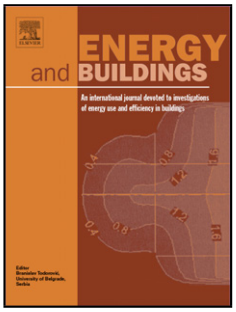

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# Possible effects of future domestic heat pump installations on the UK energy supply

*This research study investigates the effects of the large-scale installation of domestic heat pumps on the UK electricity supply over the short to medium term. A BREDEM-based dwelling energy model, incorporating a model of heat pump performance, is enhanced for the effects of varying monthly temperatures. Data from the English Housing Survey (2007) is analysed using this model to estimate electricity consumption to 2020 and 2050, and simulate scenarios for replacing existing heating systems by ground or air source heat pumps. The type of heat pump (ground or air source) is determined by dwelling plot dimensions data from the EHS. Modelling results for 2020 showed that a policy of replacing the heating systems with the highest emissions could reduce or at least minimise the increase in electricity consumption and carbon emissions. Results for 2050 showed that replacement of some 80% of current gas-fired systems would enable the UK to meet its target of 80% carbon emissions reduction in this sector when accompanied by simultaneous decarbonisation of the electricity supply. These results provide some support for the UK government's policy of subsidizing heat pump installations through the Renewable Heat Incentive payments whilst indicating that meeting emission targets requires far greater adoption of these systems than current ambitions.*

# 1 Introduction

## 1.1 Background to this study

Current policy-making on energy in the UK is faced with some significant challenges: the first is the “gap” in the UK electricity supply in the order of 22 GW, which will occur when the most of the current “fleet” of nuclear power stations are decommissioned in the period up to 2025, reducing the UK’s generating capacity by about 10 GW out of 85GW [1] and when a further 12 GW of fossil fuel-fired power stations are forced to close because of the requirements of the Large Combustion Plant Directive (LCPD), which regulates emissions of sulphur and nitrogen oxides [2]; the second is the need to ‘de-carbonise’ the UK electricity supply as part of the requirements of the 2008 Climate Change Act [3] for an 80% reduction in carbon dioxide emissions; a third is the requirement to generate 20% of the UK’s heat requirements from renewable sources by 2020, [4] under the requirements of Article 4 of the European Renewable Energy Directive (2009/28/EC): lastly, the fall in output which means that the UK has once again become an importer of natural gas [5].

To meet the latter requirement, the UK Department of Energy and Climate Change put forward a scheme to subsidise the production of heat from renewable resources, the Renewable Heat Incentive (RHI), for which the initial proposals were that owners, domestic or non-domestic, of newly-installed air and ground source heat pumps would be paid a subsidizing rate per nominal -'deemed' - kilowatt hour [6]. With a change of government in 2010, these proposals have been revised to exclude domestic users from receiving the output-related subsidy but instead to receive a one-off payment, the "Renewable Heat Incentive Premium Payment" (RHPP) for which both main categories of heat pumps will be eligible[7], with the original RHI proposal still under consideration for residential systems. While domestic heat pumps are not the only system types eligible for these payments, the possible effects of a considerable increase in the number of electrically-powered systems are worthy of analysis, both for their effects on the UK electricity supply and for their contribution to carbon emission reduction.

***The paper reports on research carried out as part of a 3.5 year project funded by the Engineering and Physical Science Research Council (Grant no. CASE/CNA/06/82) to assess the potential of ground source heat pumps in reducing energy-related carbon emissions from UK housing in a changing climate.***

## 1.2 Study objective

Given the challenges facing the UK electricity generation system and the possible disruptive effect of the installation of heat pumps on heating systems in UK housing, the objective of this study is to estimate the effect of the possible numbers of heat pumps on the UK electricity supply, both in terms of extra loads and also in terms of meeting the UK targets for carbon emission reduction. This is of concern, not only because of the shorter term electricity supply problems but also because of the necessity of replacing the current monoculture of gas-fired systems in UK dwellings in order to take advantage of the decarbonisation of the UK electricity supply. The manufacturing of a large number of heat pump systems will involve substantial embedded carbon, which must also be considered. Further aspects of the conversion to heat pumps which will have an impact on electricity demand is the possibility of the adoption of heat pumps that provide space cooling as well as heating - "reversible" heat pumps - and of the possible installation of photo-voltaic systems to balance this extra summer-time load.

