared to the 1990 level.

⁴ At the end of 2018, smart meters were installed in c27% of GB homes with mains electricity and c25% with a gas connection [21].

⁵ DUKES first published in 1950.

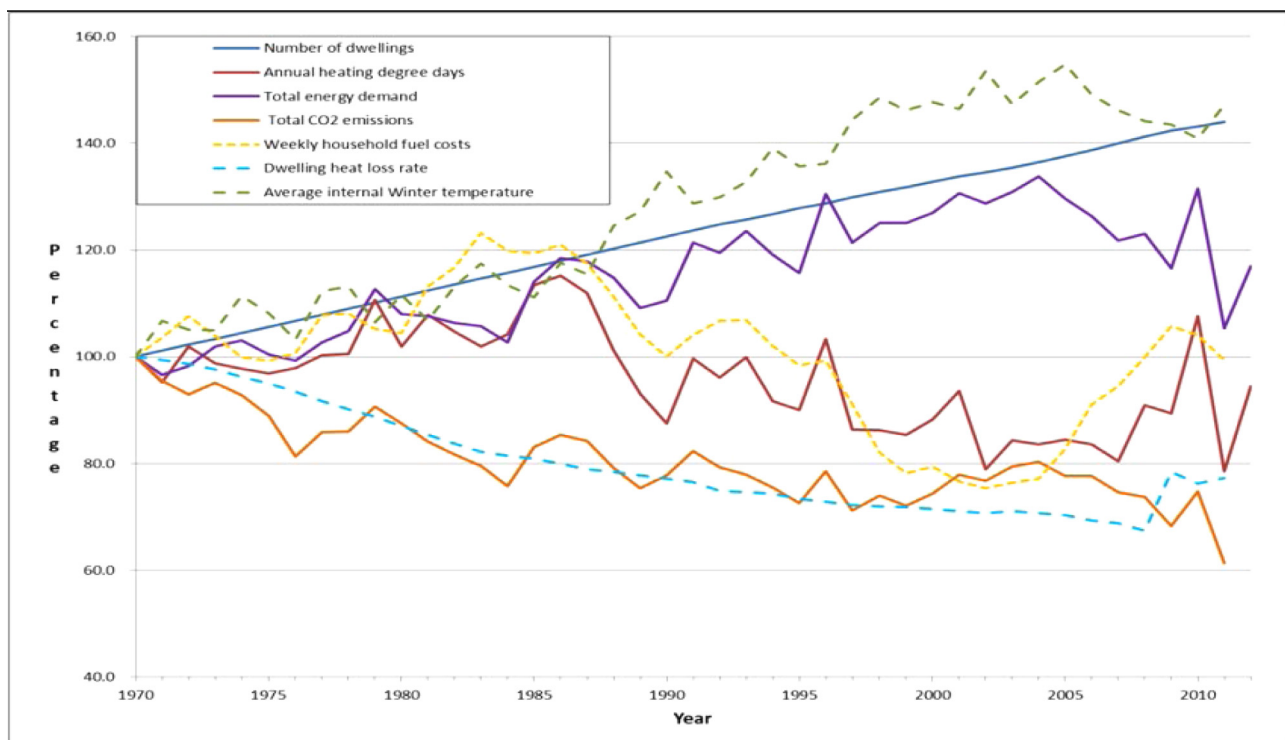


Fig. 1. Trends in the number of UK dwellings, the average heat loss, internal temperature and fuel costs, and the total stock energy demands and CO₂ emissions (derived from data tables associated with [55]).

annual weather data [16],⁶ a breakdown of energy demand by sector and the usage UK [17],⁶ GHG emissions [18] and household fuel bills [19]. Most of these data sources have associated tabular data or Excel files^{7,8}. Supplementary Information to this paper illustrates the functioning of the DOR equations for three selected homes and from the sample as a whole [42] and Excel tables provide the underpinning data [43].

2. Established energy rating schemes and the DOR scheme

If any proposed UK DOR scheme is to gain traction, it must complement, and sit harmoniously alongside, the existing well-established energy rating systems. A brief web-based review of international energy rating schemes revealed 17 asset rating schemes but only four operational rating schemes (see also [1]).

2.1. Dwelling asset rating schemes

All but two of the asset rating schemes, including the UK schemes, are mandatory and developed in response to the European Energy Performance of Buildings Directive (EPBD) [29], or its recast [30] and subsequent revisions (e.g. [31]). These, and a more recent Directive [32], require that “*The methodology applied for the determination of the energy performance of a building shall be transparent and open to innovation*”.

All the European schemes place a dwelling within a rating band (usually identified using an A to G scale) based on the calculated energy demand per year normalised by dwelling floor area. The

Cyprus, French, Ireland and Spanish schemes also produce a rating based on annual normalised GHG emissions. Asset ratings must be produced when dwellings are built or sold.

The UK Standard Assessment Procedure (SAP) is an exception because the Energy Efficiency Rating (EER_{SAP}) is based on the normalised annual energy costs,⁹ although an Environmental Impact Rating (EIR_{SAP}), based on the normalised annual GHG emissions, is also calculated and included on a dwelling’s Energy Performance Certificate (EPC) (Fig. 2).¹⁰ The two ratings are determined, using standard energy cost and GHG emission factors, from the calculated annual regulated energy demands. These are the energy demands that are controlled by the Building Regulations [37] and which therefore exclude the energy used by plug-in appliances, which was c26% of all UK domestic demand in 2016 [17].

As for other asset rating schemes, the data needed for SAP calculations is obtained from a home energy survey undertaken by a qualified assessor. A reduced data SAP, rdSAP, is invariably calculated as this has less onerous survey data requirements. The national Energy Performance of Buildings Register, currently holds over 18 million records, each of which includes the dwellings’ total usable floor area (TFA)¹¹ and the heating fuels used. The SAP has evolved through six or more official versions [4] culminating in the 2012 official version [22]. Although SAP2016 has been documented

⁹ Which perhaps portrays its 1986 origins as the Milton Keynes Energy Cost Index [48].

¹⁰ The EPCs were issued to the DEFACIO residents (e.g. Fig. 2) at the time the government was promoting The Green Deal. Launched in 2013, the scheme sought to help homeowners finance the installation of energy efficiency measures. The Green Deal was however, as the Secretary of State at the time, Edward Davey put it, ‘clunky and complex’ [23] and ultimately, it was disbanded, with the National Audit Office concluding that it ‘not only failed to deliver any meaningful benefit, it increased suppliers’ costs’ [49].

¹¹ Which is required for normalising the measured energy demand in the proposed DOR scheme and is defined in the Building Regulations as ‘the total area of all enclosed spaces measured to the internal face of the external walls’.

⁶ Available annually since 1970.

⁷ The documents and associated data files emerge frequently, but every attempt has been made to use the most up to date information at the time of authoring this paper.

⁸ To ensure that the basis of the DOR is traceable, the exact table from which data has been taken is provided wherever possible.

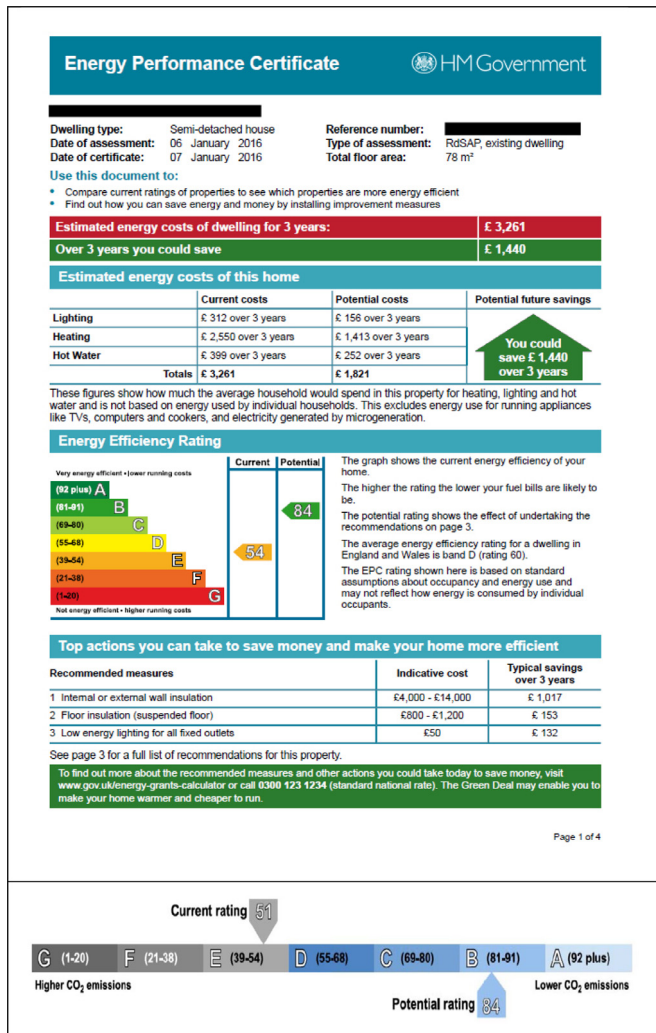


Fig. 2. Example Energy Performance Certificate (EPC) for D114 House #8: a. EPC page one showing the Energy Efficiency Rating and Band (EER_{SAP}, EERB_{SAP}) and b. excerpt from page 4 showing the Environmental Impact Rating and Band (EIR_{SAP}, EIRB_{SAP}).

[6], it will be overtaken by SAP10 [7] in 2019/20; the essential features of all three are, however, the same.¹²

A more complete explanation of the UK asset rating, set against the backdrop of trends in UK domestic energy demand, the building regulations and the introduction of smart meters, is given in further Supplementary Information to this paper [41].

2.2. Dwelling operational rating schemes

There is no UK operational rating for dwellings but a brief international review [41] revealed four schemes; in the USA, China, Germany and Latvia. All the schemes rated dwellings based on normalised and weather-corrected annual energy demands. The German scheme can generate two types of energy certificate (Energieausweis), an energy demand certificate (Bedarfsausweis) and an energy consumption certificate (Verbrauchsausweis). The de-

mand certificate provides an asset rating following the usual EPBD-compliance approach, while the consumption certificate reports an operational rating. One or other must be provided when a dwelling is bought or sold. Interestingly, the operational rating is seen as a cheaper and simpler alternative. Ratings for both the delivered and primary energy are based on fuel bills for three accounting periods and the location of the building (postcode), the age of the building, the floor area and the age of the heating system. The energy demand is weather-corrected, and the main focus is on space and hot water heating [39].

The US 'Energy Star: Home Energy Yardstick' provides households with a direct means of comparing their energy use with that of similar households via a free-to-use web-based calculator [27]. The yardstick was used about 14,000 times in 2017 [38]. The underlying method is an updated version of that reported in [28], the inputs to which are the homes' zip code, floor area, number of occupants, fuels used and 12 months of energy bills for each fuel. The rating is given on a scale of 0–10 where 0 is the worst, 10 the best and 5 average (median) when compared to a distribution. The distribution was calculated from 12,093 homes sampled as part of the 2009 Residential Energy Consumption Survey [26] using a multiple linear regression model that was trained to predict the annual energy demand from floor area, number of occupants and heating and cooling degree days. The homes in the sample were then ranked by the ratio of their actual energy use to the regression model prediction [28]. The web-based calculator uses the regression model to calculate the ratio for any home and compares the ratio to the distribution to give the rating.

2.3. Operational rating in the UK

Although there is currently no UK operational rating scheme for dwellings, there is for non-domestic buildings.¹³ The rating is calculated using approved software (e.g. [50]) based on the measured total¹⁴ annual fossil fuel and electricity consumption. From these data, the normalised GHG emissions for the year in question are calculated and compared to a bespoke benchmark emissions figure for that building. This benchmark is the 'stock average' normalised GHG emissions of all buildings in the same category [2]. Standard benchmarks for 29 categories of building (e.g. general office, large fuel store, etc.) can be found in CIBSE Technical Memorandum TM46 [10].

The building-specific benchmark figure is calculated by adjusting the standard value to account for the duration of occupancy and location (and so weather conditions) during the year of metering. The weather-correction is based on the local degree-days to base 15.5 °C, compared to a national average figure of 2021 °C.days. Corrections are, however, only applied to a proportion of the fossil fuel and electricity demands because only a portion of each fuel is deemed to be weather dependent.¹⁵

The operational rating must be renewed annually and the Display Energy Certificate (DEC) must show the rating obtained for the last two years. The DEC also, like a domestic EPC, also contains other useful data including the asset (EPC) rating. Further insight into UK operational rating is given in Lomas and Allinson [41].

¹³ An asset rating (EPC) is also required for non-domestic buildings, and these must be updated when the building changes hands. The rating is based on the calculated monthly regulated energy use and GHG emissions for a standard occupancy regimen and calculated using the Simplified Building Energy Model (SBEM) or other approved calculation programme used [50].

¹⁴ I.E. not just the regulated energy, as used for asset rating of both non-domestic and domestic buildings.

¹⁵ Part of the energy demand is also excluded from the calculation, the so-called separable energy. This is the energy used for process within the building such as trading floors, regional server rooms, bakery ovens, sports flood lighting, furnaces and blast chilling and freezing plant, etc.

¹² At the time of writing, the proposed 2016 version was available for consultation but not for official use [6]. Very recently it has become apparent that this 2016 version is unlikely ever to come into force and will be overtaken by SAP10, the content of which is published [7]. There is no difference between these versions in all aspects that affect the DOR except that the emissions rating for grid electricity has fallen substantially between SAP2012 and SAP10.

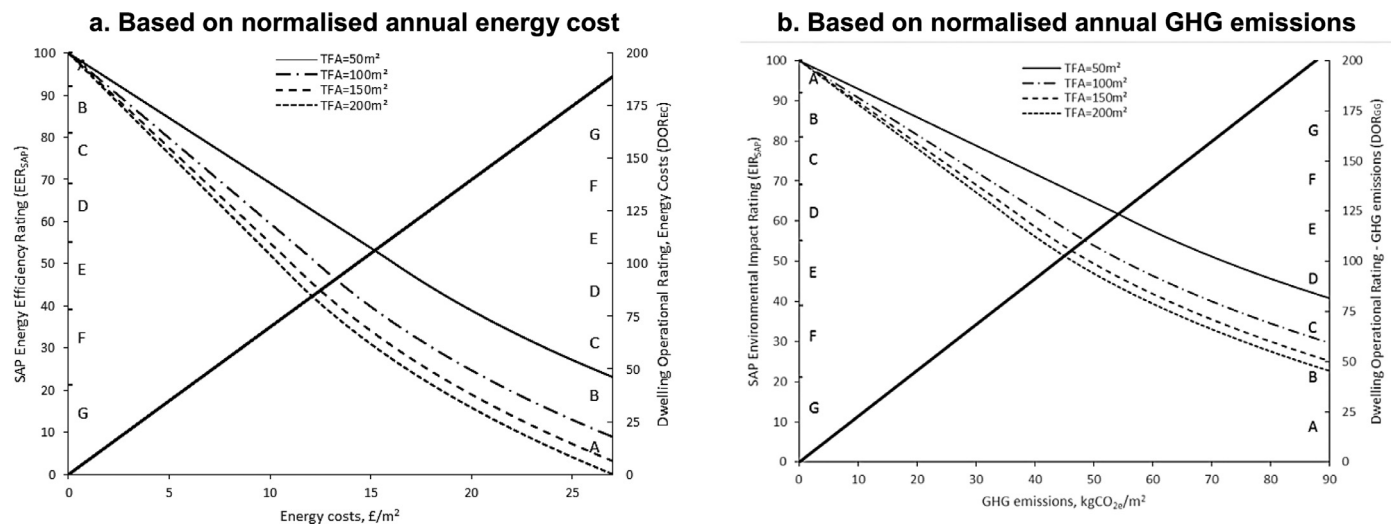


Fig. 3. Comparison of rating and banding scales as used in the UK for domestic asset rating (a. non-linear and b. non-linear), for non-domestic operational rating (b. linear), and as proposed for the DOR (a. linear and b. linear).

2.4. Operational and asset rating scales

An important decision when considering a DOR is the choice of rating scale, both the underlying calculation and the definition of the rating bands. The rating scale used to produce the EER_{SAP} is curious, being partly linear and partly non-linear with respect to the energy costs (kWh/m^2 pa) and largely, but not quite, independent of the dwelling's floor area (see [Appendix A](#)). The scale is framed such that a home that has zero annual energy costs is rated 100 and the rating falls as the energy costs increase ([Fig. 3a](#)). The EIR_{SAP} curves mirror the EER_{SAP} rating scale with a zero-emission dwelling having a rating of 100 ([Fig. 3b](#)). The rating bands are of unequal 'size'¹⁶ and the divisions can be set to produce any desired distribution of bandings across the national stock [36].

In contrast, the scale used to produce an operational rating for non-domestic buildings (and also the non-domestic asset rating) is quite different ([Fig. 3b](#)), being linear such that lower emissions produce a lower rating and a better the rating band (a rating of 0 to 25 is Band A). The bands are divided into equal increments of 25 rating points and organised so that a building with zero GHG emissions is rated zero and a building that produces the stock average GHG emissions is rated 100, which is positioned at the interface between Band D and Band E. The simple equations to calculate the operational ratings for energy costs and GHG emissions¹⁷ are given in [Appendix A](#).

Self-evidently, any chosen DOR scale cannot simultaneously align with the UK domestic asset rating scales and with the non-domestic operational rating scales.

2.5. Features of the DOR scheme

Flowing from the discussion above, the key features of a functioning UK DOR scheme can be outlined. Most obviously, it should be applicable to all UK homes and use a transparent and reliably replicable method of calculation. It should capitalise on the best

international practice for the operational rating of dwellings but it must operate in harmony with the existing UK domestic asset rating [22]. The DOR can therefore capitalise on the known dwelling fuel types and TFAs, which are provided by the asset rating survey.

In developing the DOR, the idea of comparing measured energy demand, GHG emissions and costs to external benchmarks is adopted, much like the approach used for UK non-domestic operational rating. Also, in keeping with this approach, and because the measured energy demands of the DEFACIO homes affirmed its appropriateness (see [Section 4](#)), a degree-day base of $15.5^\circ C$ was used of weather normalisation. However, in contrast to the UK non-domestic operational rating scheme, the actual energy demands of homes are weather-corrected rather than the benchmark against which uncorrected demands are compared.¹⁸ This correction method inherently adjusts the proportion of each fuel that is weather-corrected (depending on the mode of space and DHW heating demand and the fuel used).

Concerning rating scales, a linear scale has clear advantages: being simpler and more transparent but still offering flexibility to governments or other regulatory bodies to set any desired rating band intervals, as in the SAP method. A linear scale is also much easier for a household to understand and it enables the impact of changes in energy demand, GHG emissions and energy costs to be estimated. For example, for dwellings with a near stock-average floor area of $100 m^2$ ([Table 4](#)), an annual reduction in energy cost of £14.40 would always yield a reduction (improvement) in the rating of one point (see [Fig. 3a](#) scale).¹⁹

The DOR certificate might follow the style of EPC certificates and include multiple ratings for energy demand (DORED), GHG emissions (DORGG) and energy costs (DOREC) and also additional information to guide households that wish to reduce their energy

¹⁶ If EER_{SAP} or EIR_{SAP} is greater than 92, the Band is A; 91 to 81 Band B; 80–69 Band C; 68–55 Band D; 54–39 Band E; 38–21 Band F; and 20 or less Band G ([6]; [Figs. 2 and 3](#)).

¹⁷ The equations are shown for benchmark costs and emissions of $14.40 £/m^2$ and $46.17 kgCO_{2e}/m^2$ respectively. A linear rating scale based on energy demand can also be easily constructed.

¹⁸ The problem with weather-correcting the benchmark, is that the proportion of the benchmark energy demand that is weather-sensitive, and so to be corrected, has to be chosen. In practice, whilst this might be possible for non-domestic buildings, the proportion to be corrected could vary markedly from home to home, and for any given home, from year to year. Thus, any assumption about the proportion of the benchmark to be weather-corrected cannot be correct for all homes simultaneously.