This study consists of the analysis of possible heat pump deployments, which, along with rules as to which dwelling types systems are to be applied and other parameters, have been termed *'scenarios'*. This employs the typology described by Dixon[8], who defines this type of 'future thinking' as *"use[ing] imagination to consider possible future alternatives"*, though the term *'technical scenario'* distinguished by McDowall and Eames[9] as "*emphasis[ing] the technical feasibility and implications of different options, rather than explore how different futures might unfold"* might be more appropriate as this study does not attempt to indicate the path that will be taken to reach any of the scenarios, a characteristic which Dixon attributes to other 'future thinking' types such as *'roadmaps'*, *'transitions'* and *'pathways'*.

Those proposed do not encompass all the various social, technological and political aspects of the future of energy use in the UK included in the UK Government's Foresight report[10]. This suggested four scenarios, with slightly fanciful titles, encompassing visions where regions are autonomous in energy generation, "Resourceful Regions" ; where fossil fuel continues to be dominant along with carbon capture and storage, "Carbon Creativity"; where energy efficiency, demand reduction - of all kinds, and distributed generation are most significant, "Sunshine State"; and where large scale renewables - the Severn Barrage, off-shore wind and north African solar - are predominant, "Green Growth". These have been superseded to some extent by the legal target of 80% reduction in carbon emissions in the Climate Change Act[3] and by current government energy planning [11]. Consideration of the energy generation proposals in these scenarios does, however, bring some insight. Thus, under "Resourceful Regions", mass heat pumps installation would be improbable because of the lack of coordination; under "Carbon Creativity", perhaps extremely expensive because of carbon taxation; unlikely and perhaps un-necessary due to the lack of generating capacity under "Sunshine State", but would be reasonably supported under the "Green Growth" scenario by large-scale, low-carbon generation. These are useful, though not subtle, insights, and do not provide a solution to the problem elicited by Fawcett [12] of the domestic heat pump as "following technology", whose credentials as low carbon technology are dependent on large-scale supply of low-carbon electricity, the retrofit of badly insulated housing stock and the change-over to low temperature heat distribution systems. Added to these issues are possibly short-term problems in installation and performance found by the Energy Savings Trust heat pump trials [13, 14] and serious, but localised, deficiencies in the electricity distribution network identified in the North Blyth project by Lacey[15], where the connections to dwellings could only support heat pump installations in every other dwelling.

### 1.3 Previous work

Conventionally, this type of study is performed by means of a disaggregated ('bottom-up') domestic energy model for the UK housing stock, since this provides a mechanism for the input of possible technological changes in heating systems[16]. Estimation of stock-level values involves energy modelling for each of a set of archetypal dwellings, before and after an intervention, and grossing-up the results according to the estimated proportion of these archetypes in the housing stock. There are at least five models of this type for the UK housing stock: BREHOMES [17-19], UK Domestic Carbon Model(UKDCM) [20], DECarb model[21-24], Community Domestic Energy Model (CDEM) [25], Johnston[26, 27], employing as their basis widely different numbers of archetypal dwellings, ranging from 2 (Johnston's model) up to 20,000 (UKDCM). BREHOMES modelling is used by BRE, the UK authority for housing energy statistics, to generate the statistics to compile the annual Domestic Energy Fact File[28]. BREHOMES employs a BREDEM-type [29-31] model for dwelling-level modelling, as do the other four, albeit with various enhancements, making BREDEM the *de facto* standard model for this purpose. Other modelling such as that by Ward [32] has used SAP for a segment of the UK stock to examine the effects of rising temperatures on overheating under conditions of climate change.