¹⁹ A zero-cost dwelling has, quite logically, a rating of zero and, if a house has embedded generation, a 'profit' from the sale of energy would yield a negative cost, which could be recognised, for example, by the creation of an A+ rating band.

Table 1
Desired features of a DOR scheme.

- Applicable to all UK dwellings irrespective of type, insulation standards, heating system and occupancy.
- Calculation should be transparent, simple and clearly documented.
- Complementary to established asset rating systems (the Standard Assessment Procedure).
- Based on the total, not just regulated, normalised and weather-corrected annual energy demands.
- Annual ratings should be possible starting at any point in time.
- Produces ratings for all fuel types, not just those that are regularly metered.
- Minimal need for any data other than that from smart meters.
- Disaggregation of space heating, domestic hot water and electrical energy use.
- Respectful of household's privacy, and so based on measurements at daily, or less frequent, intervals.
- Provides ratings for energy demand (DORED), GHG emissions (DORGG) and energy costs (DOREC).
- DORGG should be sensitive to changes in the grid and locally generated energy.
- DOREC should be sensitive to changes in annual fuel prices.
- All ratings should be stable year-on-year in the absence of energy saving actions.
- DOR certificates might provide other useful energy, GHG and cost-related information to households.
- Information to households might be relayed in an easy-to-assimilate manner through an in-home display.
- Enables a national stock-wide data base of energy demand, GHG emissions and energy costs.
- Supports moves towards performance-based regulation of domestic energy demand.

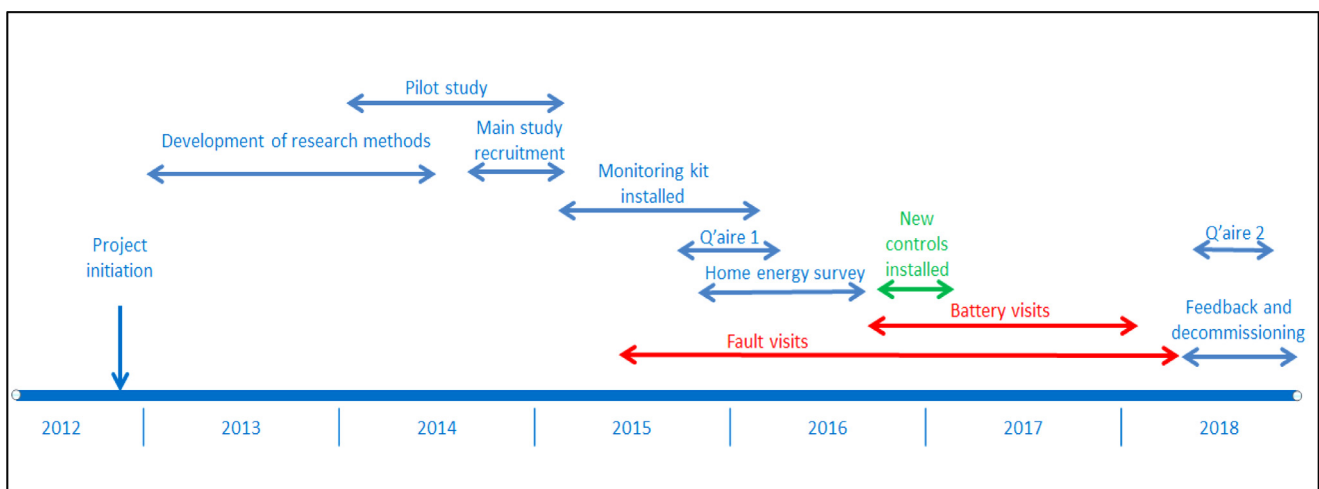


Fig. 4. DEFACTO project time line (after [35]).

demand, costs or GHG emissions. Such information emerges from the proposed DOR calculation strategy. The established 'rainbow' colour palette for the energy bands can be adopted.

Other desirable features of a DOR scheme are also listed in Table 1. Whilst framed in the context of the UK, these features would guide the development of a DOR scheme for any country. Importantly, the DOR scheme will drive the creation of a national, stock-wide data base of in-use energy demand, GHG emissions and energy costs. This would provide a solid platform for developing national domestic energy policy.

3. Description of the data set

3.1. The DEFACTO cohort

The development of the DOR was made possible through the collection and analysis of the data gathered as part of the DEFACTO project, which started in November 2012 and ran to October 2018 (Fig. 4). The cohort of owner-occupied, semi-detached, gas centrally-heated homes, were located in the English Midlands in seven clusters, each with an associated weather station (Fig. 5). The sample was chosen because less is known about the energy demand of owner-occupied homes compared, say, to households in social housing, and the house type and heating system are representative of the most frequently occurring combination in the UK

stock. The central location ensures that the weather conditions will be close to the UK average.²⁰

Of the 393 households²¹ recruited to the study, a full set of half hourly gas measurements, and two minutely electricity demand measurements were available from 186 homes²² for the period from 1st September 2015 to 31st August 2016. When aggregated these produce a half-hourly dataset analogous to that from smart meters. In addition, all 393 households completed a recruitment interview, 167 the initial household questionnaire, and a home energy survey (EPC+) was undertaken for 174 homes; 163 homes had all three sets of information, and 134 all three sets of information and monitored energy demand data. This is believed to be one of the largest and longest unbroken streams of domestic half-hourly gas and electricity energy use data in the UK that has matched dwelling and occupant data²³.

²⁰ The primary aim of the DEFACTO project was to measure the energy saving capability of, so-called, smart heating controls when used with gas-fired, low-pressure hot water central heating systems. The evidence for the energy savings and cost effectiveness of such controls is either very weak or non-existent [44].

²¹ Of the 400 that agreed to take part, seven withdrew immediately and before their addresses were passed to the research team.

²² Temperatures were also measured in all the rooms of the homes at 5 minute intervals. Gas metering only, was installed in 63 homes and electricity and space temperature monitoring only in 2 homes.

²³ For example, the 2017 English Housing Survey collected gas data from c160 homes.

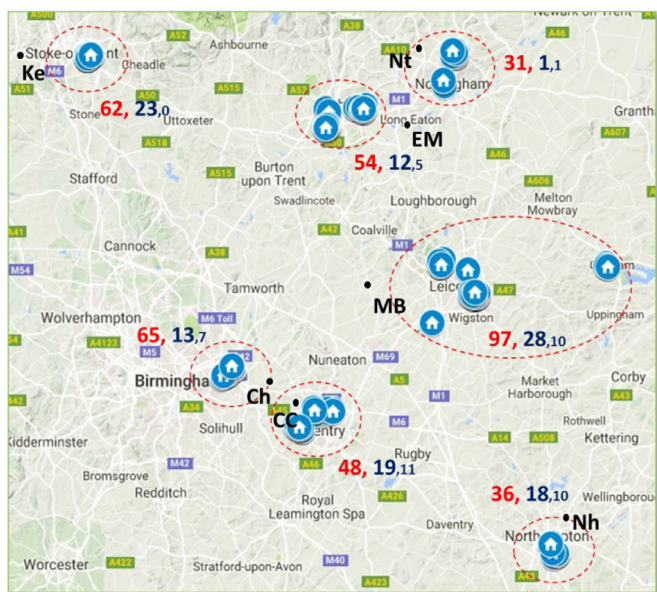


Fig. 5. Location of homes in the DEFACTo study showing: Red - numbers recruited (total 393); Blue, large - the number in the D114 Year 1 sample; Blue, small - the number in the D114 Year 2 sample; and Black - the weather station codes (see Table 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The EPC+ survey was an extended version of that used to generate the Energy Rating (EER_{SAP}) of the homes. It yielded the total usable floor area (TFA), which is needed for the DOR calculations, as well as the dwellings' SAP rating. Considerable effort was directed towards ensuring the reliability of the EPC+ survey data. Detailed information about the recruitment, questionnaires, EPC+ survey, energy monitoring, data cleaning and cohort maintenance processes can be found elsewhere [35].

Throughout the DEFACTo project, considerable effort was directed towards maintaining the largest possible cohort of homes. Nevertheless, there was gradual attrition as households withdrew from the study, and, ironically, as smart meters were installed; such attrition is not unusual with longitudinal studies of this type.

3.2. The D114 sample

The DOR scheme was developed and illustrated using a subset of 114 homes, which were drawn from the 134 for which a recruitment interview, household questionnaire, EPC+ survey, and monitored data for the year (of 366 days²⁴) from 1st September 2015 to 31st August 2016 was available. For 20 homes, data inspection and cleaning indicated that some of the data may not have been sufficiently reliable for derivation of the DOR scheme.²⁵

Daily energy use data for the subsequent year, 1st September 2016 to 31st August 2017, was also used in order to evaluate the stability of the values produced by the DOR scheme. Cohort attrition meant that, of the 114 homes selected for Year 1, only 44 con-

tinued to produce reliable gas and electricity data for the whole of Year 2.

3.2.1. Comparison with English housing stock

The resulting D114 sample is different from the English housing stock of 14,755,000 homes for those features that were deliberately selected: tenure, house type and heating system (Table 2). The proportion of condensing combi-boilers was also much higher compared to the English stock (62% cf. 39%); hence the percentage of standard (non-condensing) boilers was much lower.

Although the average floor area of the D114 homes was similar to the English average, because all the homes were semi-detached, the variation in floor area was compressed, with notably fewer homes having a floor area of <69 m² (4.45%, cf. 16.8% nationally), which is typical of flats and apartments. The households were larger than the English stock as a whole, there were fewer household representative persons in full time work and a larger proportion that were in the 'other inactive' category.²⁶ The income of the D114 households was however similarly distributed across the income quintiles. Concerning the energy efficiency of the homes, which is important for the development of the DOR, the homes spanned the SAP bands but there were fewer very inefficient homes (Bands F and G) than in the English stock.

3.2.2. The weather conditions

The weather data were collected from seven sites operated by the British Atmospheric Data Centre, which were located close to the D114 homes (Fig. 5). Each site reported hourly ambient air temperatures from which the mean daily and monthly temperatures and the degree-days to base 15.5 °C were calculated. During the period of interest, 1st September 2015 to 31st August 2016, the lowest mean daily temperature was −0.41 °C on 20th January 2015 at Coventry and the highest 24.7 °C on 19th July 2016 at Coleshill. Because of the close proximity of the clusters of dwellings, the mean daily temperatures differed very little: by less than 2 K across all seven sites for all but 22 of the 243 days in the nominal heating season (September 2015 to April 2016); the largest difference during this period was 3.3 K on 27th December. The mean monthly temperatures were therefore also similar, never differing from each other by more than 1.3 K (December 2015), with Keele, which is the northern-most site, being cooler than the other sites in every month of the year (Table 3). Because of the geographically central location of the D114 homes, the mean monthly temperatures were also close to the reported Central England Temperature (CET)²⁷ and GB-wide means for the same period (Table 3).

During the monitoring period, the weather conditions were very close to the long-term average for GB, the UK and the English Midlands region (Table 3), all of which are very similar. In the first half of the winter (November, December and January) temperatures were lower than the long-term averages²⁸ but during the second half they were higher. The net result was that the degree-days to base 15.5 °C ($DD_{15.5}$), ranged from 2186 °C.days in Keele to 1920 °C.days in Coventry, with an average across all seven sites of 1995 °C.days. This average is very close to the average value for GB as a whole for the same period, 1984 °C.days [16] and also close to, but a little less than, the long term Midlands and UK average degree-days of 2080 and 2021 °C.days respectively (Table 3). The latter value is used for weather correction when calculating the operational rating of non-domestic buildings [10].

²⁴ The extra day during the leap year of 2016, was ignored as the effect of the extra day on energy demand calculations, is small, <0.3%. Adjusting for the extra day also adds unnecessary complexity, but in a full implementation of the DOR this adjustment could be made.

²⁵ Daily gas data: for many homes, there were days of zero gas demand scattered throughout the year and in some cases, periods of two weeks or more of no gas use. If gas demand was recorded in the subsequent winter, the home was retained in the sample. Daily electricity data: some meters were found to be faulty and so replaced but this resulted in large gaps in the electricity data and so these homes were excluded. Two homes were excluded because they were found to no longer meet the original project inclusion criteria, e.g. solar PV panels had been installed.

²⁶ In making these comparisons it is assumed that the householders that preferred not to disclose information were proportionately distributed across the positive response categories.

²⁷ The Central England Temperature (CET) represents that recorded in the triangle joining Bristol, London and Lancaster, and is the world's longest unbroken stream of mean monthly data, stretching back to 1659 [56].

²⁸ In fact, nationally, December 2015 was the warmest December since 1910.

Concerning the development and evaluation of the DOR scheme, a disadvantage of the weather experienced by the D114 homes is that, because it is close to the long-term average, the approach to weather-correction is not rigorously tested. An advantage

is that valid comparisons might be made between the energy demand of the D114 sample and the national average energy demands for the same year.

Table 2

Comparison of D114 cohort and 2015 English housing stock.

		D114 % ^a	English Stock 2015 % ^b	Data sources and comments
Households: tenure, size, work status and income ^c				
Tenure	Owner occupied	100	62.7	[46], AT2, Fig 2.1. Number of owner occupied homes: DEFACTO 114; English stock, 14,755,000. Average time living at the current address: D114, 20.5 years; owner occupied homes national average 17.8 years. (Owned outright 24.4 years, owned with mortgage, 10.2 years, [46], Headline report).
	Private rented	0	20.1	
	Local authority	0	7.0	
	Housing assoc.	0	10.2	
Number in household	1–2	47	64	ONS [52]. Average household size: DEFACTO 3.1 persons, English stock 2.4 persons [52,53].
	3–5	41	36	
	>5	13		
Age of Household	16–24	0	0.5	MHCLG [46] Table AT1.3 owner occupied homes
	25–34	5	8.9	
Represent. Person ^d	35–44	20	15.4	
	45–54	23	21.3	
(years)	55–64	31	19.0	
	65 or over	21	34.9	
Economic status of HRP	Full-time work	45	52.9	MHCLG [46] Table AT1.3 owner occupied homes.
	Part-time work	8	8.2	
	Retired	31	35.3	
	Unemployed	3	0.9	
	Full-time education	1	0.2	
	Other inactive	12	2.6	
Income band (£)	First quintile	11	12.8	Approximated by condensing DEFACTO decile bandings to annual gross income bands calculated from MHCLG [46] Table AT1.3. Owner occupied homes only. The quintile bands are: First quint ≤ £14,803; Second £14,804 to £23,795; Third £23,796 to £35,631; Fourth £35,632 to £53,695 Fifth quint. ≥ £53,696.
	Second quintile	16	17.0	
	Third quintile	27	20.0	
	Fourth quintile	20	23.7	
	Fifth quintile	26	26.6	
Dwellings: type, age and construction ^e				
Type	Terraced	0	26.0	MHCLG [46] Fig 2.3 Owner occupied dwellings.
	Semi-detached	100	30.6	
	Detached	0	25.1	
	Bungalow	0	10.3	
	Flats/apartments	0	8.0	
Usable floor area (m ²)	<50 m ²	0	3	MHCLG [46] Fig 2.4, and Table AT2.1 'Usable floor area', owner occupied dwellings. Values for all forms of tenure are very different. Average floor area: D114, 100 m ² ; English stock, owner occupied homes, 108 m ² , all tenures, 94 m ² .
	50 – 69	5	13.8	
	70–89	40	29.8	
	90–109	26	19.7	
	>110 m ²	29	33.8	
House age (years)	Pre 1919	12	20.3	MHCLG [46] Fig 2.2, Table AT2.1, owner occupied homes. DEFACTO values interpolated from age bands used in questionnaire survey.
	1919–1944	32	17.7	
	1945–1964	17	19.1	
	1965–1980	35	19.6	
	1981–1990	0	7.9	
	1991–2002	1	7.9	
	post 2003	3	7.5	
Wall construction And insulation	Cavity wall no insulation	12	20.6	MHCLG [46] Table AT2.13, owner occupied homes of all types.
	Cavity wall insulated	61	49.6	
	Solid wall no insulation	23	25.8	
	Solid walls insulated	1	2.2	
	Other	2	1.8	
				D114, 'Other', were all timber framed.
Loft insul'n	200 mm or more	40	37.8	MHCLG [46] Table AT2.12, all tenancies.
Glazing	Double glazed	96	81.4	MHCLG [46] Table AT2.12, all tenancies.
Heating system ^e				
System type	Central heating	100	95.3	MHCLG [46] Table AT2.9, owner occupied.
	Storage heating	0	3.2	
	Fixed or port. heat.	0	1.6	

(continued on next page)

Table 2 (continued)

		D114 % ^a	English Stock 2015 % ^b	Data sources and comments
Boiler type	Standard non-cond.	7	21.4	MHCLG [46] Table AT2.11 figures for owner occupied homes and all dwelling types.
	Standard cond.	17	19.9	
	Combi. boiler	12	11.0	
	Combi. cond.	64	39.0	
	Back boiler	0	3.1	
	No boiler	0	5.6	
SAP rating band ^c				
	Band A/B	3	1.0	MHCLG [46] Table AT2.7, owner occupied homes, rating bands.
	Band C	26	22.7	MHCLG [46] Table AT2.6, owner occupied homes, mean SAP rating 60.5.
	Band D	63	52.4	
	Band E	8	18.7	D114 mean rating 63.9.
	Band F	0	4.2	DBEIS [17], Table 3.15, mean SAP rating for all UK homes, 62.
	Band G	0	1.0	

Bold italic deliberately selected feature of DEFACTO cohort.

^a In general, percentages given for the owner occupied homes only, exceptions are noted.

^b Percentages ignore null responses, which were: Household size 28 responses (24%); Age of HRP, 25 responses (22%); Economic status, 29 responses 25%; Income band, 40 responses (35%).

^c D114 from household questionnaire surveys.

^d The Household Representative Person was usually the person that completed the recruitment questionnaire.

^e D114 values from EPC + Home Energy Survey.

Table 3

Weather conditions in Year 1 and regional, GB and UK comparators.

	Year 01/09/ 2015 to 31/08/2016									Averages and standard values				
	Measured at DEFACTO weather stations									CET ^a GB ^b		GB ^c Av. 1981–2010		
	Nt	Nh	Ke	EM	Ch	CC	MB	Av.	Range			Mid's ^d	UK ^d	
Monthly mean temperatures/°C														
Sep	12.3	12.5	11.7	12.4	12.2	12.4	12.1	12.2	0.8	12.6	12.7	14.0	14.0	14.1
Oct	10.6	10.8	10.2	10.9	10.6	10.7	10.5	10.6	0.7	11.0	10.9	10.6	10.5	10.6
Nov	8.9	9.4	8.5	9.3	9.4	9.4	9.0	9.1	0.9	9.5	9.5	7.3	7.1	7.1
Dec	9.2	9.9	8.6	9.8	9.9	9.8	9.4	9.5	1.3	9.7	9.5	4.7	4.2	4.2
Jan	5.3	5.3	4.7	5.7	5.5	5.4	5.1	5.3	1.0	5.4	5.7	4.6	4.3	4.3
Feb	4.7	4.9	4.1	5.0	4.9	5.0	4.6	4.7	0.9	4.9	5.1	4.6	4.8	4.9
Mar	5.4	5.3	4.8	5.6	5.6	5.6	5.1	5.4	0.8	5.8	6.1	6.5	6.6	6.5
Apr	6.9	7.2	6.6	7.1	7.3	7.3	6.9	7.0	0.7	7.5	7.5	8.4	9.0	8.9
May	11.9	12.2	11.8	12.1	12.2	12.4	11.8	12.1	0.6	12.5	12.2	11.4	11.8	11.7
Jun	14.6	14.7	14.3	14.9	15.1	15.1	14.6	14.8	0.8	15.2	14.9	14.1	14.8	14.6
Jul	16.9	17.3	15.5	17.1	17.0	17.2	16.6	16.8	0.8	16.9	16.7	16.4	16.6	16.6
Aug	16.8	17.4	15.6	17.0	17.0	17.2	16.7	16.8	0.8	17.0	16.9	16.2	16.5	16.4
Average	10.3	10.6	9.7	10.6	10.6	10.6	10.2	10.4	0.8	10.7	10.5	9.9	10.0	10.0
Annual Degree days to base/15.5 °C														
Annual	2018	1939	2186	1928	1931	1920	2042	1995	266	–	1887 ^e	2176 ^f	2080 ^g	2021 ^g

Key: Nt, Nottingham Watnall; Nh, Northampton Moulton; Ke, Keele; EM, East Midlands; Ch, Coleshill; CC, Coventry Coundon; MB, Market Bosworth.