Largely, the studies performed using these models examine the effectiveness of various strategies in attaining the carbon emission reduction policy targets current in the UK at the time of their development, viz. 60% or 80% reduction by 2050, and make comparisons with the outcomes without these interventions. Strategies modelled include demand side, ie. improved insulation and more efficient appliances and heating systems, and supply side, ie. reductions in the carbon intensity of electricity generation. However, none of the interventions include substantial numbers of heat pump systems, restricting their application to new-build and country properties, despite the fact that heat pumps are the most efficient heating systems currently available as a replacement for gas systems. [33, 34]

The modelling systems developed by Gadsden et al[35] and Gupta[36] provide energy and carbon dioxide emission estimates from a survey of a section of the housing stock, representing a parallel path of dwelling energy modelling.

These tools employ data reduction techniques to set values for the principal BREDEM parameters based on built form and date of construction, largely the same mechanism as that in the domestic energy models, but based on survey data from actual dwellings.

Kavgic et al[37], in their review of the five main models in the list above, make the point that data from the English Housing Survey(EHS) is the most suitable basis for such models, in order to mitigate against the issue of reduced reproducibility of results from previous studies because of the non-availability of the detailed input data and assumptions.

## 2. Methodology

### 2.1 Development of heat pump and building energy model

To estimate changes in energy consumption and carbon emissions for the English housing stock due to heat pump system take-up, a version of the standard BREDEM-8 building energy model [29] enhanced with a detailed heat pump model [38] was used to process the samples from the English Housing Survey 2007 data [39], employing parameter reduction techniques [40, 41] based on built form and date of construction to provide values for the model parameters which are not present in the EHS data. Since the BREDEM-8 model does not provide estimates for flats, this process was performed on an extract of samples for single-family houses only.

Use of the EHS data permits the following:

values obtained from this study can be compared with the BRE Domestic Energy Fact File [28];

dwelling plot variables from EHS data allow the plot size to be calculated to allocate the source type for the heat pump system;

sample weights from EHS samples can be used to gross-up estimates without further estimation;

accurate comparison between estimates for the heat pump system and the existing system, since these details are included in the EHS sample;

Hence, the per-sample consumption estimates obtained from this process were grossed-up by the dwelling sample weights included with the Survey to obtain estimated total consumption values for the English housing stock.

Scenarios - “deployment scenarios” - for short-term take-up for 2020 of heat pump systems were taken from the background studies to the RHI proposals [42], while a long-term take-up scenario was developed from the requirements of the UK Climate Change Act [3], 'pathways' for heat pump take-up to 2050 from Department of

Climate Change Pathways Calculator [43] , with climate data taken from the UK Climate Projections 09 'Key Findings' data [44].

From the deployment scenario values, a second level of scenarios -"application scenarios" - was built, reflecting the criteria applied to select the dwellings for heat pump installations, by assigning heat pump installations to dwelling samples, totalling the weights of those samples until the total of the selected sample weights are equal to the deployment scenario values. Total estimates for each application scenario were calculated from the products of the sample weight and the sample estimates for the energy consumption and carbon dioxide emission reductions. For the most realistic and effective application scenarios, monthly energy consumption was estimated to provide an indication of effects on winter and summer peak electricity loads.

### 2.2 Domestic heat pump model

The heat pump regression model is described in our previous paper [38].

For heating, three source temperature estimates are used: average monthly air temperature for air source heat pumps, annual average air temperature for a vertical borehole ground source and a monthly soil temperature for the Julian day number of the middle day of each month estimated by a sinusoidal function of collector depth, annual air temperature amplitude, and soil thermal diffusivity. This function is the result of work in the United States by Kusuda and Achenbach [45] and has been shown to be valid for the UK by Jenkins et al [46]. The estimating method for sink temperature depends on the presence or absence of weather compensation control and the distribution type for the system. If weather compensation controls are not present, then sink temperatures are set to 35ºC and 55ºC, for underfloor heating (UFH) and wet radiator distribution, respectively [47]. If weather compensation is present, then the distribution temperature is set according to a regression function calculated from the manufacturer-provided 'curves' – in this case, straight line graphs - defining the relationship between external temperature and the target temperature for the heating system. The curve slope to be used by the controller for the particular installation is defined by a single value set by the user, with radiator systems necessitating a higher value than UFH. The values are taken from the controller manufacturer's documents which illustrates the relationship between the external and target temperatures defined by the curves.