^a Central England Temperature record, source [56].

^b DBEIS [16] Table 1.1.9. Mean air temperatures.

^c DBEIS [16] from Table 1.1.7. Mean air temperature deviations.

^d The Standard Assessment Procedure (SAP), mean monthly temperatures for the English Midlands and for UK as a whole are given in SAP 2012 [22], SAP 2016 [6] and SAP10 [7].

^e Calculated for the period from 01/09/15 to 31/08/16, using the monthly degree-days from 17 weather stations in DBEIS [16] Table 1.1.8.

^f The GB average for the period from 1981 to 2010, DBEIS [16] Table 1.1.8.

^g Technical Memorandum TM46 [10], Table A1.1.

3.2.3. The energy demand and estimated GHG emissions and energy costs

The credibility of the measured D114 mean energy demands, and the mean energy costs and mean GHG emissions calculated using SAP2016 conversion factors, can be assessed by comparison to the known mean values for the UK stock of 27,672,000 homes, for all types and tenure for the year 2016²⁹ [17], (Table 4).

The D114 sample has mean gas and electricity demands that are higher than the UK mean, the total demand being 9% greater. However, because the D114 homes have, on average, a larger floor area than the national average (100.1 m² cf. 94 m²), the normalised mean gas, electricity and total energy demands are only 3 to 4% greater than the UK stock mean. This small difference could be because the D114 homes experienced colder conditions than the UK stock of 2016.³⁰ The mean split between gas and electricity de-

²⁹ Government statistics are given by calendar year. It is not possible to determine the UK stock values for the exact same year as the DEFACTO homes' measurements. The figures available are not broken down by tenure.

³⁰ The D114 average degree-days for 2015/16, 1995°C.days, is 5% higher than the UK average for 2016 of 1887°C.days [16].

Table 4

Comparison of the energy demand, GHG emissions and energy costs of the D114 homes with the mean for the 2016 UK stock.

Fuel	Symbol	Units	D114 Homes					UK stock 2016 ^a	Source
			Mean	Median	Max.	Min.	Sd.		
Energy demand									
Gas	EDg	kWh	14,977	13,588	45,068	2691	6437	13,810	DBEIS [15], Table3.03, 2016
Elec.	EDe	kWh	4290	3896	12,730	993	1908	3889	
Total	EDt	kWh	19,267	17,888	57,799	5800	7708	17,699	
Split: gas/elec.		%	77:23	78:22	90:10	–36:64	-	78:22	
GHG emissions ^b									
Gas	GGe	kgCO ₂	3115	2826	9374	560	1339	3843^c	DBEIS [18] Table 3, 2016
Elec.	GGg	kgCO ₂	1707	1550	5067	395	759		
Total	GGt	kgCO ₂	4823	4460	14,441	1619	1886		
Split: gas/elec.		%	64/36	65/35	83/17	23/77	–		
Energy cost ^e									
Gas	ECg	£	742	682	2042	211	278	620^h	DBEIS [19] Table 2.3.2
Elec.	ECe	£	724	664	2017	219	292	549^d	
Total	ECt	£	1466	1373	4059	614	508	1169	
Split: gas/elec.		%	51/49	51/49	71/29	20/80	–	53:47	
Floor areas									
–	TFA	m ²	100.1	92.0	210	62	28.8	94.0^e	
Normalised energy demand, GHG emissions and Energy costs ^f									
Gas	EDgn	kWh/m ²	151.3	147.8	286.0	32.5	51.6	146.9	As above divided by 94
Elec.	EDen	kWh/m ²	43.2	42.5	95.0	12.9	15.0	41.4	
Total demand	EDt _n	kWh/m ²	194.5	194.8	338.6	57.4	57.1	188.3	
GHG emissions	GGt _n	kgCO _{2e} /m ²	48.7	47.6	80.9	16.0	13.5	40.9	
Energy costs	ECt _n	£/m ²	14.89	14.52	22.96	6.45	8.3	15.59	

^a UK stock mean for 2016 all tenures, breakdown by tenure type not available.^b The GHG emissions for the D114 homes are estimated by using the SAP2016 GHG emissions intensities of 0.208 kgCO_{2e}/kWh for gas and 0.398 kgCO_{2e}/kWh for electricity [6].^c Figure derived by dividing the UK stock GHG emissions of 106.7 MtCO_{2e}, as given in the stated source, by total number of UK households in 2016, 27,672,000 ([17], Table 3.03).^d The cost of electricity was derived by averaging the cost of 3800 kWh of standard tariff electricity (i.e. ignoring Economy 7 tariffs) for all three methods of payment, and for all three UK administrations, England/Wales, Scotland and Northern Ireland as given in the stated source. The resulting cost of 14.13p/kWh was then scaled to the actual mean demand of the UK stock, 3889 kWh.^e The floor area of the UK stock was not readily available. Figures presume the 2016 UK stock has same mean floor area as English homes, i.e. 94 m² (see Table 2).^f The normalisation for the D114 homes is undertaken on a house by house basis, whilst for the UK stock it is obtained by dividing the mean values by the mean floor area (94 m²).^g The costs of energy for the D114 homes are estimated using the SAP2016 [6] values of £95 standing annual charge and 4.32 p/kWh for gas, and £67 standing charge and 15.32 p/kWh for electricity.^h The cost of gas was derived by simply averaging the costs of 15,000 kWh for all three methods of payment for both England/Wales and Scotland as given in the stated source. (Nb. the figure is thus for GB not the UK, as incorrectly stated by DBEIS in the title of the reference). The resulting cost 4.49 p/kWh, was then scaled to the actual mean demand of the UK stock, 13,810 kWh.

mand of 77%:23% is very similar to the split for the UK stock as a whole.

The estimated mean energy cost for a D114 household, which was deduced from the standard gas and electricity costs given in SAP2016, was £1466 pa. This is 25% more than the UK mean, but after normalisation by floor area is just 4.5% less. The normalised GHG emissions of 48.7 kgCO_{2e}/m² are greater than the UK mean by 19%, which, given the similarity of the energy demands, is clearly a consequence of the emissions factor associated with the DEFACTO measurements. In fact, the difference may be entirely due to the fall in the emissions from electricity generation³¹; the SAP2016 emissions factors for electricity is about 71% greater than the emissions factor used in SAP10 [7]. Whilst these comparisons give assurances about the reliability of measured energy demands and calculated energy costs they suggest that the absolute GHG

emissions might be overestimated,³² the consequence of rapidly changing GHG emissions (and energy costs) for a DOR scheme is discussed later (Section 10).

Within the D114 sample, there was considerable variability in the energy demands of the individual homes. The highest consuming household used 17 times more gas and 13 times more electricity, and 10 times more energy in total, than the lowest consumer (see max. and min. values in Table 4). The gas demand was significantly positively skewed.³³ After normalising, the variation between the highest and lowest consumers was reduced with the highest gas, electricity and total energy using households using, respectively, 8, 7.4 and 5.9 times more energy (Table 4). The gas demand distribution remained significantly positively skewed,³⁴ though slightly less so than the non-normalised distribution. The variations in the energy costs and GHG emissions are similar.

The split between the gas and electricity demand varied markedly from home to home (Table 4), from 90%:10%, gas: elec-

³¹ The emissions factor for mains gas of 0.208 kgCO₂/m³ has remained stable over the last three versions of SAP, whereas the value for electricity has fallen progressively as the proportion of renewable and low-carbon energy sources has increased; SAP2012, 0.519; SAP 2016, 0.398; and SAP10, 0.233. Had the SAP10 emissions factor for standard electricity of 0.233 kgCO_{2e}/kWh rather than the SAP2016 value of 0.398 been used, the mean D114 household emission from electricity would have been 999 kgCO_{2e} rather than 1707 kgCO_{2e} giving a total of 4114 kgCO_{2e}, which is 41.1 kgCO_{2e}/m²; just 0.5% higher than the UK stock average of 40.9 kgCO_{2e}/m².

³² But, provided the same emissions factors are adopted in developing the GHG emissions benchmark, the operational rating based on GHG emissions (DORGG) will not be affected (see Appendix B).

³³ Shapiro-Wilk test 0.940, skewness 0.596.

³⁴ Shapiro-Wilk test 0.967, skewness 0.312.

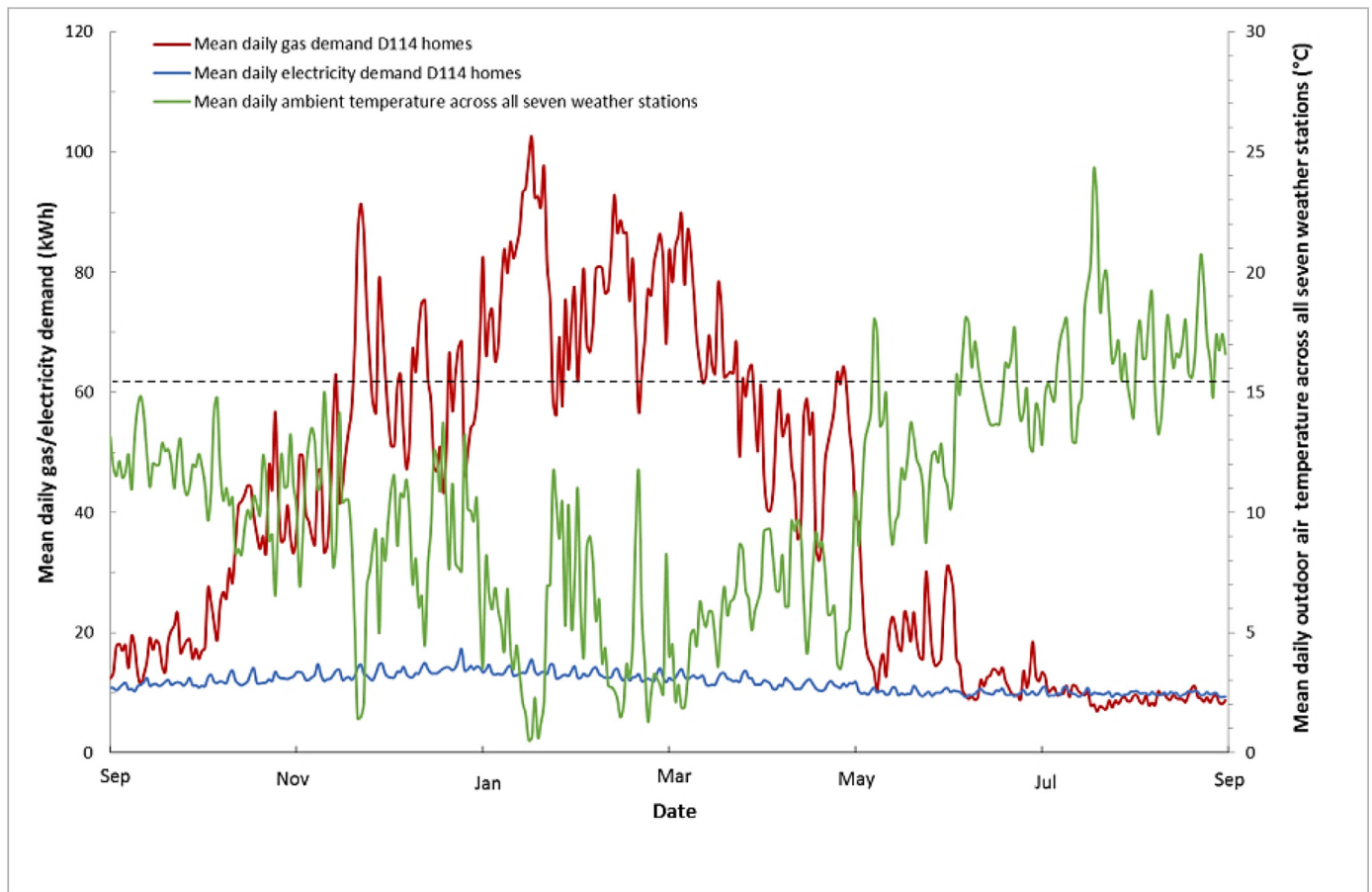


Fig. 6. Variation of the mean daily gas and electricity demand of the D114 homes with the mean daily ambient temperature recorded across the seven weather data sites.

tricity to 36%:64%, gas: electricity. Clearly, any advice associated with a DOR about how to save energy would be very different depending on whether a household has a high or low energy use and whether it is their gas or electricity demand that is particularly high.

4. The D114 homes and weather correction

Central to any DOR scheme is the approach used for weather-correction. Two things need to be considered, the ambient temperature (degree-day base) below which corrections should be applied and the proportion of any fuel that should be corrected (see Section 2). In the UK a degree-day base temperature of 15.5 °C has been used for many years but given the gradual improvements to the thermal efficiency of the fabric of UK dwellings (Fig. 1), this may no longer be appropriate. To explore these matters, the relationship between ambient temperature and the energy demand of the D114 homes was investigated.

The mean daily gas and electricity demands of the D114 homes show distinct, but different, variations with ambient temperature (Fig. 6). In summer, the mean daily gas demand was just c9kWh and largely independent of temperature, but in winter the demand was highly temperature dependent reaching a peak of c100kWh in mid-January when the mean daily temperature averaged across all seven weather stations was about 1 °C. In contrast the mean electricity demand increased slowly from summer (mean daily demand c9kWh) to winter (c16kWh) and was largely independent of ambient temperature. These observations suggest that for the D114 homes, gas demands should be weather-corrected but the electricity demands not.

To explore further, the daily normalised gas and electricity demand of every D114 home was plotted against ambient temperature. Here, and in subsequent sections, three homes with similar SAP ratings are used as exemplars, #41, SAP Rating (EER_{SAP}) 67, which had the largest floor area of the D114 homes, #199, Rating 69, which had the smallest floor area, and #345, Rating 65, which had a floor area close to the mean of all D114 homes. As a group they illustrate features observed within all 114 homes.

It is evident that the electricity demand for these three homes (Fig. 7) is only lightly temperature dependent and is greater in winter than in summer. There may be genuine weather-related reasons for this, for example more cooking of hot meals and drinking hot beverages as the days become colder and, as the day length (which is loosely correlated with temperature) decreases, the use of electric lighting will increase, and TVs and other electronic devices may be used more.

The demand for gas is also very low and largely independent of temperature at mean daily ambient temperatures above 15.5 °C, $T > 15.5$. This is to be expected as in mild weather gas is used mainly for hot water heating and cooking rather than space heating. Interestingly, home #345 used no gas at all in summer; this house had an electric immersion heater to provide hot water and, presumably, the household cooked using electricity.

When the mean daily ambient temperature was below 15.5 °C, $T < 15.5$, the gas demand in the homes began to increase with decreasing ambient temperature. In some homes, e.g. #41 and #345 the relationship between temperature and gas demand is clear, whilst in others there was much greater scatter with occasional days with zero demand being evident (e.g. #199). There are both physical and behavioural reasons for the observed scatter.

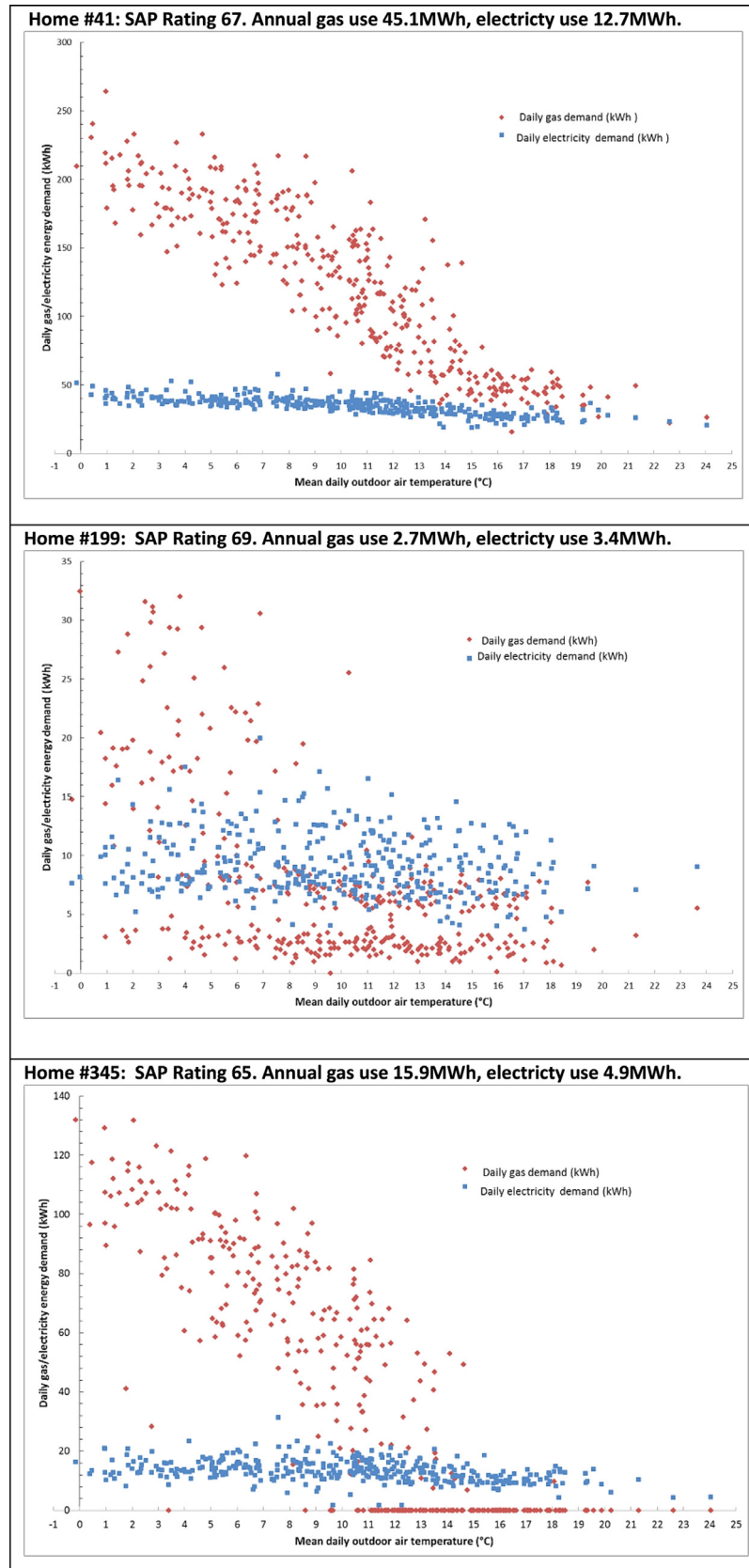


Fig. 7. Variation of daily gas and electricity demand with the local mean daily ambient temperature: homes #41, #199 and #345.

At temperatures just below 15.5 °C, fabric heat loss, which is ambient temperature dependent, is small and so other factors such as solar gain, wind (which influences infiltration), internal heat gains, and thermal mass effects, which are not captured in the simple ambient temperature/demand plots, can be important influences on heat flows. In these cool, but not cold conditions, warmer and perhaps sunny days are interspersed with cooler days (e.g. Fig. 6) so occupants might choose to 'endure' the colder morning conditions rather than switch on the heating system, perhaps knowing that the day will warm up later.

At all ambient temperatures, interventions to switch the heating on and off, rather than simply leaving the programmed heating schedule to operate may occur, reducing, and sometimes eliminating, the daily gas use. Such actions, perhaps undertaken in an effort to save money, are normal in the UK.

The important observations for the development of the DOR was that none of the D114 homes displayed clear evidence of gas space heating until the mean daily ambient temperatures dropped below 15.5 °C, $T_{<15.5}$. Therefore, it might be concluded that weather-correction using the standard base temperature of 15.5 °C (see Section 2) is suitable for the D114 homes.

The implications for homes that do not use space heating until the ambient temperature is lower than 15.5 °C is discussed later (Section 10). It is equally evident that the electricity demands should not be weather-corrected using a degree-day method; this matter is also discussed later.