For domestic hot water generation, a COP is calculated for a lift with source temperature as before and a sink temperature of 55ºC, while for cooling, the COP is based on a lift value for a nominal sink value inside the dwelling of 18ºC and the source value for the current month.

The heat pump model was incorporated into the BREDEM-8 model by replacing the single efficiency parameter by individual monthly COP values for space heating, DHW generation and space cooling calculated using the monthly standard BREDEM table of average temperatures for the heating degree day region of the dwelling [29, Table D.17]. Routines estimating secondary system energy consumption based either on simultaneous use of the secondary system - bivalent parallel operation - or its replacement use - bivalent alternate operation - were added to the BREDEM model, along with a routine to estimate space cooling energy consumption, based on the SAP equivalent [48], and calculations of $CO_2$ emissions.

### 2.3 Domestic energy model based on EHS tables

This was developed in a three stage process. The initial stage was to create an extract from the complete set of EHS tables to reduce the number of variables to a manageable number. For the second stage, the additional variables required were created: BRE heating degree region (regions with similar heat load) corresponding to the Government Office Region from the sample; BREDEM heating system types and fuel types converted from those used in the EHS variables; dwelling plot area and area of plot to the rear of the dwelling. A randomising routine is used to allocate the heating degree region according to the Government Office Region based on the proportions of the housing stock in the component counties within the different region types. The third step was to process this completed table using the enhanced BREDEM model to build the domestic energy model. In this stage, a heat pump configuration (source type, operating mode) was first assigned to each sample, then the samples were processed with the enhanced BREDEM-8 model. This stage was repeated where necessary for the creation of estimates for an application scenario.

### 2.3.3 Assignment of heat pump configurations to dwelling samples

The heat pump configuration for each sample was determined according to the dwelling plot size, SAP rating and age. A horizontal ground loop was assigned for plots greater than twice the dwelling floor area, an air source was assigned for rear plot sizes greater than 4 $m^2$, and otherwise a vertical borehole was assumed. For the operating mode, monovalent mode was assigned if the SAP energy efficiency rating was greater than 51 and either type of ground source collector had been assigned. Bivalent parallel mode was assigned if the SAP energy rating for the dwelling was greater than 51 and an air source heat pump had been assigned, or the date of construction was post 1965. For dwellings older than 1965 currently with central heating installed, then bivalent alternate mode was assigned. If after these two selections, no operating mode has been selected, then no estimates are created for the sample in the next stage.

### 2.3.4 Energy, emissions and operating cost estimates

After the source type and operating mode have been assigned, the details of the dwelling location, built form and dimensions, age of construction, window types, current heating and DHW generation from the each sample are passed to the enhanced BREDEM-8 model to estimate the current energy consumption, CO2 emission and cost estimates and those for the generic heat pump system. If required, these include estimates for cooling energy.

Parameters available in the EHS data required for the BREDEM-8 model are extracted from a sample, others must be assigned using the reduced data technique developed by Rylatt et al and Gupta [35, 36] in which built form (detached, semi-detached, mid-terrace etc.) and date of construction serve as proxies to determine lower level parameters of the model. For this technique, the dwelling built form is used to determine the proportions of roof, floor and window area, and the number and type of thermal bridges assigned to the two heating zones assumed in a BREDEM model. The dwelling's date of construction is used to assign u-value estimates for building elements and values for storey height, numbers of open chimneys, air-tightness of doors and windows and for other parameters.

For the purposes of the modelling process, a rectangular floor plan is assumed, with all floors and the roof equal in area to that of the ground floor area. This simplification may not have been necessary as the EHS does contain details of the building shape, but this did not translate easily into the BREDEM-8 parameters. Windows and doors are assigned to the front and rear aspects only. The EHS survey does not record the orientation of the dwelling, so a value for this generated from the row number of the dwelling sample in the data table.