5. The DORs for energy demand, GHG emissions and energy costs

There are five main steps in the calculation of the DORs (Fig. 8):

- 1 Weather-correction of the measured daily gas and electricity³⁵ demands;
- 2 Calculation of the total weather corrected energy demands, GHG emissions and energy costs;
- 3 Normalisation of the energy demands, GHG emissions and energy costs;
- 4 Selection of suitable benchmarks; and
- 5 Production of the operational ratings for energy demand (DORED), GHG emissions (DORGG) and energy costs (DOREC) and the associated rating bands.

The general equations used in each step for homes that use any mix of fuels for space heating and other purposes are given in Sections 5.1–5.5. Comment is also made about the veracity of the approach with three homes used as examples, #41, #119 and #345. A more thorough reflection on the DOR scheme is contained in the Discussion (Section 10).

The specific equations for homes that use electricity and gas for heating are in the Supplementary Information [42], which includes illustrative results for three further homes #8, #11 and #250, and for the D114 cohort as a whole. Data tables of the measured and derived values for all D114 homes are available at [43].

5.1. Weather correction

The first step in deriving the DORs is to weather-correct the measured energy demands. By doing so it is possible to: compare the ratings of homes in different locations, which experience different weather; make comparisons with fixed nationally-applicable benchmarks, and so generate ratings and rating bands; and this

should yield DORs that are stable from one year to the next despite the changing weather.

The general equation for the weather corrected energy demand of a fuel, EDf_w , is given by:

$$EDf_w = EDF + EDF_{<ddb} \times WCWf \times (WCFF_{ddb} - 1) \quad \text{kWh} \quad (1)$$

where:

EDF = Measured annual total fuel demand	kWh
$EDf_{<ddb}$ = Total fuel demand on days when the mean daily ambient temperature, T , is below the degree-day base temperature, ddb	kWh
WCWf = Weather correction weighting for the fuel	(0–1)
$WCFF_{ddb}$ = Weather correction factor for the fuel.	

With $WCFF_{ddb}$ given by:

$$WCFF_{ddb} = DDS_{ddb} / DD_{ddb} \quad (2)$$

where:

DDS_{ddb} = Standard degree days to base temperature	°C.days
DD_{ddb} = Actual degree days at the dwelling location	°C.days

Similar equations are used for all other heating fuels used in the home.

For the D114 homes, the calculations used the conventional degree-day base temperature, $ddb = 15.5$ °C for weather corrections and, for the standard year, a value of $DDS_{15.5} = 2021$ °C.days was adopted, which is the UK-wide value used in the asset rating of all UK non-domestic buildings [10]. The weather correction factors for gas demand ($WCFF_{15.5}$) varied from 1.053 to 0.925 depending on the location (Fig. 5) of the home³⁶ (see [42]).

The weather correction weighting, $WCWf$, defines the proportion of the fuel used on days when the ambient temperature is below the base temperature that is to be weather-corrected. For example, in a home that uses a particular fuel only for heating, the weighting would be one. If a fuel is not used for heating, e.g. the electricity used in most UK homes, the weighting might be small or zero. Values between these extremes are appropriate when a proportion of a fuel is used for heating and a proportion for other non-heating purposes, for example homes that use gas for both heating and cooking, or homes which use electricity for all purposes. These complexities for are discussed further in Section 10.

In the D114 homes, to maintain simplicity, and because gas is predominantly used for space and water heating, all the gas used on days when $T < 15.5$ °C was weather-corrected ($WCWg = 1$). This represented between 84.1% and 99.9% of the annual gas use of the homes [42]. Because electricity was not the primary mode of space heating, and because the mean electricity demand of the D114 homes showed no clear change at any particular threshold temperature (Figs. 6 and 7) none of the electricity was weather-corrected ($WCWe = 0$). These simplification gloss over the complexities introduced by the few D114 homes that often (6 homes) or occasionally (12 homes) use electricity for heating, or which sometimes use open fires.³⁷ In a fully functioning national DOR scheme protocols to deal with such cases would need to be developed³⁸ (Section 10).

³⁶ If the measurement year is colder than the standard year, the actual degree days to base, ddb , are more than the standard value, and the right hand term in Eq. (1) becomes negative; thus scaling down the weather-related fuel demand. The reverse is true if the measurement year is warmer than the standard year.

³⁷ But this does not undermine the proposed DOR scheme's development.

³⁸ The protocol for disaggregating the gas demand so that which is used for hot water heating and cooking is not weather corrected, or not corrected in the same way as the gas used for space heating, could also be established.

³⁵ All or part of the electricity demand may, or may not be weather-corrected, depending on whether electricity is used for space heating.

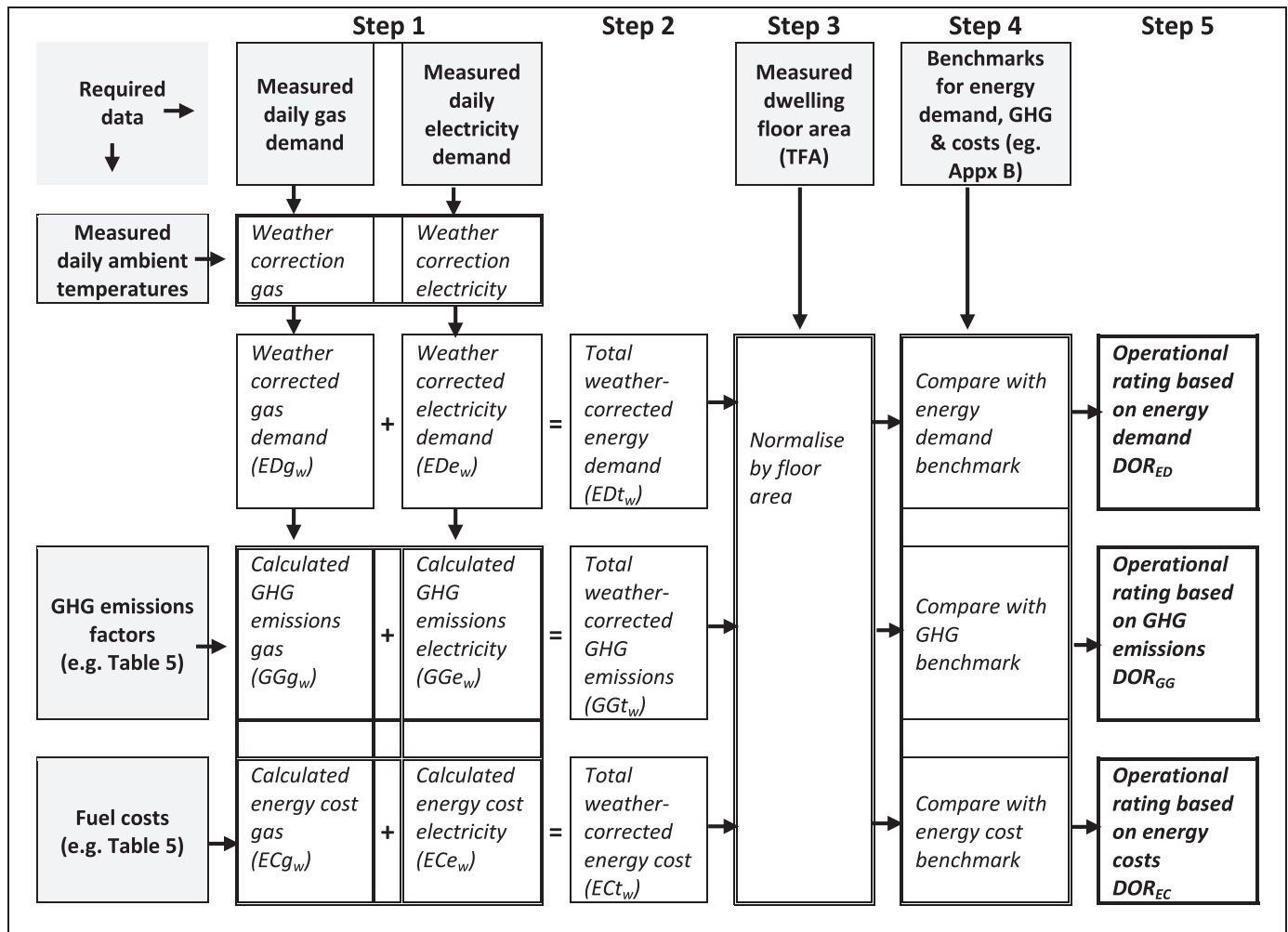


Fig. 8. Overview of approach to calculating DORs for gas heated homes: required external values in bold, calculated values in italics.

5.2. Calculating the GHG emissions and costs

Determination of the gas emissions and energy costs can be done most expediently by applying simple conversion factors to the energy demand for each fuel. Derivation of the annual weather-corrected GHG emissions, GGf_w , is thus given by:

$$GGf_w = EDf_w \times GGf \quad \text{kgCO}_2\text{e} \quad (3)$$

where:

$$GGf = \text{GHG emissions factor for the fuel} \quad \text{kgCO}_2\text{e/kWh}$$

Similarly, for the annual weather-corrected energy costs:

$$ECf_w = EDf_w \times UCf + SCf \quad \text{£} \quad (4)$$

where:

$$UCf = \text{Cost per unit of fuel used} \quad \text{£/kWh} \quad (5)$$

$$SCf = \text{Annual standing (i.e. fixed) charge of the fuel} \quad \text{£}$$

Using the approach outlined here, both the GHG emissions and energy costs are simple linear multiples of the measured demand of each fuel. However, because the proportion of each fuel used differs from one home to another, the relative total GHG emissions and energy costs differ, and so too do the relative DORs for energy demands, GHG emissions and costs.

The actual cost of fuel and the actual GHG emissions from a home in any specific year can, of course, be estimated by using the non-weather corrected fuel demands within Eqs. (4) and (5). The SAP documents (e.g. [6]), conveniently lists 'approved' values for all the fuels used in UK homes, including values for various mains electricity tariffs and for community energy schemes, etc. To estimate the GHG emissions factors and energy costs for the D114 homes the values listed for 'mains gas', and 'standard tariff, electricity' were adopted (Table 5).

This approach is of course very simple, yet it maintains compatibility with the SAP asset rating approach for UK homes, produces stable year-on-year ratings (the SAP emissions and cost factors change only slowly) and enables compatible benchmark values to be generated (Appendix B). However, it fails to reflect the real energy cost to the household, which may be quite different and change frequently as the supplier alters (usually increases) prices and the household choose a different tariff. In the UK such changes are frequent. Likewise, the approach fails to account for the different emissions factors associated with the electricity from different suppliers. These and other related matters are discussed below (Section 10).

5.3. Normalising and total energy demands, GHG emissions and costs

One reason for differences in energy demand (and GHG emissions and energy costs) compared to other homes and benchmark values, may be simply because houses differ in size. Energy rating

Table 5
Emissions factors & energy costs.

Fuel	GHG emissions factor (EF) kgCO _{2e} /kWh	Fuel Cost	
		Standing charge (SC) £	Cost per unit (UCx100) p/kWh
Mains gas	0.208	95	4.32
Elec. Stand. tariff	0.398	67	15.32

All values drawn from SAP2016 [6].

Table 6
Benchmark values.

Benchmark	Units	Symbol	Value
Energy demand	kWh/m ²	BED _{twn}	188.58
Energy cost	£/m ²	BEC _{twn}	14.40
GHG emissions	kgCO _{2e} /m ²	BGG _{twn}	46.17

Table 7
Number of D114 homes in each Dwelling Operational Rating Band.

Rating Band	Rating	DORBED	DORBGG	DORBEC
A	0-25	0	0	0
B	26-50	2	1	1
C	51-75	19	17	14
D	76-100	32	31	41
E	101-125	38	40	33
F	126-150	15	15	20
G	≤151	8	10	5

schemes, whether asset rating or operational rating, therefore normalise energy demands, GHG emissions and costs by total usable floor area (TFA).

The normalisation of the weather-corrected energy demand for each fuel, EDf_{wn}, is simply given by:

$$\text{EDf}_{\text{wn}} = \text{EDf}_w / \text{TFA} \quad \text{kWh/m}^2 \quad (6)$$

where:

$$\text{TFA} = \text{Total floor area of dwelling} \quad \text{m}^2$$

The total floor area of dwellings in the UK is increasingly made available, for example a value derived from a home energy survey is given in all Energy Performance Certificates.

The total weather corrected and normalised energy demand, EDt_{wn}, is then given by:

$$\text{EDt}_{\text{wn}} = \sum_{f=1}^n \text{EDf}_{\text{wn}} \quad \text{kWh/m}^2 \quad (7)$$

where:

$$n = \text{the number of fuels used by the household.}$$

The same approach is used to obtain the normalised and weather-corrected GHG emissions, GGf_{wn}, and energy costs, ECf_{wn}, for each fuel and for the total emissions (GGt_{wn}) and energy costs (ECT_{wn}) (see [42]).

The variation of the total weather-corrected and normalised gas, electricity and total energy demands between the different D114 households was considerable (Fig. 9). The highest gas, electricity and total energy-using households, respectively, 8.6, 7.7 and 5.8 times more energy than the lowest consuming household [42].

5.4. Establishing the benchmarks

The 'Energy Consumption in the UK' tables [17] provide annual figures for the energy demand, and weather-corrected energy demand, by fuel type for the entire UK housing stock. The calculated mean weather-corrected and normalised total energy demand for the calendar year 2016, which is the year closest to the period for which the DEFACIO homes were monitored, was calculated (see Appendix B) and used as the benchmark, BED_{twn}, for assessing the D114 homes (Table 6).

Authoritative government sources also exist for UK domestic GHG emissions and energy costs, ([18],[19]).³⁹ Ideally, these tabulated values, or the principles behind the derivation of them (e.g.

the assumed fuel emissions factors and costs) would form the basis for the benchmark GHG and energy cost values. Unfortunately, it is not clear how the energy costs were derived and whether the costs and GHG emissions are compatible with the tabulated fuel use figures. Therefore, to ensure both calculation compatibility and alignment with the UK approach to the asset rating of dwellings, the benchmarks for GHG emissions (BGG_{twn}) and energy costs (BEC_{twn}) were calculated from the published consumption of each fuel type (Appendix B), using the emissions factors and costs of each individual fuel as given in SAP2016 [6]. The resulting benchmark values are also given in Table 6.

Any proposed benchmarks could be retained for a period of time, but then changed as the energy demands, fuel mix, associated GHG emissions and costs for the UK stock change. How, when this is done, the implications of different approaches for the complexity and stability of a DOR scheme would need careful consideration.

5.5. Calculating the dwelling operational ratings

The approach used to produce the operational rating of UK non-domestic buildings [10], was used to calculate the dwelling operational ratings (See Section 2). The method is simple and transparent and produces a rating on an easy-to-understand, linear, rating scale:

$$\text{DORED} = 100 \times \text{EDt}_{\text{wn}} / \text{BED}_{\text{wn}} \quad (8)$$

$$\text{DORGG} = 100 \times \text{GGt}_{\text{wn}} / \text{BGG}_{\text{wn}} \quad (9)$$

$$\text{DOREC} = 100 \times \text{ECT}_{\text{wn}} / \text{BEC}_{\text{wn}} \quad (10)$$

The operational rating bands, DORED, DORGG and DOREC, could be set to produce any desired proportion of the dwelling stock in each band (see Section 2). Here though, the rating bands are set at equal increments of 25 rating points (Table 7). A dwelling with a weather-corrected and normalised energy demand equal to the benchmark value thus sits at the interface of Bands D and E.

The calculated DORED of the D114 homes (Fig. 9 and Table 7) span the range from Band B to Band G; lowest rating 31.4 and highest 182.8. All but 10 homes were in Bands C to F. The mean

³⁹ These sources produce average annual household values of 40.9 kgCO_{2e}/m² and 15.59 £/m² (Table 4).

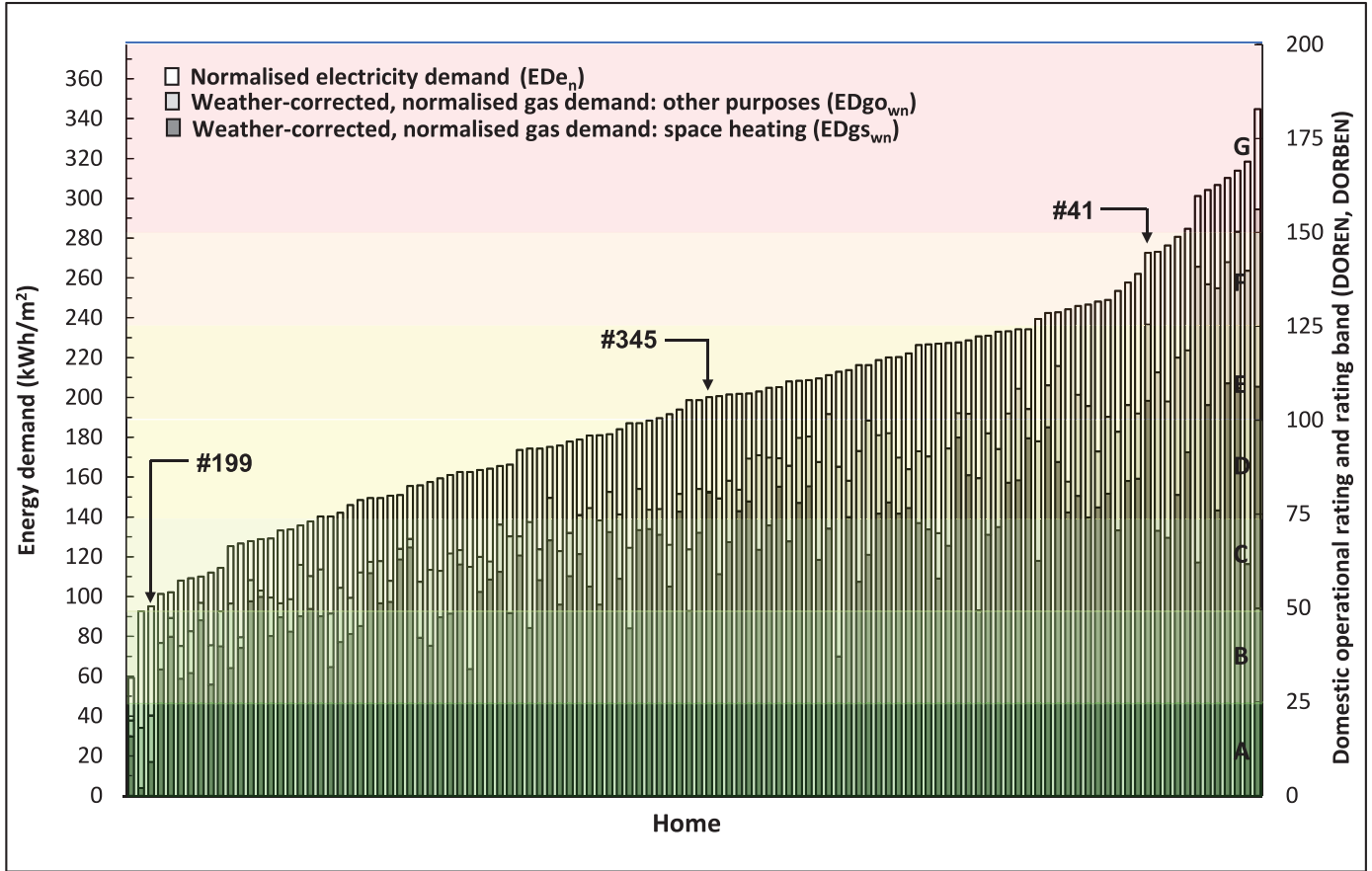


Fig. 9. Weather-corrected and normalised gas and electricity demand for the D114 homes, split of gas use for space heating and other purposes, and the corresponding Domestic Operational Rating and Rating Band.

rating of all the 114 homes was 103.5 [42], which might be expected as the mean normalised total energy demands of the D114 homes was just 3.3% higher than the 2016 UK stock mean normalised demand (Table 4). The DORGG and DOREC values exhibited a spread of values similar to the DORED (Table 7), with mean ratings of 105.7 and 103.6 respectively [42].

It is not surprising that the total number of homes in any given Rating Band is similar across all three rating scales; all the D114 homes use mains electricity, and gas for heating. Many homes produced the same, or a similar, rating by all three scales (e.g. home #41 rated F on all three scales and home #345, E). Some homes however, use a very different mix of electricity and gas and so their operational ratings differ depending on the scale used, for example, #199 (Table 8). It is homes like these that illustrate the benefit of using three different scales, even when the form of heating and the fuel used is nominally the same. The value of the different scales would be even more clearly demonstrated across homes with different forms of heating and which use different fuels.

5.6. The DOR certificate

The DOR certificate might most usefully be presented in a form similar to that used for dwelling Energy Performance Certificates (Fig. 2) and non-domestic Display Energy Certificates. Such certificates might include information about the dwelling, the DORs and also energy demand, GHG emissions and cost data used to calculate the DORs. Information relevant to the three exemplar homes, #41, #199 and #345, is given in Table 8.

There are clear differences between the SAP and DOR ratings for the exemplar homes (Table 8). The differences for all the

D114, and possible reasons for the differences, are considered in Section 9.

6. Additional useful information

Other parameters that describe the energy demand of a home can easily be produced as a by-product of the DOR calculations and some of these will be of value to households, energy efficiency advisors, and those concerned with national energy demand.

6.1. The relative demand for different fuels

From a householder's perspective, knowing the actual split of energy demands, GHG emissions and costs associated with each fuel in the specific year of measurement is perhaps most helpful; even if a home is heated by one fuel, say gas, the annual spend on another fuel might be higher. For those concerned with energy policy, the weather-corrected and normalised splits might be more appropriate.

For a household using just two fuels, one electricity, *e*, and the other for heating, *h*, the percentage of the total energy used that is for heating, $PED_{h_{wn}}$, and the percentage used as electricity, $PEDe_{wn}$ are given by:

$$PED_{h_{wn}} = (ED_{h_{wn}}/ED_{t_{wn}}) \times 100 \quad \% \quad (11)$$

$$PEDe_{wn} = (EDe_{wn}/ED_{t_{wn}}) \times 100 \quad \% \quad (12)$$

where:

$ED_{h_{wn}}$ = weather corrected and normalised heating energy demand kWh/m²
 EDe_{wn} = weather corrected and normalised electrical energy demand kWh/m²

Table 8

Information that could appear on a Domestic Operational Rating certificate: examples for three dwellings.

About the Dwelling					
Address		#41	#199	#345	
House type	-	Semi-detached			
Primary heating system	-	Gas central heating			
Secondary heating	-	Electric fire	None	None	
Secondary DHW heating	-	Immersion	None	None	
Floor area	m ²	210	62	103	
SAP Rating	-	67	69	65	
SAP Band	-	D	C	D	
Period covered by DOR certificate					
Start		01/09/15	01/09/15	01/09/15	01/09/16
End		30/08/16	30/08/16	30/08/16	30/08/17
Measured Energy Use, GHG emissions and energy costs					
Gas use	kWh (%)	45068 (78%)	2691 (44%)	15893 (77%)	14620 (76%)
Electricity use	kWh (%)	12730 (22%)	3395 (56%)	4885 (23%)	4618 (24%)
Total fuel use	kWh	57799	6086	20779	19238
Gas cost ¹	£ (%)	2042 (50%)	211 (26%)	782 (49%)	727 (48%)
Electricity cost ¹	£ (%)	2017 (50%)	587 (74%)	815 (51%)	774 (52%)
Total fuel cost ¹	£	4059	798	1597	1501
Total GHG emissions ²	kgCO _{2e}	14441	1911	5250	4879
Calculated Energy Use, GHG Emissions and Energy Costs for a Standard Year					
Gas use	kWh/m ²	212.5	40.3	152.7	141.2
Percentage of gas used for space heating	%	63%	42%	100%	100%
Percentage of gas used for other purposes	%	37%	58%	0%	0%
Electricity use	kWh/m ²	60.6	54.8	47.4	44.8
Total energy use	kWh/m ²	273.2	95.1	200.2	186.0
Total energy cost	£/m ²	19.24	12.74	15.44	14.54
Total GHG emissions	kgCO _{2e} /m ²	68.3	30.2	50.6	47.2
Dwelling Operational Ratings					
Energy Demand Rating and Band	-	144.9 F	50.4 C	106.1 E	98.6 D
Energy Cost Rating and Band	-	133.6 F	88.5 D	107.2 E	101.0 E
GHG Rating and Band	-	148.0 F	65.4 C	109.7 E	102.2 E

Similar equations can be used to find the split of GHG emissions and costs⁴⁰ resulting from the use of each fuel [42]. The DOR calculations also yields the splits in energy demand, GHG emissions and costs at temperatures below and above the degree day base temperature⁴¹ [42].

The split between the gas and electricity demand for each of the D114 homes is illustrated in Fig. 9. The average split, PED_{g,wn}:PED_{e,wn}, was 76.9%:23.1%, which produced a mean split of 64.1% GHG emissions from gas and 35.9% from electricity, and a split in the annual energy costs of 50.8% for gas and 49.2% for electricity. For individual homes however, the splits varied substantially, home #211 had the highest proportion of gas to electricity demand, 90.7%:9.3%, which yielded the highest ratios of gas to electricity GHG emissions, 83.6%:16.4%, and costs 71.2%:28.2%. The home with the lowest percentage of gas compared to electricity use was #318, 36.7%:63.3%, which produced gas to electricity ratios for GHG emissions and costs of 23.2%:76.8% and 20.5%:79.5% respectively. Interestingly both homes had all electric kitchen appliances but home #318 had particularly low absolute gas demand (the lowest of the D114 sample) and the electricity demand was not particularly high. Clearly, the advice provided to households would focus on different fuels depending on whether the aim is

to reducing energy demand, GHG or energy costs and the focus would change from home to home. The splits for three example homes are given in Table 8.

6.2. Estimating the split of heating fuel for space heating and for other purposes

An estimate can be made of the way that the heating fuel use is split between that used for space heating⁴² and that used for other purposes; primarily domestic hot water (DHW) heating but also for gas cooking, although the latter is generally quite small ([17], Table 3.07). To do this, the assumption is made that, on all of the days when the ambient temperature is above the degree-day base temperature, the heating fuel is used only for purposes other than space heating. The mean of the daily fuel demands on these days can be calculated and an assumption made that the same (mean) daily demand is used for other purposes on the days when the ambient temperature is below the base temperature. Of course, this is not absolutely correct because in winter a little more heat is needed to produce a given amount of DHW (because the supply temperature is lower), people may use more hot water to bathe on colder days and more heating fuel may be used for cooking, because more hot meals may be prepared in winter (Section 4). Account could be taken of these small differences but only if a simple

⁴⁰ But the standing charge for energy supply must be apportioned on an equivalent daily basis.

⁴¹ To calculate the split of energy costs separately for temperatures above and below the degree day base temperature, the standing charge for the fuel must be apportioned on a daily basis.

⁴² The fuel may be burned by the central heating system or by a secondary heater (such as a gas fire). Clearly, the meaning of this sort of split is less clear for homes that have a large kitchen range, which is permanently on, and used both for cooking and for heating part of the house.

model is presumed.⁴³ Here, in the spirit of retaining a transparent and wholly data driven approach, these effects are ignored, and the estimated split between the heating fuel used for space heating ($ED_{hs_{wn}}$), and that used for other purposes ($ED_{ho_{wn}}$), is calculated as follows:

$$ED_{ho_{wn}} = DY_a \times ED_{h_{wn>ddb}} / DY_{>ddb} \quad \text{kWh} \quad (13)$$

and

$$ED_{hs_{wn}} = ED_{t_{wn}} - ED_{ho_{wn}} \quad \text{kWh} \quad (14)$$

where

DY_a = Total days in year in year, e.g. 365 or 366 for a leap year.
$DY > ddb$ = Number of days when the ambient temperature is above the base temperature
$ED_{h_{wn>ddb}}$ = Total weather corrected and normalised heating fuel demand when the ambient temperature exceeds the ddb.

The split for the D114 homes is illustrated in Fig. 9.

The estimated split between the heating fuel used for heating and for other purposes, expressed as a percentage of the heating energy demand,⁴⁴ is thus:

$$PED_{hs} = ED_{hs_{wn}} / ED_{h_{wn}} \times 100 \quad \% \quad (15)$$

$$PED_{ho} = ED_{ho_{wn}} / ED_{h_{wn}} \times 100 \quad \% \quad (16)$$

The split of the GHG emissions resulting from space heating and other purposes is the same as for heating energy demand. The split for energy costs is not quite the same, because the standing charge of fuels is fixed and not proportional to energy use.⁴⁵ The splits for three example homes are given in Table 8.

For the D114 homes, the mean split of the weather-corrected gas demand between that used for heating and that used for other purposes was 78%:22%. The higher value for space heating is expected both because there are more days when the ambient temperature is below 15.5 °C than above (302 to 323 days below, depending on the weather station, 43 to 64 days above) and because on cold days the energy used for space heating is much greater than that used to heat water. For 2016, the gas split for the UK domestic stock is reported as 85%:15% [17], but this is (also) based on modelling rather than actual measurement.

Interestingly, there were marked differences between the homes in the cohort. Home #345 used virtually no gas use when $T > 15.5$ °C, possibly because an electric immersion heater was used to provide hot water, thus 100% of any gas used is attributed to space heating⁴⁶ (Table 8). At the other extreme it was estimated that home #318 used just 12% of the gas for space heating and 88% for other purposes.

Whilst an estimation of the splits of heating energy demands, GHG emissions and costs that result from space heating and other heating purposes uses may give some useful insight, further work is needed to understand how reliable the estimates are for different household types.

⁴³ For example, the SAP [22] assumes that the DHW is c11K colder in January than in July. The DBEIS split of fuels into end use is also based on this modelling [17].

⁴⁴ The alternative is to express the fuel used for space heating and other purposes as a percentage of the total energy. However, the split of the heating fuel uses is only approximate whereas the split between the heating fuel(s) and electricity use is exact. Therefore, distinguishing between the two types of split is preferred.

⁴⁵ The standing charge must be spread across the individual days, e.g. 1/365th of the standing charge per day. This portion of the cost is thus fixed per day rather than being proportional to the energy used per day.

⁴⁶ It might be that the gas boiler, rather than the immersion heater, was used to heat water in the winter. The estimation method cannot account for this change between the summer and winter; and so gas used for winter DHW heating is wrongly attributed to space heating.

7. Year-on-year stability of the DOR

It is important that any DOR remains stable over time, providing essentially the same DOR value unless purposeful changes which influence energy demand are made. To test the year-on-year stability of DOR calculations, the values calculated for the D114 homes, Year 1, were compared with the values calculated for the subsequent year, 1st September 2016 to 31st August 2017, Year 2. However, because of the gradual loss of participants from the study this inter-year comparison could only be made for a sub-sample of forty-four homes, D44. Prior to analysis, the Year 2 data were checked, cleaned and missing data filled, as described for Year 1 [35] and the Year 2 DOR calculations were made in exactly the same way as for Year 1.

Of course, although no purposeful interventions were made by the DEFACTo research team in the D44 homes, it is impossible to be sure there were no changes that might have affected energy demand. Therefore, the inter-year comparison is not a rigorous test of the DOR calculations' stability. However, if the Year 1 and Year 2 values are, on average, for the whole D44 sample, the same, and if there are no systematic differences in the DORs of the individual homes, and if the scatter from year to year is relatively small, it would tend to indicate that DOR values remain stable in the absence of purposeful interventions.

Encouragingly, there was actually a very close overall correlation between the energy demand, GHG emissions and costs between the two years, and so the DORs were also similar. For example, for the DOR based on energy demand DORED (Fig. 10), linear regression ($R^2 = 0.913$) produced the relationship:

$$DORED_{Y2} = 1.01 \times DORED_{Y1} + 0.32 \quad (17)$$

The mean DORED value of the D44 sub-sample changed by only a small amount; from 94.8 kWh/m² in Year 1 to 95.7 kWh/m² in Year 2. Only 7 homes changed rating by more than ± 10 points. Of these, the two that changed most (#8, +19.9 points, and #186, -13.7 points) were both occupied by retired couples, aged over 65, on low income, £15k to £20k pa. The rating of these two homes changed by one band as did the rating for 9 others, five improving by one Band and six to a Band lower. Clearly, any change in Rating will change the Band for homes that have a DOR close to the Band boundary.

From this analysis, it is concluded that the DOR is suitably sensitive to changes in the year-to-year energy demand changes but that, in the absence of substantive or behavioural energy-saving interventions, it will yield stable year-to-year values. Clearly, further exploration is needed.

8. Energy demands on a cold day and a reduced data DOR

A number of researchers in the domestic energy demand field (e.g. [54,57]) have used the heating and electrical energy demand at a mean daily ambient temperature of 5 °C as an indicator of annual energy demand. Whilst not necessary for the calculation of the DOR, the energy costs on a cold day could be interesting and useful information for households and enable comparisons between different dwellings using a readily understandable metric. It is also straight forward to calculate the GHG emissions on a cold day.

More importantly, if the energy demands on a cold day are well-correlated with annual energy demands it might be possible to calculate a reduced data Domestic Operational Rating (rdDOR), which is based on the energy demands measured on just a few cold days, thus obviating needing a whole year's data. This possibility is also investigated for the D114 homes.

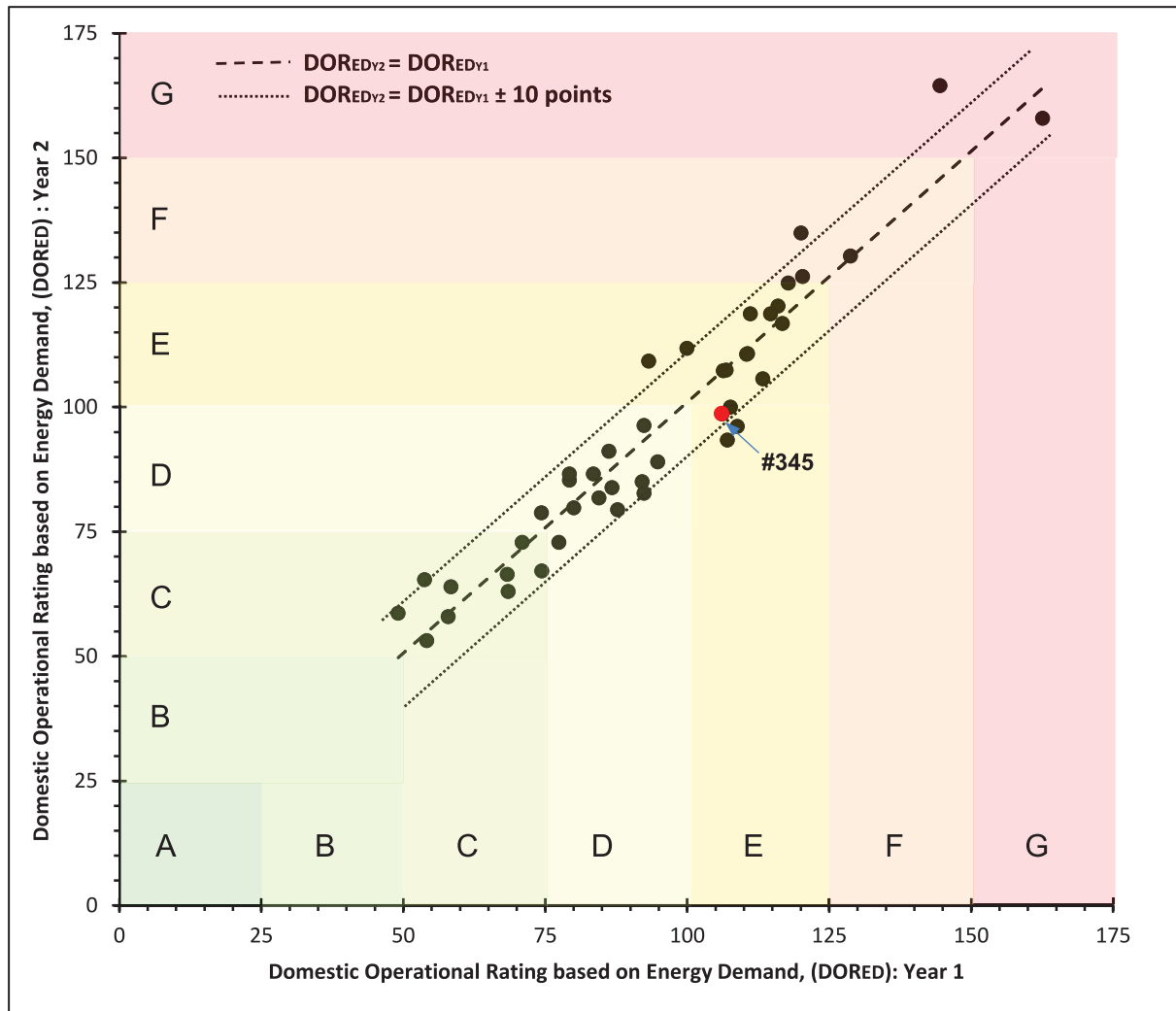


Fig. 10. Comparison of the DORED based on energy demand for two successive years. Data are from the D44 sub-sample.

8.1. Energy demand on a cold day

By calculating the total energy demand GHG emissions and the consequential energy costs, it might be possible to provide information that is readily understandable to households, e.g. 'how much energy is used in your home on a cold day. What are the GHG emissions and how much does it cost you?'. The beauty of the approach is that the need for weather-correction is obviated because the mean temperature on the energy-sampling days is always the same, even though the overall year may be warmer or cooler than average. It therefore seems worth exploring the value of including such a measure on a DOR certificate.

Previous researchers have placed a regression line through a graph of daily heating energy demand versus mean daily ambient temperatures (T) to interpolate the demand at $T=5^\circ\text{C}$; which is called here a 'cold day'. This can, however, be unreliable (note the data scatter in Figs. 6 and 7) so here, in keeping with the philosophy of simplicity and transparency, the mean⁴⁷ fuel demand (EDf_5) when the mean daily ambient temperature, T , was in the

range $4^\circ\text{C} < T < 6^\circ\text{C}$ was calculated:

$$\text{EDf}_5 = \left[\sum_{d5=1}^{d5=DY5} \text{EDf}_{d5} \right] / DY5 \quad \text{kWh} \quad (18)$$

where:

$d5 =$ a day with a mean ambient temperature, T , such that $4^\circ\text{C} < T < 6^\circ\text{C}$.
 $\text{EDf}_{d5} =$ measured fuel demand on a d5 day kWh
 $DY5 =$ total number of d5 days in the year.

The total energy demand on a cold day is calculated by simple addition of the measured demand for each fuel, and the GHG emissions and energy costs by multiplication by each fuel's GHG emissions factors and the unit energy costs⁴⁸ (Table 5).

For such metrics to be robust, the number of days, $DY5$, for which $4^\circ\text{C} < T < 6^\circ\text{C}$, must be sufficiently large to produce reliable values for the cold-day fuel demands irrespective of house location and, ideally, for all weather years both now and in the near future. To investigate, four of the CIBSE weather years released in 2016 [11,59], for each of 14 UK locations, were interrogated: the current Test Reference Year (TRY) and Design Summer Year 3 (DSY3), which represents a long hot year; and the TRY and DSY3 for 2050 assuming a 90 percentile high emissions scenario. The DSY3 years are likely to have the smallest number of cold days. In the current

⁴⁷ Other approaches to determining the energy demand values were considered, such as weighing the energy demand values based on how close the ambient temperature was to 5°C , $\text{EDf}_{T5} = \sum_{d5=1}^{d5=DY5} [\text{EDf}_{d5} \times (1-|T-5|)]$, but this added complexity for no gain in accuracy.

⁴⁸ With the standing charge for energy costs applied on a per-day basis.

Table 9

Information that could appear on a Reduced Data Domestic Operational Rating Certificate: examples for three dwellings, Years 1 and 2.