## 3. Estimation issues

For validation, the overall total of the enhanced BREDEM estimates for energy consumption due to main and secondary space heating and domestic hot water generation were compared with the official UK Energy Consumption statistics [49] in Table 1.

### 3.1 DECC / BREDEM-8 variations

The initial comparison (Table 1) showed that the estimated consumption from the enhanced BREDEM-8 model for general fuel types exceeded the DECC values by a wide range(Table 1, column 6), with only electricity consumption being less than the DECC value by about 18%. Possible reasons for these discrepancies are that:

- BREDEM estimates do not include energy consumption for flats or apartments, an omission that could account for the discrepancy in the electricity consumption values, since electric heating is more common flats to avoid fire risk;
- BREDEM-8 estimates are based on a demand temperature for the living space of 21ºC for all dwellings, a condition which is not necessarily true for all dwellings, since occupants' thermal comfort requirements and

behaviour have been found to be immensely variable [50-52]. Occupants of less efficient dwellings may not be able to afford the cost of heating either the whole or part of the dwelling to the BREDEM standard temperature.

- the sample weights used in the grossing-up process for the housing stock estimates are related to the known housing stock by dwelling tenure within GO Region, a division which does not necessarily bear any relationship to dwelling energy consumption. However, as the EHCS and the later English Housing Survey (EHS) have been designed and are used extensively for the energy efficiency analysis of the UK housing stock on meeting government targets for the reduction of "fuel poverty" - defined as occupants' expenditure on space heating energy exceeding 10% of their income, then this would seem unlikely to be the cause.

**Insert - Table 1 Adjustment factors to be applied to EHS / Enhanced BREDEM-8 energy consumption estimates**

To compensate for the omission of estimates for flats and to adjust the estimates generally, an analysis was made of the original EHS data to calculate the total of the weighted total floor area by dwelling type and main type of space heating fuel. These values were then summarised into two dwelling type categories - simply "flat" and "house" - and the four main fuel types, electricity, gas, heating oil and solid fuel. From this, a ratio was calculated between total stock flat and house floor areas for each fuel type, giving column 1 of Table 1 which was used to calculate the proportion of total domestic energy consumption (column 2) due to flats (column 5), and that due to houses (column 6) which, when compared with the total stock energy consumption estimate for houses from the enhanced BREDEM-8 model (column 5), gave an adjustment factor in column 7 of Table 1. Finally, a primary energy conversion factor is applied to each energy consumption value to estimate the primary energy required. This is obtained from SAP 2005, Table 12[53] for each fuel type, with values ranging from 1.07 for house coal and anthracite to 2.8 for all electricity supply types.

## 4. Scenarios for 2020

### 4.1 Scenario creation

Deployment scenarios were modelled by means of a scenario weight variable, which was set either to the value of the EHS sample weight, or to a proportion thereof, and then used to gross-up the sample-level energy, emission and cost estimates into the scenario estimates. The application scenario rules were used to determine which samples were included in the energy and emissions estimates for that application scenario.

### 4.2 Source of installation scenario data

The base data for these scenarios was obtained from NERA/AEA studies for the UK Dept for Energy and Climate Change[42], as part of that department's consultation on the proposed Renewable Heat Incentive. These are summarised in Table 2.

**Insert - Table 2 NERA scenarios for heat pump installations 2015, 2020**

The deployment scenario values were generated in two different ways by NERA. For ASHPs, this was by analogy with installation trends across Europe and, for ground source heat pumps (GSHP), by consulting with industry and academic bodies and with manufacturers. The higher values for GSHP installations - 1.1 million by 2020 as against 720,000 ASHPs - would tend to indicate that the latter process contains an element of wishful thinking, since, for individual householders, the barriers to GSHP installation - higher cost and outside space requirement, and much greater inconvenience of installation - are far higher than those for ASHPs. Despite this caveat, the 2020 scenarios have been used in this study, as they were recommended to the UK government as part of the decision to proceed with the Renewable Heat Incentive. An anomaly should be noted in that the installation values for the “2015 Stretch” are lower than those for the “2015 High” in the scenarios for ASHPs.

It is assumed for the deployment scenarios for 2020 that there will be no reduction in the per-kilowatt hour emissions from electricity generation over the scenario period and the value of 0.517 kg/kWh used in SAP 2009 is used in calculating $CO_2$ emissions. While the current targets for the carbon intensity of electricity generation for the UK are those shown in Table 3 [12, 54, 55], the current White Paper on "Energy Market Reform"[11] main focus is on constraining new fossil-fueled generation to the Energy Performance Standard of 450 $gCO_2$/kWh, while providing some financial incentives for renewables and nuclear power. Considerable reliance is being place on the construction of new nuclear power stations in the period up to 2020, based on a lead time of 7 years, but of the two reactor types under consideration, the construction record of one type has been mixed, with those at Olkilouto in Finland and Flamanville in France meeting with considerable problems, though other, later-starting, examples are apparently on time and on budget. Twelve units of the second type, on two sites, are under construction in the People's Republic of China, apparently without problem, though these are the first of this type to be built. Thus a conservative value for emissions in 2020 seems appropriate.

Insert - **Table 3 UK Targets for carbon intensity of electricity generation**

A further assumption is that the heat pumps will not be using electricity at ‘off-peak’ rates, i.e. will operate continuously, depending on load requirements, throughout the day. This is current practise with the IVT heat pumps monitored in the earlier part of this study, and is deemed by their manufacturer to be required for weather compensation control, allowing the heat pump to respond to all changes in external temperature as quickly as required[56]. It is also perceived that weather compensation control allows lower distribution temperature for which there is evidence in the data collected for the initial part of this study [38] where these temperatures ranged between 38 and 52 ºC. The widespread occurrence of this practise is probably also due to the origin of a substantial proportion of heat pumps (particularly GSHP) in Sweden, where there are no off-peak periods in electricity supply. In contrast, a UK manufacturer of GSHPs, Kensa Engineering, recommend that their heat pumps utilise ‘off-peak’ electricity, particularly the “Economy 10 Off-Peak” charging system which allows three periods per day at a reduced rate[57].

### 4.3 Application scenario 1 - Heat pump installations only

An initial set of results was created for a scenario reflecting the effect of the installation of heat pump systems without the implementation of any other energy efficiency measures or constraints on the energy efficiency of the selected dwellings other than those detailed in Section.2.3.3 above. Therefore, the scenario construction process made no assumptions about the dwellings, selecting samples using a pseudo-random process and within samples setting the scenario weight to a pseudo-random proportion of the sample weight, up to the numbers required by the scenario. The 'pseudo-random' nature of the processes ensures that the same selections and weights will be reproduced if the processes are repeated, even though the initial selections and weight values are random.

### 4.4 Application scenario 2 - Heat pump installation with improved insulation

A second scenario considered an amendment enforcing limited improvements to insulation as a pre-condition for the installation. The improvements to be made were: increase of roof insulation to 300 mm, insulation of wall cavities (where possible), insulation of hot water storage with 80mm of foam. The estimates for this scenario were created by applying the improvements to the sample followed by re-executing the BREDEM-8 model for each sample selected for scenario 1.  Of the dwellings in the scenario, 88 - 90% received roof insulation improvements, 62% DHW tank improvements, and 31- 34% cavity wall insulation.

### 4.5 Application scenario 3 - Maximising reduction of $CO_2$ emissions

A third scenario looked at maximising the carbon emission reduction by selecting those samples for which the estimated $CO_2$ savings were greatest, by sorting the sample table in descending order of total $CO_2$ emissions estimates for the grossed-up samples and assigning the entire sample to the heat pump system selection. This, in theory, should ensure the highest emissions reduction possible for the given number of installations in the scenario.

### 4.6 Application scenario 4 - Replacement of high $CO_2$ emitting technologies

The fourth scenario considered technology replacement, i.e. selecting the highest $CO_2$ emitting heating systems for heat pump replacement by processing the sample table by heating system type within fuel $CO_2$ emissions rate. The effect of this scenario was to allocate heat pump installations first to dwellings with direct electric heating, followed by coal and similar solid fuel, followed by oil.