About the Dwelling				
Address		#41	#199	#345
Dwelling data	-	See Table 8		
Period covered by DOR certificate				
Winter	-	2015/16	2015/16	2015/16
Energy use, GHG emissions and energy costs on a cold day ¹				
Gas use	kWh (%)	176.8 (82%)	10.6 (52%)	85.1 (85%)
Electricity use	kWh (%)	39.1 (18%)	9.8 (48%)	14.8 (15%)
Total fuel use	kWh	216.0	20.4	99.9
Gas cost	£ (%)	7.90 (56%)	0.72 (30%)	3.94 (62%)
Electricity cost	£ (%)	6.18 (44%)	1.69 (70%)	2.46 (38%)
Total fuel cost	£	14.08	2.41	6.39
GHG emissions	kgCO _{2e}	52.36	6.10	23.60
Estimated Energy Use, GHG Emissions and Energy Costs for a Standard Year				
Gas use	kWh/m ²	190.1	21.1	180.4
Electricity use	kWh/m ²	60.6	55.0	48.6
Total fuel use	kWh m ²	250.8	75.2	229.0
Total fuel cost	£/m ²	18.3	11.9	16.8
Total GHG emissions	kgCO _{2e} /m ²	63.7	26.1	56.9
Reduced Data Dwelling Operational Ratings				
Energy Demand Rating and Band	-	133.0 F	39.9 B	121.4 E
Energy Cost Rating and Band	-	126.9 F	82.7 D	116.8 E
GHG Rating and Band	-	137.9 F	56.5 C	123.2 E

TRYs and DSY3s there were 18 or more days at all locations with T in the range $4^{\circ}\text{C} < T < 6^{\circ}\text{C}$, i.e. $DY_5 \geq 18$, and in the future TRYs there were at least 10 such days, $DY_5 \geq 10$. It was concluded therefore, that cold day metrics could always be calculated with reasonable accuracy using the simple averaging approach (Eqs. (18)). For the D114 homes, DY_5 was between 33 and 42 depending on the weather station (Table 3).

The total energy demand (EDT_5), GHG emissions (GGT_5) and energy costs (Ect_5) on a cold day were calculated for all the D114 homes: the mean values were 82.2 kWh, 19.5 kgCO_{2e} and £5.38 per day. The largest house in the sample, #41 produced the highest figures: 216 kWh, 19.5 kgCO_{2e} and £14.08 (Table 9). The smallest house in the sample, #199 62 m², had almost the lowest figures: 20.37 kWh, 5.85 kgCO_{2e} and £2.05 per day (Table 9). A pleasing feature of these figures is that they have a magnitude that can be readily assimilated by people, e.g. 'it costs £5.38 to heat this house on a cold day'. Normalised daily costs are harder for people to envisage and the figures are small giving the impression that energy is rather an insignificant cost to a household; they varied from 0.7 p/m², home #98, to 8.3 p/m², home #45, with a D114 mean of 2.8 p/m².

8.2. A reduced data DOR

If the energy demands on a cold day are well-correlated with the annual energy demands for particular categories of dwellings and households, there is the prospect of calculating a reduced data domestic operational rating, rdDOR, which is analogous to the concept of rdSAP used for the asset rating of UK homes [41].

As well as producing a DOR more quickly, and with less data, rdDOR calculations would be much simpler because the measured cold day energy demands inherently incorporates weather-correction. This is because, irrespective of whether the winter as a whole is especially mild or particularly cold, the data sample is always taken from within the same temperature window $4 < T < 6^{\circ}\text{C}$. Therefore, because no weather-correction is needed, the mean energy demand measured on a few cold days might be

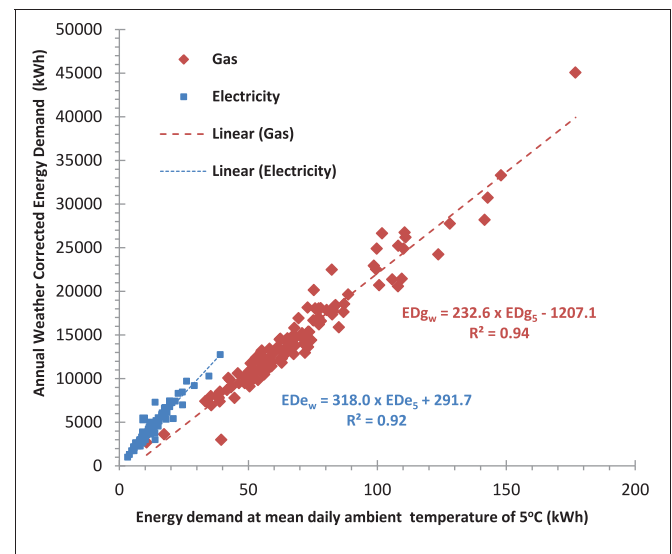


Fig. 11. Relationship between the annual energy demands and the energy demands at a mean ambient temperature of 5 °C.

used directly as a short-cut way of estimating the actual annual, weather corrected energy demands.

To test this proposition, the mean gas demand on a cold day, ED_{G5} , for the D114 homes was compared with the annual weather-corrected gas energy demand, ED_{Gw} ; regression analysis produced a strong correlation, $R^2 = 0.94$. There was a similarly strong relationship, $R^2 = 0.92$, between the electricity demand on a cold day, ED_{E5} , and the calculated annual weather-corrected electricity demand, ED_{Ew} (Fig. 11).⁴⁹

⁴⁹ Equally strong correlations were obtained when the normalised and weather corrected annual gas and electricity demands were plotted against the normalised

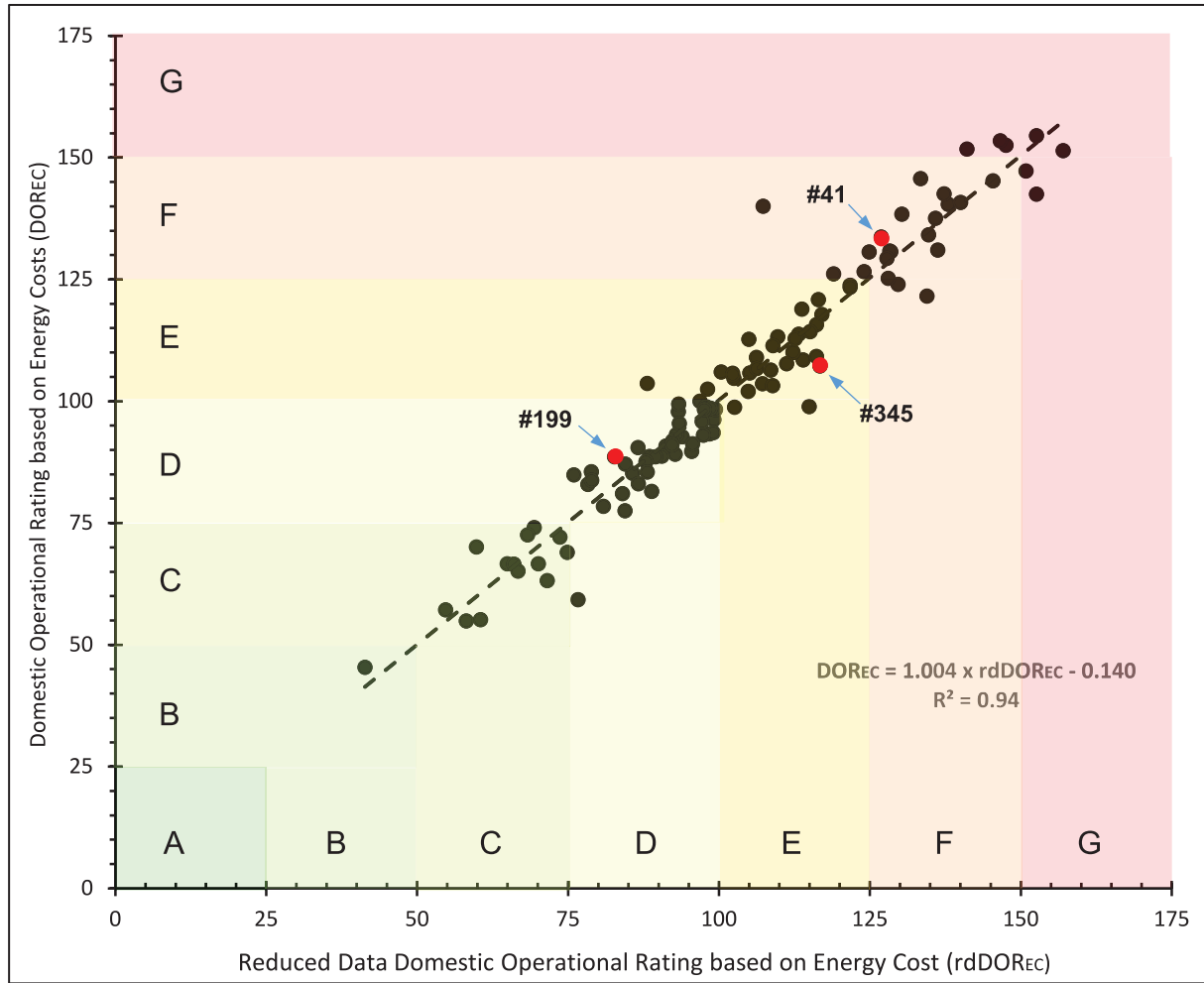


Fig. 12. Comparison of the actual DOR with an estimated value, rdDOR, based on a few cold days' data.

In general, for any dwellings and households for which the demand for each fuel on a cold day, EDf_5 , is strongly correlated with the corresponding annual weather corrected fuel demand, EDf_w , it is possible to estimate of the annual weather corrected fuel demand, EDf_{ew} , from:

$$EDf_{ew} = Mf \times EDf_5 + Cf \quad \text{kWh} \quad (19)$$

where:

Mf is the slope of the EDf_w versus EDf_5 regression line
 Cf is the x-axis intercept of the regression line/kWh

For the D114 homes, the values of Mf and Cf for gas demand were 232.6 and -1207 kWh respectively, and for electricity demand 318.0 and 292 kWh respectively (Fig. 11).

By using the estimated fuel demands, EDf_{ew} , in place of the actual fuel demands, EDf_w , in Eq. (6) onwards, it is possible to produce a reduced data DOR for energy demand, rdDOR_{ED}, GHG emissions, rdDOR_{GG}, and energy costs, rdDOR_{EC}; and hence produce rating bands (Table 7). The specific equations for gas and electrically heated homes, e.g. the D114 homes, are given in [42].

For the D114 homes, there was a very strong correlation ($0.92 < R^2 < 0.94$) between the actual DORs (calculated from a whole years' data) and the rdDORs (based on a few cold days of data), and the slope was very close to unity; see e.g. Fig. 12 for

the comparison based on energy costs. This result is intriguing and might have value in domestic energy demand research beyond simply the calculation of an rdDORs (see Section 10).

The strong correlation between each DOR and rdDOR offers the prospect of generating rdDOR certificates for some classes of dwelling and occupancy that would be beneficial even if the amount of data included is necessarily less than on a standard DOR certificate (Table 9).

9. Comparison of operational (DOR) and asset (SAP) ratings

It is illuminating to compare the Energy Efficiency Rating of the D114 homes as calculated by the SAP, EER_{SAP} , which is based on the normalised cost of fuel, to the DOREC rating. Whilst the former is essentially an asset rating and the latter an operational rating, one might expect some agreement between the two. In particular, even if the ratings and the rating bands were not the same, one might expect that, the rank order of the homes to be similar by each assessment.

In practice however, there was a very poor correlation between the DOREC rating and the EER_{SAP} rating ($R^2 = 0.06$, Fig. 13). The DOREC ratings were also much more widely distributed across the rating scale than were the EER_{SAP} . Whereas the DOREC ratings spanned from 46.3 (Band B) through to 156.9 (Band G), average 103.8 (Band E), the EER_{SAP} ratings spanned from 91 (Band B) to just 44 (Band E), and the average rating 64 (Band D) was higher (Fig. 13).

demands on a cold day, the slopes and intercepts for gas and electricity were exactly the same.

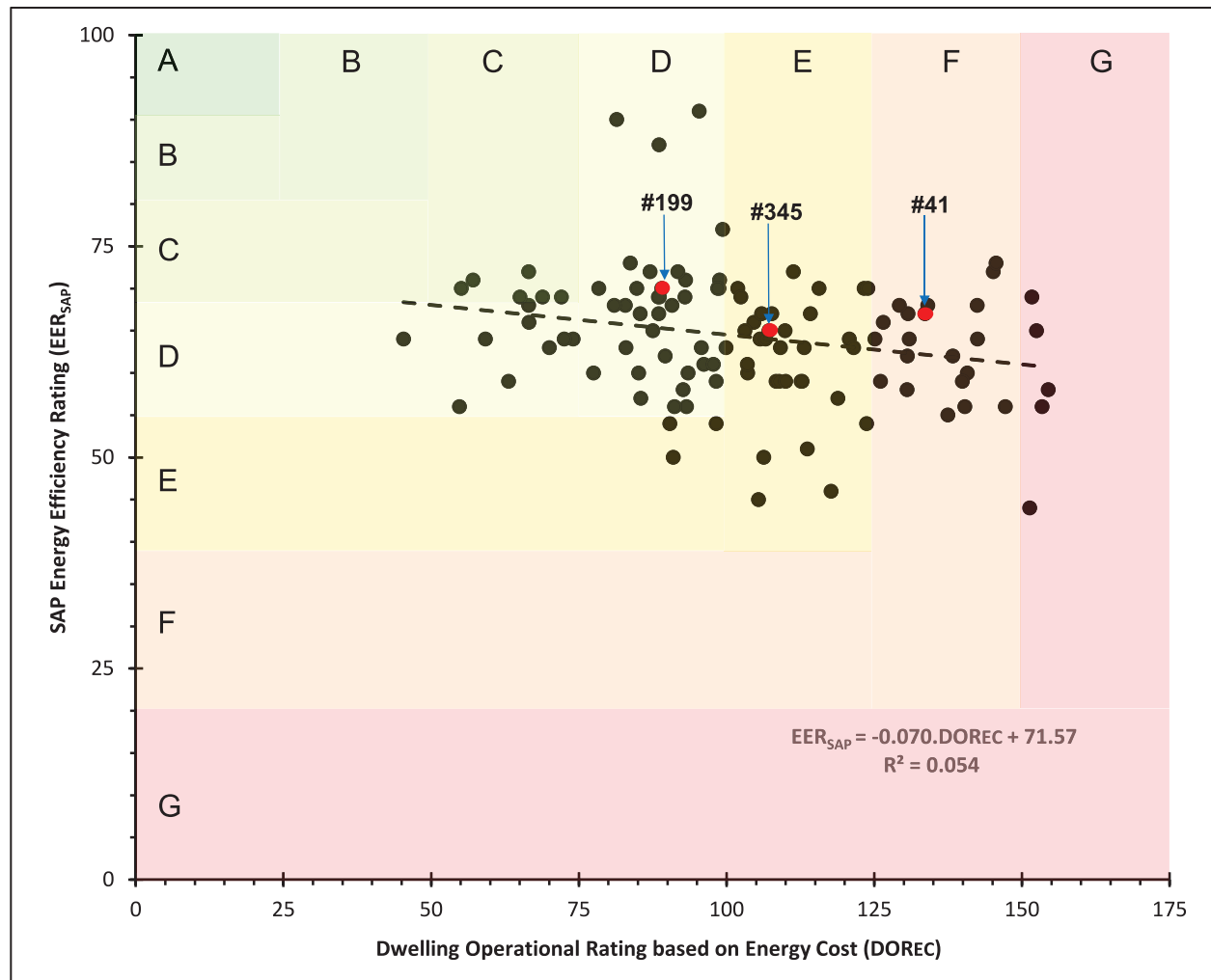


Fig. 13. Comparison of SAP energy efficiency rating of the D114 homes with the DOR energy cost rating.

To investigate further the rank ordering of the EER_{SAP} values for the D114 homes was compared with the rank order of the ratings by the DOREC method. The Spearman rank correlation test produced a weak correlation coefficient of 0.3 and the sign test revealed a significant difference in the rankings ($p < 0.05$). The results are not simply due to the different rating scales (and the way that the DOR was calculated). When the measured energy costs (EC_{fw} , Eq. (4)) were fed into the SAP2016 rating scale equations (Appendix B), the ratings spanned from 73 (Band C) to 16 (Band G), average 42 (Band E), i.e. quite different from the EER_{SAP} values.

Although the results reported here are for a particular set of homes for just one year, they do indicate that the SAP Energy Efficiency Rating (EER_{SAP}) is significantly different from the corresponding, measured, operational energy cost rating.

It is concluded that the SAP is a poor indicator of the actual energy demands and costs of occupied homes. The compressed range of energy demands, and thus ratings, produced by the SAP is to be expected because asset rating schemes deliberately exclude the effect on energy demand of households' behaviour; and it is differences in behaviour that drive variability in energy demand, even between households that inhabit houses with similar inherent energy efficiency. These results reinforce the need to move to a more realistic, measurement-based, approach to quantifying the energy demands of homes.

10. Discussion

A simple and transparent strategy for producing DORs, which could operate alongside the existing dwellings asset rating (SAP) system, has been demonstrated and tested. There are, however, a number of areas that are worthy of discussion. Firstly, there are matters related to the method of calculation that need to be resolved before a fully-functioning, nationally-applicable DOR scheme could be launched. Secondly, looking to the future, the relationship between the dwellings and the energy system will become more interactive, with wider use of embedded generation and storage, and time-of-use pricing. In such an energy system, the proposed 'static' DOR, which uses 'standard' fuel prices and GHG emissions factors, may be inappropriate and instead a 'dynamic' DOR, which can account for changes in fuel price and emissions between homes and over time would be more appropriate. Thirdly, the value of the DEFACTO data set in supporting the development of either sort of DOR, and the need for new data, is discussed.

10.1. Developing a nationally applicable DOR

10.1.1. Occupancy effects: holidays and household size

Some of the non-UK dwelling rating systems reviewed (Section 4) excluded periods when occupants were not at home, basing the rating on energy used on the remaining, occupied days. The DOR

developed here included all days of the year, whether occupants were present or not. Whilst a DOR based on the annual 'occupied-only' energy demand might be possible, there would be difficulties and it is questionable whether it should be done.

Firstly, it is hard to identify reliably when a house is unoccupied based only on the metered daily energy use. Low or zero heating energy demand might mean the home is unoccupied, alternatively it may simply reflect the purposeful (energy saving) behaviour of the occupants. For example, choosing not to heat all or part of the house or selecting a lower heating set-point temperature. To exclude such a period would mean that the DOR fails to reward purposeful energy saving behaviour. Secondly, in homes where heating fuel is not metered on daily basis, e.g. because the fuel is delivered in bulk, it is not possible to identify unoccupied periods, so all such homes would be systematically advantaged if a DOR calculation were to account for absences.⁵⁰ Thirdly, whilst the energy demand of homes could be based on fuel used per occupied day, national fuel use benchmark will always include all energy used by all homes, occupied or not.⁵¹ Finally, and probably most importantly, there is the question of personal privacy and intrusion and households would, quite rightly, be concerned if they felt the timing and duration of their absences was being inferred from metered energy data.

Some rating schemes offer different benchmarks, depending on the number of people in a household. Such an approach enables homes with more people to use more energy without a detrimental impact on the DOR. Aside from the philosophical question of whether such an approach is desirable, questions of privacy mitigate against taking account of the number of people, and the numbers may be practically impossible to define, for example in homes of multiple occupancy, where tenants come and go frequently. An alternative approach might be to alert people, perhaps by a note on the DOR certificate, to the fact that larger households tend to use more energy.⁵² Occupants moving into a new property with a DOR certificate could then infer how demand might change purely because they have a larger or smaller household than the previous occupiers.

10.1.2. Weather correction and degree-day base temperature

In the proposed DOR scheme, the weather-correction weighting of a fuel (WCWf) makes it possible to correct only the proportion of the fuel that is weather sensitive. It is therefore possible to accommodate homes that use a mix of fuels for heating, e.g. gas central heating with secondary electric heating, and homes in which the same fuel might be used for space heating as for other purposes, notably in all electric homes. A set of agreed, standard, weighting conventions might be devised for all plausible combinations of heating systems and fuels; much like the many look-up tables needed for asset rating (SAP) calculations. The existing database of EPC surveys provide the fuels and heating systems used in each home. Alternatively, it might be possible to infer the weightings to use based only on the measured (smart meter) data, which would be a much easier approach, and one tailored to, but varying with, each home's use of fuels.