## 5. Application scenario results

Table 7 summarises the results of assignments for all four application scenarios for 2020.

Two main sets of results are presented:

percentage reductions in $CO_2$ emissions for each fuel (mains or natural gas, propane, different forms of coal etc.) or energy (standard rate electricity, different forms of off-peak electricity) over all the scenarios;

percentage change in energy consumption for each of the above for each scenario;

electricity consumption for each scenario.

**Insert - Table 4 Summary of application scenario / dwelling assignments**

For application scenarios 1 and 2, the characteristics of the dwellings selected are fairly close to the average SAP rating for the UK housing stock of 52[28] and to the average total floor area for those in the EHS data of 91 $m^2$. Those selected by application scenario 3, being those where the largest carbon emission savings are possible, and conversely, responsible for the largest emissions, are significantly larger and at the lower end of the SAP scale. Those selected by application scenario 4 tend to be much smaller than the average with much lower than average SAP ratings commensurate with the high carbon emissions of their heating systems.

The following Figures 1 and 2 indicate the overall estimated effect of the four scenarios on overall electricity consumption.

**Insert - Figure 1. Electricity consumption for 2020 Application Scenarios**

**Insert - Figure 2. Standard (peak) rate electricity consumption for 2020 Application Scenarios**

**Insert - Figure 3. CO2 emissions reductions for 2020 Application Scenarios**

Figure 3 indicates that the most substantial reductions in $CO_2$ - over 7.5% for the “2020 Stretch” installation scenario - comes from targeting the highest emitters, but these reductions come with a substantial penalty in additional electricity generation of some 23 TWh per annum at peak rate for the "2020 Stretch" scenario. Compared with the 'heat pumps only", Scenario 2 brings no extra reduction in emissions. Scenario 4, that of targeting dwellings where the heating system utilises the highest emitting fuels, is not as effective as Scenario 3 in reducing $CO_2$, but, in compensation, creates only modest increases in electricity generation over current values for all installation scenarios. In the “2020 Stretch” scenario, the increase in peak rate electricity consumption is about 19 TWh in return for a reduction of just under 7% in carbon dioxide emissions. The "Centre" scenario achieves a reduction in overall electricity consumption of 3 TWh with consumption under the "Higher" scenario more or less unchanged. Figure 4 indicates the changes which occur with greater numbers of heat pump installations under this scenario, with, initially, the replacement of solid fuel systems burning coal and, secondly, systems burning fuel oil. Some proportion of electricity consumption is reduced with the replacement of storage heater systems using off-peak electricity, but a large proportion of these remain in place, indicating that that section of dwelling stock where these systems are installed is currently unsuitable for heat pump installations under the rules from section 2.3.3. Systems burning gas in all forms and biomass remain unaffected, though the dominance of mains (natural) gas-fired systems does mean that changes to energy consumed by other system types have a limited effect on overall energy consumption as indicated by Figure 5.

**Insert - Figure 4 Percentage change in energy consumption due to Scenario 4**

**Insert - Figure 5 Energy consumption for Scenario 4 - Fuel / technology replacement**

### 5.1 Practicalities

In labelling the inner layer of scenarios in this study as “application scenarios”, there is an implication that these scenarios could be applied as the basis for government policy for the implementation of the Renewable Heat Incentive or a similar scheme. For the rules governing these scenarios to function as policy, it is necessary either that they apply to all dwellings within the housing stock or that, if their success depends on applying the policy to a subset of the housing stock, then that subset should be identifiable. Of the four application scenarios, Scenarios 1 and 2 were applied randomly across the whole housing stock. Application Scenario 3, with the aim at an optimal assignment of installations to reduce carbon emissions, has no obvious method of implementation. While the individual dwellings surveyed for the EHS samples might be identifiable, those dwellings that are notionally grouped with each sample by the grossing weights are very likely not, having no obvious defining characteristics. However, Scenario 4, which focuses on the type of heating system to be replaced, does provide a fairly precise basis for such a policy and so this type of scenario was used to examine monthly electricity loads for 2020. Application Scenarios 1 and 2, which basically constitute a 'null' option and a minimal approach to improving energy efficiency, do not provide in these estimates any confidence that the current targets for the reduction of carbon dioxide emission will be met.