The DOR calculation could begin on any day and be based on the energy demand for the subsequent year. The year could begin as soon as a property changes hands for example. To enable this, however, the weather-correction factor would need to be known

for every dwelling and location for a year which starts on any one of 365 days. This is perfectly possible to do, but is might be simpler to constrain DOR calculations to start at, say the beginning of each month, thus enabling the generation and publication of 'approved' regional or sub-regional monthly degree days. This would retain the simplicity and transparency but capitalise on the inherent flexibility of the DOR scheme.

A degree-day base temperature of 15.5 °C was adopted for weather-correction in the DOR scheme, which is the value commonly used in UK energy demand calculations. It is worth considering the likely errors of using a fixed value for all homes, and the possible alternative approaches. Regarding errors, if the degree-day base temperature is too high for a particular dwelling, the energy used between the chosen base temperature and the true base temperature will be weighted when it should not be. The reverse is true if the base temperature is too low for the dwelling in question. However, the heating energy demands on days near the base temperature are small, e.g. compared to those on much colder days, and so the effect of the error is small. Secondly, and more importantly, because weather-correction is based on the ratio between the degree-days in a standard year and those at the dwelling location (Eq. (2)), the choice of base temperature will have only a small impact on the correction factor.⁵³ Even though any errors are small, in the interests of rigour, other approaches to defining the base temperature are worth investigating.

Broken stick regression, using plots such as those in Fig. 7, were explored as a route to identifying house-specific degree-day base temperatures. Whilst, for many homes this method proved satisfactory, for other homes, the regression coefficient was very poor and for some, no credible regressions line was produced. The physical reasons for this are clear: firstly, people intervene in their heating⁵⁴ and so the energy demand is not entirely ambient temperature-driven; secondly, secondary heating, which may or may not use the same fuel, or may be used alongside or instead of the central heating system; and finally, the degree-day base temperature would depend on the heating schedule, being lower if the heating is on only during the day rather than for 24 h per day.⁵⁵ This latter point is interesting and has perhaps not been highlighted before.

An alternative strategy would be to use the Heat Loss Coefficient, which is calculated as part of an EPC energy survey as the basis for determining the base temperatures (in fact, SAP ratings used to be based on a variable-base degree day calculations). This does however introduce complexity, further entwines the DOR scheme with the asset rating scheme, and yet still entails an estimation of the base temperature.

The standard number of degree-days used in this work was 2021 °C.days. This value could change over time, for example as the climate warms. However, provided the same value is used for deriving the weather-corrected national benchmark energy demands then the effect of a change on DORs will be very small.

⁵³ The number of degree days in the standard year will change with any change in degree-day base temperature but the degree-days at the dwelling location will also change and by a similar percentage.

⁵⁴ Interventions to central heating systems might include: turning the heating off entirely, e.g. when on holiday, when a set-back temperature may or may not be set; adjusting the thermostat setting; adjusting the heating schedule; or increasing or decreasing the flow temperature from the boiler.

⁵⁵ For example, in a home heated for 24 hours per day, the heating might be initiated when the mean ambient daily (i.e. 24 h) temperature drops below, say, 15.5 °C. If the schedule in the same house were set to daytime only heating, it would be switched on when the mean daytime (i.e. excluding the night time hours) drops below 15.5 °C; the corresponding 24 h mean temperature would almost certainly be lower than 15.5 °C, because it is usually colder at night. Thus, the effective degree-day base temperature is likely to be lower in homes with daytime only heating than in those with all-day heating.

⁵⁰ Because including days with no occupancy and no heating fuel use will depress the annual daily mean demand.

⁵¹ Thus, homes that are actually or apparently unoccupied for a period of time will have a higher demand per occupied day relative to the benchmark.

⁵² Larger household tend to use more energy so fuel poverty calculations use fuel cost equalisation factors which, for households of one, two, three, four and five or more people are, respectively, 0.82, 1.00, 1.07, 1.21 and 1.32 [20].

A final point revolves around how to weather-correct fuels that are not used for space heating, in particular fuel used for hot water heating and, perhaps, cooking. Likewise, electricity demands vary from summer to winter and so weather correction should be considered. For these fuels, the usage increases steadily as ambient temperatures fall rather than when temperatures fall below a particular threshold (e.g. Figs. 6 and 7). This might be due to the overall temperature decrease from summer to winter, or due to other factors, like a shortening of the day length resulting in greater use of lights and appliances. For such fuel usage, weather-correction might more credibly be based on the average, whole year, temperature, or some other measure,⁵⁶ rather than a degree-day threshold weighting. The effect on the calculated DORs, whether or not such fuels are weather corrected, is though, likely to be small.

10.1.3. Benchmarks, the rating year and rating bands

The selection of robust benchmark values is crucial to the credibility of the DOR scheme. To this end, UK government originated weather-corrected energy demands for 2016 were used [17] with the benchmarks for GHG emissions and the energy costs calculated using the SAP-tabulated emissions factors and energy prices for each fuel (Appendix B). The way that the energy demands, GHG emissions and costs for each house were calculated was however a little different: the approach to weather-correction may have differed from that used by DBEIS; the GHG emissions factors, especially for electricity, are likely to have been different (see Section 4)⁵⁷; and the same electricity prices were used for all houses irrespective of the tariff. In a fully functioning DOR however, such inconsistencies could easily be resolved, for example by using the fuel tariff used to generate each home's EPC (SAP2016, lists eight electricity tariffs and 17 community energy prices).⁵⁸

The benchmark values will change over time. For example, decarbonisation of the grid will decrease the emissions factor for electricity but the emissions factor used to calculate each DOR would also change. Thus, the evolution of the grid, which is beyond the control of households, can be reflected in changed benchmarks without affecting the DORs. (In the SAP, which doesn't use external benchmarks for rating, any change in emissions factors immediately changes the SAP rating of homes; thus, revisions to the SAP are made infrequently.) Improvements to the energy efficiency of the national housing stock, e.g. through refurbishment and new build, would gradually decrease the energy demand benchmark and so homes that do not remain in step would have a gradually increasing DOR. This would, quite properly, create an incentive for individual households to become more energy efficient.

To comply with the forthcoming EU directive it is required that "The energy performance of a building shall be expressed by a numeric indicator of primary energy use in kWh/(m².y)" [32]. It is anticipated therefore that the UK rating schemes will shift to a primary rating basis.⁵⁹ A DOR based on primary energy demand (DORPE) might readily be calculated since the SAP documentation includes primary energy conversion factors. In SAP 2016 [6] these are 1.127 and 2.364 for gas and electricity respectively. The ratio of these, 1:2.10, is actually close to the SAP-listed ratio between the GHG emissions for gas and grid electricity, 1:1.98; the DORGG and DORPE values for homes might therefore be rather similar.

The approach to producing ratings and rating bands mimicked that used for UK non-domestic operational rating. In a fully operational DOR however, it would be possible to set the linear rating scale differently, for example with 100 representing the median or modal stock-wide value (of energy demand, GHG emissions and energy costs). Also, and perhaps more importantly, the banding divisions could be unevenly distributed, for example so that each band captures a chosen percentage of the national housing stock. The distribution of the national stock energy demands, GHG emissions and costs, would be readily available once smart meters are deployed.

10.1.4. Reduced data DORs

A method of producing a reduced data DOR (rdDOR) has been proposed based on the energy demands measured on a few cold days. Although the approach was successful for the D114 homes, the sample consists of homes with similar geometry and heating system type and they were exposed to similar weather condition that were very close to the long term national average.

Whilst the approach offers intriguing possibilities, it may be less successful for other dwelling types. For example, dwellings that are much better insulated, or which have greater thermal inertia, will respond to temperatures evolved over several days rather than those on a particular day. Likewise, if solar gain contributes a high proportion of the space heating demand, mean daily solar air temperature [9] may, for example, correlate better with daily energy demands than the mean daily dry-bulb temperature. There is therefore, a need to test the rdDOR concept for other types of homes subject to different and atypical weather conditions. Should the method remains robust, it may be possible to devise simple rdDOR equations (like Eq. (19)) for different classes of dwelling and occupants.

10.1.5. A DOR for non-daily metered fuels

The DOR scheme proposed will not work for homes that use fuels that are not metered daily (so, called, non-daily metered (NDM) fuels). This is likely to be the case for homes that use heating oil, biofuel and coal, where only delivery notes and infrequent manually meter readings may be available. For such UK homes, a way of estimating the DOR from an annual measure of fuel use may be necessary, i.e. a reduced annual DOR, raDOR. One way to do this might be to specify the proportion of each fuel that is to be weather corrected, the approach used in the UK non-domestic operational rating system [10]. Unfortunately, there is like to be a large inter-home variation in the proportion of fuel that should be corrected. (In the DOR homes, the mean gas demand to be corrected was 96.7% but this varied from 84.1% to 99.9%.⁶⁰) Furthermore, the proportion to be corrected will vary with winter temperature; with a higher percentage to be corrected in cold years and lower percentage in a mild year. Further exploration is therefore needed to develop a raDOR for homes with bulk fuel deliveries.

10.2. A dynamic DOR

The DOR described in this paper uses static, standardised values for GHG emissions and energy costs that change occasionally to reflect the evolution of the whole energy supply system. Such an approach fails to address some features of a heterogeneous new energy system, in which there is a much more dynamic interaction between the buildings that consume energy and the energy system. Such a system is characterised by small scale 'community energy schemes', dwellings that supply and store energy, innovative time-of-use fuel tariffs, new energy suppliers and energy ser-

⁵⁶ In the case of electrical energy use, and considering day-length as being a demand driver, time of year and latitude might be used?

⁵⁷ For example, working from the residential fuel use in DBEIS [17] and applying the SAP emissions factors produces a value of 4299 kgCO_{2e} per UK dwelling for 2016, which is a little larger than the value of 4150 calculated from other sources [18].

⁵⁸ Although this increases the extent to which the DOR depends on EPC data, it does avoid the need to know the exact fuel tariff for every fuel in every household.

⁵⁹ Although, at the time of writing, BREXIT 'negotiations' meant that there was considerable uncertainty over the future relationship between the UK and the EU.

⁶⁰ These are the proportion of gas used at ambient below 15.5 °C.

vice companies, and innovative energy pricing structures; all supported by the introduction of smart meters. A DOR that is sensitive to GHG emissions factors and energy costs that change over time on a daily, or even hourly basis, and from house to house would support such changes. It would foster the emergence of dwelling-integrated and community-based energy systems, and low carbon and renewable energy systems, stimulating households to search for lower-cost fuel tariffs.

To effect such a DOR, it would be necessary to know the daily energy demand along with the corresponding GHG emissions factor⁶¹ and fuel cost on that day. These two values would be needed either in real time or retrospectively shortly after the day in question in order to calculate the rolling year DORGG and DOREC values; in effect, adding a daily GHG emission factor and energy cost alongside the smart meter-recorded energy demands.

Just as daily energy demands recorded by smart meters could be collected centrally to produce the national energy benchmarks on a rolling year basis, so too could the corresponding GHG emissions factors and energy costs data for every UK home. The technical challenges are not insurmountable, and the data flows are not, by today's standards, large; but the procedures would need to be evolved, tested and refined.

Any fully dynamic DOR system would require the cooperation of energy suppliers who would know the fuel costs and the daily emissions factors for each household that they supply. Such data are likely to be confidential, both to protect the suppliers' commercial interests and the privacy of the households that they supply. However, it may not be possible to operate a fully dynamic DOR system using a government backed intermediary organisation that is independent of, but trusted by fuel suppliers.⁶²

Any DOR system, whether static or dynamic, could provide feedback to households through an in-home display (IHD) alongside advice and guidance on how the households' DORs might be improved. Such advice, perhaps delivered independently of the energy supplier, would stimulate business opportunities, e.g. for new energy suppliers, energy service companies, providers of energy efficiency advice etc. It would also stimulate household behavioural change, driven by GHG emissions and energy cost concerns, based on real past behaviour rather than artificial behaviour norms.

Of course, a much more dynamic DOR system would immediately divorce it, both philosophically and in its practical operation, from the SAP asset rating system. The latter is highly transparent and static in time, and it is purposefully designed to be so. In contrast, a dynamic DOR system would, by intent, be responsive to spatial variations and short term changes in the use of energy and the associated costs and emissions. It would be a system for a smart meter-enabled, 21st century energy system.

10.3. Limitations of the DOR dataset

Whilst the D114 dataset had undoubted value for developing the DOR, it does have inherent limitations. Most obviously, all the homes had gas central heating, were owner occupied and semi-detached. Also, they were all located in the English Midlands and exposed to weather close to the long-term UK average.

To fully evaluate and refine the DOR, there is clearly a need for data from a much wider range of homes, including flats, large detached homes, homes without central heating and which use fuels other than gas, and homes that use non-daily metered fuels. Likewise, data from homes exposed to more extreme weather would

enable the veracity of the weather-correction process to be more severely tested.

The viability of the DOR also needs to be tested for homes with new and renewable energy systems such as PV and heat pumps as well as for homes which might be very well insulated and so have very low energy demands.

Finally of course, the DEFAC data were surrogate smart meter data, and whilst this posed its own challenges with regard to data cleaning, such issues will also arise with smart meter data. The extent to which this could help or hinder the development of a nationwide DOR scheme needs to be explored.

11. Conclusions

A method for rating the energy performance of UK homes based on metered gas and electricity demand is presented for the first time in this paper. The proposed Domestic Operational Rating (DOR) scheme is complementary to the scheme used in the UK to provide the asset rating of domestic buildings, the Standard Assessment Procedure (SAP), and is in harmony with the method used for the operational rating of non-domestic buildings.

The DOR scheme is transparent, simple to calculate and clearly documented. In addition to a household's daily energy demands, only the dwelling floor area and the annual degree-days for the region are needed. Energy costs and GHG emissions are calculated using standard conversion factors. The proposed DOR could therefore readily be produced for all UK homes with daily-metered energy demands, e.g. daily smart meter data.

The DOR scheme was developed using of a new primary data set collected from 114 semi-detached, centrally-heated, privately owned and internet connected homes located in the English Midlands. Gas and electricity demand data were collected at 30 min and two minute intervals respectively. An energy survey and household questionnaire surveys were also undertaken. The data were cleaned, organised and averaged to produce a stream of daily gas and electricity use lasting up to three years.

The D114 homes were exposed to monthly temperatures close to the UK average for the years studied and, fortuitously, winter-time temperatures close to the long-term UK average. The measured mean annual normalised gas and electricity demands of 151 kWh/m² and 43 kWh/m², and mean annual estimated energy cost of £14.89/m², are all within 4.5% of the UK stock-wide figures. It is concluded that the homes therefore offer a sound platform on which to develop a nationally-applicable DOR scheme.

For all D114 homes, the gas demand was low during the summer, but increased when the mean daily ambient temperature fell below 15.5 °C because space heating was initiated. Electricity demand showed no clear temperature-initiated demand increase. Therefore, the total gas demand at temperatures below 15.5 °C was weather-corrected by the ratio of the site-specific degree days to the national long-term average value, 2021 °C.days. Electricity demands were not corrected.

Three DORs are calculated based on annual energy demand (DORED), GHG emissions (DORGG) and energy costs (DOREC). The DORED is derived by comparing the measured, annual, floor area normalised and weather-corrected total fuel use with a national, stock-wide, benchmark derived from annually-published government sources. Simple linear rating scales are used, such that zero points represent a zero-energy home, and 100 points, a stock average home. Equal rating bands of 25 points, are constructed such that Band A represent a home that uses less than 25% of the benchmark demand, and Band G more than 150% of the benchmark demand; DORGG and DOREC rating scales and bands follow the same principle. The D114 homes had DORED ratings between 31.0 (Band B) and 182.8 (Band G).

⁶¹ In practice GHG emissions factors change through the day (e.g. half hourly) and so a mechanism for providing daily effective factors would need to be devised.

⁶² Note, only the running annual total energy demands, GHG emissions and energy costs are needed, not the daily values.

For 44 of the homes that produced good quality data for two successive years, the DORs scheme produced ratings in year two that were very similar to those in year 1; and there was no significant difference in the ranking of the DORs between the years. The result suggests that, in the absence of purposeful energy saving actions, the DOR scheme produces ratings that are stable year-on-year.

There was a very poor correlation ($R^2 = 0.06$) between the DOREC of the D114 homes and the SAP asset rating, which is also based on energy costs. There was also a significant difference in the relative ranking of the homes by the two metrics. These results indicate that SAP ratings are a very poor indicator of the actual energy demand and energy costs of occupied homes. The DOREC ratings were also much more widely spread across the rating scale, suggesting it is a better discriminator of the relative energy demand of different homes.

A method of producing a reduced data DOR has been proposed based on the energy demands measured on a few cold days. The approach was successful for the D114 homes, producing rdDORs very similar to the DORs calculated using a whole years' data. A method of producing a DOR for homes that use non-daily metered fuels is also desirable, a reduced annual DOR. The robustness of the rdDOR approach and a concept for an raDOR needs testing using a more diverse range of dwellings subject to different, non-average weather conditions.

The proposed DOR scheme is compatible with existing international asset and operational rating schemes, notably those used in the UK. There is however, a need to test the scheme using a much more diverse set of dwelling types, with different modes of home ownership, which use different heating systems and which are exposed to a wider range of winter weather conditions. Such a dataset would enable the approach to weather-correction, deriving benchmarks and producing rating bands to be tested more thoroughly.

Finally, there is merit in exploring the benefits of a much more dynamic approach to producing DORs, one that captures fully the spatial and temporal variability in homes' energy costs and greenhouse gas emissions, most obviously as the mix of electricity generators changes. Costs and emissions are likely to vary much more, both spatially and temporally (e.g. half-hourly), in the integrated energy system of the future. Capturing this variability will be increasingly important in a DOR scheme as heating shifts from fossil fuels to electricity.

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Conflict of Interest

I wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.07.021.

Appendix A: The SAP rating equations and rating bands

The SAP rating scales are partly linear and partly non-linear and do not make use of any external, e.g. stock averaged, benchmark value. The Energy Efficiency Rating (EER) is framed such that a building which has zero energy cost achieves a rating on 100:

$$\begin{aligned} EER_{SAP} &= 117 - 121 \times \log_{10}(ECF) & \text{for } ECF \geq 3.5 \\ EER_{SAP} &= 100 - 13.95 \times ECF & \text{for } ECF < 3.5 \end{aligned} \quad (A1)$$

where:

$$\begin{aligned} ECF &= DEF \times \text{total energy cost} / (TFA + 45)^{63} & \text{£/m}^2 \\ TFA &= \text{total dwelling floor area} & \text{m}^2 \\ DEF &= \text{Energy cost deflator} = 0.42 \end{aligned}$$

The energy cost deflator is used to maintain continuity of SAP ratings over time despite changing fuel costs [36]. In SAP2016 [5] the energy cost deflator is 0.42 as it was in SAP2012 [22] and as is proposed for SAP10 [7].

The Environmental Impact Rating (EIR_{SAP}) has a very similar form, and is framed such that a zero emissions building has a rating of 100:

$$\begin{aligned} EIR_{SAP} &= 200 - 95 \times \log_{10}(CF) & \text{for } CF \geq 28.3 \\ EIR_{SAP} &= 100 - 1.34 \times CF & \text{for } CF < 28.3 \end{aligned} \quad (A2)$$

where:

$$CF = (\text{CO}_{2e} \text{ emissions}) / (TFA + 45) \quad \text{kgCO}_{2e} / \text{m}^2$$

The addition of 45 to the total floor area in both equations was introduced in SAP2001 [24] to render the ECF, and so the energy efficiency rating, far less sensitive to dwelling floor area. In SAP1998 and earlier, the denominator in the calculation of the ECF was TFA and not TFA+45 [3].

To produce the rating bands (EER_{SAP} and EIR_{SAP}), the EER_{SAP} and the EIR_{SAP} values are firstly rounded to the nearest whole number and then divided up into bands of equal 'size': if EER_{SAP} or EIR_{SAP} is greater than 92, the Band is A⁶³; 91 to 81 Band B; 80–69 Band C; 68–55 Band D; 54–39 Band E; 38–21 Band F; and 20 or less Band G (see [41] for further information).

In contrast to the SAP rating scales, linear scales, which might be used in any DOR scheme, are much simpler. For an energy cost benchmark of 14.40 £/m²:

$$DOREC = (ECt_{wn} / 14.40) \times 100 \quad (A3)$$

where:

$$ECt_{wn} = \text{total weather-corrected and normalised energy costs} \quad \text{£/m}^2$$

⁶³ The same banding, and energy cost deflator, is used in SAP 2012, SAP 2016 and the proposed SAP10.

Table B1

Annual UK household energy demands for 2016 and calculated standard energy costs and emissions.

Fuel	Total UK domestic 2016			Weather corrected energy demand, costs and emissions						
	Energy demand			Energy demands		Energy cost ^f			Greenhouse gas emissions	
	Total all households ^a	Demand per household ^c		Mean per UK household ^e	Fuel fraction	Standing charge	Cost per kWh	Mean per UK household	Emission factors ^g	Mean per UK households
	ktoe	GWh ^b	kWh	kWh	%	£	p	£	kgCO _{2e} /kWh	kgCO _{2e}
Coal	414	4815	173	179	1.01		4.07	£7.06	0.416	72
Solid	168	1954	70	73	0.41		5.48	£3.86	0.045	3
Natural Gas	26,773	311,370	11,216	11,563	65.23	95	4.32	£579.52	0.208	2333
Electricity	9284	107,973	3889	3901	22.01	67	15.32	£662.83	0.398	1548
Heat sold	52	605	22	22	0.13		5.27	£1.15	0.208	5
Bio. & waste	2079	24,179	871	898	5.07		5.27	£45.90	0.074	64
Petroleum	2525	29,366	1058	1091	6.15		5.06	£53.52	0.298	315
Total	41,295	480,261	17,299	17,727	100.00			£1353.83		4340
Normalised totals (per m ²) ^d				188.581 kWh/m ²				14.40 £/m ²		46.17 kgCO _{2e} /m ²

^a Source DBEIS [17] Table 3.01.^b The conversion is 11,630 MWh per ktoe.^c The number of UK households in 2016 is given as 27,762,000 by DBEIS ([17], Table 3.03).^d The average floor area of English homes in 2016 for all tenures, assumed applicable for UK homes, was 94 m² by ([46], Table AT2).^e Factors inferred from DBEIS ([17], Table 3.03), 1.003 for electricity, 1.031 all other fuels.^f Source SAP 2016, Table 12 (BRE) [6]. Assumed mapping between DBEIS fuel names and the many fuel types listed in SAP, 2016, Table 12: Coal = House coal; Solid = Wood pellets; Natural Gas = Mains Gas; Electricity = Standard tariff; Heat sold = Community heat network, mains gas boilers; Bio. & waste = Community heat network, boiler, waste combustion; Petroleum = heating oil.^g Source SAP 2016, Table 12 (BRE) [6]. Emissions factors for fuels sources mapped as above.

For a GHG emissions benchmark of 46.17 kgCO_{2e}/m²:

$$\text{DORGG} = (\text{GG}_{\text{wn}}/46.17) \times 100 \quad (\text{A4})$$

where:

GG _{wn} = total weather-corrected and normalised GHG emissions	kgCO _{2e} /m ²
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The rating bands for UK non-domestic buildings span equal divisions of 25 rating points. Thus a building that produces the same GHG emissions as the benchmark (rating 100) sits at the interface between Band D and B and E

Appendix B Benchmark energy demand

The benchmark values against which the weather-corrected and normalised energy demands, GHG emissions and energy costs are compared, need to be representative of the average demands for the UK stock as a whole. Here the benchmark values were derived from the governments' document, Energy Consumption in the UK [17], which provides annual figures for the total amount of each fuel used in the domestic sector.

The mean fuel demand per household was calculated, and the consequential GHG emissions and energy costs calculated for each fuel using the GHG emissions factors and costs listed in SAP2016 [6]; these were then normalised using the average floor area for UK homes. Fuel use figures for calendar year 2016 were used as is the year most compatible with the D114 measurement year (Table B1).

The weather correction factors used by DBEIS can be inferred DBEIS [17], and are 1.003 for electricity and 1.031 for all other fuels.

References

- [1] Implementing the Energy Performance of Buildings Directive (EPBD), Featuring Country Reports 2012, Concerted Action Energy Performance of Buildings, Porto, 2013, p. 368. ISBN 978-972-8648-27-1.
- [2] Bruhns H., Jones P., Cohen R. and Bordass B. (ND) Benchmarking for display energy certificates, [Available at: <http://www.cibse.org/getmedia/30adcefd-d4d9-4b93-8203-7efe4958a01d/Technical-Report-Benchmarking-for-DECS.pdf.aspx>, Accessed 280218].
- [3] BRE (ND) Difference in the rating scale between SAP 1998 and SAP 2001, 2 pp. [Available at: http://projects.bre.co.uk/sap2001/SAP_1998_-_SAP_2001.pdf, accessed 041018].
- [4] BRE, Guide to the government's standard assessment procedure for the energy rating of dwellings (SAP), BRE Crown Copyright (2005) 13. [Available at: <http://projects.bre.co.uk/sap2005/pdf/SAP-Guidance-document.pdf>, accessed 201018].
- [5] BRE, The Cost of Poor Housing in the European Union, Briefing Paper; Nicol, S. Roys, M. Ormandy, D. Ezratty. V. UK Building Research Establishment, 2016, p. 76. [Available at: https://www.bre.co.uk/filelibrary/Briefing%20papers/92993_BRE_Poor-Housing_in_-Europe.pdf, accessed 0409218].
- [6] The Government's Standard Assessment Procedure for Energy Rating of Dwellings, SAP Draft 2016 Edition for Consultation, Version 10.00, UK Building research Establishment on behalf of the UK Department of Energy and Climate Change, 2016, p. 179. [Available at: <https://www.bre.co.uk/filelibrary/SAP/2016/SAP-2016-10.00-July-2016-CONSULTATION-VERSION-14-07-2016.pdf>, accessed 061018] [Correct for Sap 2016?].
- [7] The Government's Standard Assessment Procedure for Energy Rating of Dwellings, Version 10.0, UK Building Research Establishment, Published on behalf of DBEIS, 2018, p. 176. [Available at: <https://bregroup.com/sap/sap10/>, accessed 060918].
- [8] CCC, Reducing UK emissions: 2018 progress report to parliament. Committee on Climate Change, June 2018, 2018, p. 267. [Available at: <https://www.theccc.org.uk/wp-content/uploads/2018/06/CCC-2018-Progress-Report-to-Parliament.pdf>, accessed 060918].
- [9] CIBSE, CIBSE Guide Volume A, Design Data, Chartered Institution of Building Services Engineers, fifth ed., 1988 ISBN 0 900953 29 2.
- [10] Energy Benchmarks, Technical Memorandum 46, the Chartered Institution of Building Services Engineers, 2008, p. 26. ISBN: 978-1-903287-95-8.
- [11] CIBSE, CIBSE Weather Data Sets, 2016 [Available at: <https://www.cibse.org/weatherdata>, Accessed 041118].
- [12] Building Regulations Part L & F Briefing, 2018, p. 9. Private comm.
- [13] Summary Report on energy Suppliers' Communication with Customers Regarding Smart Meter Data, 2018, p. 25. [Available at: (https://www.energy-uk.org.uk/files/docs/Policies/Smart%20Meter%20Policies%20%20consultation%20responses/2013/smart_meter_data_guide_version_1-june-13.pdf) accessed 070918].
- [14] English Housing Survey: Housing Stock Report 2008, Department for Communities and Local Government, London, UK, 2010, p. 174.
- [15] Digest of United Kingdom Energy Statistics 2017, 2017, p. 264. [Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/643414/DUKES_2017.pdf, accessed 100718].
- [16] DBEIS, Digest of UK energy statistics (DUKES): weather. Excel tables - Mean air temperature deviations (DUKES 1.17) Mean heating degree days 2002 to 2016 (DUKES, 1.1.8) and Mean air temperatures (averages) 1970 to 2016 (DUKES 1.1.9), 27th July 2017, 2017. [Available at: <https://www.gov.uk/government/statistics/weather-digest-of-united-kingdom-energy-statistics-dukes>, accessed 210618].
- [17] Energy Consumption in the UK, 27 July 2017 and Later Update, 26 July 2018, 2017, p. 39. [Available at: <https://www.gov.uk/government/statistics/energy-consumption-in-the-uk> accessed 100718 and 190918].

- [18] DBEIS, Final UK greenhouse gas emissions national statistics: 1990–2016, 2016 UK Greenhouse Gas Emissions: Final Figures - Data Tables, UK Department for Business, Energy and Industrial Strategy, 2017 [Available at: <https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-2016> accessed 210918].
- [19] DBEIS, Annual domestic energy bills, updated 29 march 2018, Average annual domestic electricity bills for UK countries (QEP 2.2.2) and Average annual domestic gas bills for UK countries (QEP 2.3.2), UK Department for Business, Energy and Industrial Strategy, 2018 [Available at: <https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics> accessed 210918].
- [20] Fuel Poverty: Methodology Handbook, UK Department for Business, Energy and Industrial Strategy, 2018, p. 82.
- [21] DBEIS, Smart Meter Statistics, Quarter 4 2018, Great Britain, 2019 Excel workbook. [Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/789633/2018_Q4_Smart_Meter_Statistics_FINAL.xlsx accessed 190519].
- [22] The government's Standard Assessment Procedure for Energy Rating of Dwellings, 2012 Edition, SAP 2012, Version 9.92, Rev. Feb. and June 2014 to Include RdSAP2012, UK Building research Establishment on behalf of the UK Department of Energy and Climate Change, 2014, p. 234. [Available at: http://www.bre.co.uk/filelibrary/SAP/2012/SAP-2012_9-92.pdf Accessed 080215].
- [23] DECC, Edward Davey Speech to EcoBuild Conference: Making Britain's Homes Warmer, Greener, and Cheaper to Heat, 5 March 2014, 2014. [Available at: <https://www.gov.uk/government/speeches/edward-davey-speech-to-ecobuild-conference-making-britains-homes-warmer-greener-and-cheaper-to-heat>. Accessed 110215].
- [24] The Government's standard assessment procedure for energy rating of dwellings, 2001 edition, SAP 2001 version 9.70, December, BRECSU, UK Building Research Establishment on behalf of the UK Department for Environment Food and Rural Affairs, 44pp.
- [25] M.E.H. Dyson, S.D. Borgeson, M.D. Tabone, D.S. Callaway, Using smart meter data to estimate demand response potential, with application to solar energy integration, Energy Policy 73 (2014) 607–619. <https://doi.org/10.1016/j.enpol.2014.05.053>.
- [26] Residential Energy Consumption Survey (RECS): 2009 Technical Documentation – Summary, Energy Information Association, US Department of Energy, 2013, p. 19. [Available at: <https://www.eia.gov/consumption/residential/methodology/2009/pdf/techdoc-summary010413.pdf> accessed 110119].
- [27] Energy Star, Home Energy Yardstick, 2018 [Available at: https://www.energystar.gov/index.cfm?fuseaction=home_energy_yardstick.showgetstarted, accessed 070918].
- [28] EPA, The Energy Star Home Energy Yardstick. Draft Report, US Environmental Protection Agency, 2008 11/3/08.
- [29] EU, Directive 2002/91/EC of the European parliament and of the Council, 16 december 2002, on the energy performance of buildings, Off. J. Eur. Commun. (2003) 7 [Available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:001:0065:0071:EN:PDF>, accessed 080215].
- [30] EU, Directive 2010/31/EU of the European parliament and of the Council, 19 may 2010, on the energy performance of buildings. (recast), Off. J. Eur. Commun. (2010) 23 [Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0031&from=EN>, accessed 05062018].
- [31] EU, Directive 2012/27/EU of the European Parliament and of the Council, on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC, 25 October, 2012, 2012 [Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=EN>, accessed 070918].
- [32] EU, Directive (EU) 2018/844 of the European parliament and of the Council, 30 May 2018, Off. J. Eur. Commun. (2018) [Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?toc=OJ%3A%3A2018%3A156%3ATOC&uri=uriserv%3AOJ.L.:2018.156.01.0075.01.ENG>, accessed 291018].
- [33] Escan, European Smart Metering Landscape Report: Utilities and Consumers. Deliverable D2.1 of Project: USmart Consumer – You are a Smart Consumer, Funded by Intelligent Europe, 2016 [Available at: http://www.escansa.es/usmartconsumer/documentos/USmartConsumer_European_Landscape_Report_2016_web.pdf, accessed 070918].
- [34] P. Gianniou, C. Reinhart, D. Hsu, A. Heller, C. Rode, Estimation of temperature setpoints and heat transfer coefficients among residential buildings in Denmark based on smart meter data, Build. Environ. 139 (2018) 125–133. <https://doi.org/10.1016/j.buildenv.2018.05.016>.
- [35] V.J. Haines, D. Allinson, J. Beckhelling, B. Mallaband, A. Beizaee, A. Morton, S.M. Porritt, M. Li, D. Wright, E. Foda, S. Hallin, D.L. Loveday, K.J. Lomas, The DEFACTO field Trial: Methodology and Dataset, 2019 <https://doi.org/10.17028/rd.lboro.7837940>.
- [36] J. Henderson, Private Communication, to D Allinson, Following SAP 25th Anniversary Event, 2018, p. 3.
- [37] The Building Regulation 2010, L1A Conservation of Fuel and Power in New Dwellings, Approved Document L1A, 2013 Edition - for use in England, Online version, 2014, p. 48. ISBN 1 8 85946 510 3.
- [38] Hudson, US Environmental Protection Agency, 14/8/2018 Personal communication, 2018.
- [39] Immowelt, Energy Certificate, Demand and Consumption: Differences, 2019 [Available at: <https://ratgeber.immowelt.de/energieausweis.html>, translated from English, accessed 220119].
- [40] W. Kong, Z.Y. Dong, J. Ma, D.J. Hill, J. Zhao, F. Luo, An extensible approach for non-intrusive load disaggregation with smart meter data, IEEE Trans. Smart Grid 9 (2018) 3362–3372. <https://doi.org/10.1109/TSG.2016.2631238>.
- [41] K.J. Lomas, D. Allinson, Domestic energy demand in the UK: trends, regulation and energy rating, Supplementary information, S11 to “A Domestic Operational Rating for UK homes: Concept, Formulation and Application, Energy and Buildings, Lomas KJ, et.al. 2019”, 2019, p. 16 <https://doi.org/10.17028/rd.lboro.7836317>.
- [42] K.J. Lomas, A. Beizaee, Calculating the domestic operational rating of gas fired, centrally-heated homes: equations and results for example homes and the D114 sample, Supplementary Information, S12 to “A Domestic Operational Rating for UK homes: Concept, Formulation and Application, Energy and Buildings, Lomas KJ, et.al. 2019”, 2019, p. 14 <https://doi.org/10.17028/rd.lboro.7836320>.
- [43] K.J. Lomas, A. Beizaee, D. Allinson, V.J. Haines, D.L. Loveday, Domestic operational rating: excel data tables for the D114 homes, Supplementary Information, S13 to “A Domestic Operational Rating for UK Homes: Concept, Formulation and Application, Energy and Buildings, Lomas KJ, et.al. 2019”, p. 7 <https://doi.org/10.17028/rd.lboro.7836326>.
- [44] K.J. Lomas, S. Oliveira, P. Warren, V.J. Haines, T. Chatterton, A. Beizaee, E. Prestwood, B. Gething, Do domestic heating controls save energy? A review of the evidence, Renew. Sustain. Energy Rev. 93 (2018) 52–75 doi.org/10.1016/j.rser.2018.05.002. Available on line 23 May 2018. OA.
- [45] B. Mallaband, V. Haines, A. Morton, E. Foda, A. Beizaee, J. Beckhelling, D. Allinson, D. Loveday, K.J. Lomas, Saving energy in the home through digital feedback and control systems: an introduction to the DEFACTO project, in: Proc. BEHAVE Energy Conf, Third European Conference on Behaviour and Energy Efficiency, Saïd Business School, Oxford, 3rd and 4th September, 2014, p. 12.
- [46] MHCLG, English Housing Survey Headline Report 2015 to 2016: Section 1 Household Tables and Section 2 Housing Stock Tables, 2017 ISBN 978-1-4098-5014-4. Ministry of Housing, Communities & Local Government, Last updated 9 November 2017. Available at: <https://www.gov.uk/government/statistics/english-housing-survey-2015-to-2016-headline-report> [Accessed 250618].
- [47] MHCLG, Live Tables on Dwelling Stock (Including Vacants), Table 101: Dwelling Stock: by Tenure1, United Kingdom (Historical Series), 2018 MS Excel sheet. Ministry of Housing, Communities & Local Government, Last Updated 25th January 2018 [Accessed 270218] [This was used for dwelling numbers.].
- [48] Milton Keynes Energy World, An international Exhibition of 50 Energy-Efficient Houses, Official Guide, Milton Keynes Development Corporation, 1986, p. 192.
- [49] Green Deal and Energy Company Obligation, National Audit Office, 2016, p. 56. 14 April 2016. ISBN: 9781786040428 [Available at: <https://www.nao.org.uk/wp-content/uploads/2016/04/Green-Deal-and-Energy-Company-Obligation.pdf> Accessed 030618].
- [50] NCM, UK's National Calculation Method for Non-Domestic Buildings, 2014 [Available at: <http://www.uk-ncm.org.uk/> Accessed 190618].
- [51] OFGEM, Transition to Smart Meters, 2018 [Available at: <https://www.ofgem.gov.uk/gas/retail-market/metering/transition-smart-meters/> accessed 070918].
- [52] ONS, Statistical Bulletin: Families and Households: 5th November 2015, 2015 [Available at: <http://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2015-11-05>, accessed 270218].
- [53] ONS, Statistical Bulletin: Families and Households in the UK: 4th November 2016, 2016 [Available at: <https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/bulletins/familiesandhouseholds/2016>, accessed 180918].
- [54] T. Oreszczyn, S.H. Hong, I. Ridley, P. Wilkinson, Determinants of winter indoor temperatures in low income households in England, Energy Build. 38 (2006) 245–252, doi:10.1016/j.enbuild.2005.06.006.
- [55] United Kingdom Housing Energy Fact File, Cambridge Architectural Research Limited for the UK Department of Energy and Climate Change, 2013, p. 172. [Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/345141/uk_housing_fact_file_2013.pdf, accessed 140918].
- [56] D.E. Parker, T.P. Legg, C.K. Folland, A new daily central England temperature series, 1772–1991, Int. J. Clim. 12 (1992) 317–342.
- [57] A.J. Summerfield, R.J. Lowe, H.R. Bruhns, J.A. Caeiro, J.P. Steadman, T. Oreszczyn, Milton Keynes energy park revisited: changes in internal temperatures and energy usage, Energy Build. 39 (2007) 783–791.
- [58] Climate Change Act 2008, Chapter 27, Part 1, Carbon Target and Budgeting, The Stationary Office, H M Government, 2008, p. 108. [Available at: <http://www.legislation.gov.uk/ukpga/2008/27/contents>. Accessed 07 02 15].
- [59] D. Virk, M. Eames, CIBSE Weather Files 2016 Release: Technical Briefing and Testing, 2016, p. 24. [Available at: <https://www.cibse.org/weatherdata> Accessed 041118].
- [60] T. Walne, We spy trouble: ..., This is Money, 2018 [Available at: <http://www.thisismoney.co.uk/money/bills/article-5403473/Experts-say-GCHQ-concerned-smart-meters.html>. Accessed 070918].
- [61] K. Zhou, C. Yang, J. Shen, Discovering residential electricity consumption patterns through smart-meter data mining: a case study from china, Util. Policy 44 (2017) 73–84. <https://doi.org/10.1016/j.jup.2017.01.004>.