### 5.2 Peak loading

The estimates for changes in the January loads for electricity are presented in Table 5 for the Heat pumps only, Improved insulation, and Fuel / Technology Replacement application scenarios. The additional loads deriving from any of these scenarios are not of very great magnitude, with even the "Fuel / technology replace" values for 2020 amounting to less than 1.25% of the UK capacity of about 80 GW, compared with approximately 1.75% for the "Heat pumps only" and "Improved insulation". These scenarios cover a period when UK electricity supply will be decreasing unless further capacity is built, with any increase in load or consumption being unwelcome. However, the use of heat pumps to replace off-peak storage heating does come with the penalty of added day-time load, if the practice of operating the systems throughout the day is maintained, though the effect of large-scale heat pump installation using weather-compensated controls would be to avoid sudden peaking of load at the start of each low-charge period. Since dwellings and their occupants vary considerably in their heat demands, weather compensation might even mitigate against a surge when external temperatures drop. The advantages of the progressive ramping up of the load due to the characteristics of this method have to be compared with those of the timed start-up when using off-peak electricity. Thus the emissions reductions of any heat pump installation programme must be balanced against the poorer load profile for the electricity supply and, considering this, the "Fuel / technology replace" Application Policy is advantageous.

Insert - **Table 5 Estimated changes to electricity demand and load for January**

## 6. Scenarios to 2050

### 6.1 Deployment scenarios

These scenarios are based upon the AEA Pathways to 2050 Key Results [58], the Pathways to 2050 Calculator itself [43], both of which are based on MARKAL modelling for DECC, in which mass adoption of heat pumps is envisaged in the residential sector over the period 2020 - 2035 which is covered by the 4th Carbon Budget, mandated by the UK Climate Change Act. This mass adoption is to occur in parallel to the 'decarbonisation' of the electricity supply as it is intended that during the 4th budget period the emissions intensity of grid electricity will halve (from ~0.3 to ~0.15 $kgCO_2/kWh$).

The previous NERA/AEA studies for the UK Dept for Energy and Climate Change[42] leave at least a further 16 million dwellings in England alone still using gas heating. Some reductions in carbon emissions may be made through the replacement of older, less efficient gas systems, but if the intention is to take advantage of a ‘decarbonized’ electricity supply, this is best achieved by electric heat pump systems as Figure 6 illustrates.

**Insert - Figure 6 Relative emissions of heat pump systems compared with fuel-burning systems**

To provide estimates for the numbers of heat pump installations in 2050, the sole precedent that exists in the UK is that of the original take-up of gas central heating which has been installed in about 90% of dwellings starting from virtually 0% in 1964 [28]. This, combined with the 'Pathways' forecasts, would indicate the possibility of 80% take-up of heat pump systems in the slightly longer period up to 2050, equating to approximately 15.6 million installations for the 18 million dwellings for the EHS data in this study. If this value is taken as the “2050 Stretch” installation scenario and the proportions of “Stretch” to “Central” and of ASHPs to GSHPs in the 2020 installations scenario retained, this gives estimates for installations in 2050 as per Table 6.

**Insert - Table 6 Deployment scenarios for 2050**

In such large numbers, the manufacture and supply of heat pumps would become a significant source of green house gas emissions in themselves, and so this is estimated in Section 6.6.3.

### 6.2 Application scenario

Following on from the application scenarios in Section 5, since the “Fuel / Technology Replace” scenario produced the ‘best’ results for 2015 and 2020, this is used for 2050 as well with the data from the “2020 Central” and “2020 Stretch” scenarios carried over into 2050.

### 6.3 Climate change assumptions for temperature

A replacement table of monthly average temperatures by BRE Heating Degree day region was created to allow for the effects of climate change. The adjustment values were taken from the UKCP09 data for 2050, “high emission”, ‘central estimate” data for GO Regions and further adjusted for the variations between the GO Regions and the BRE Heating Degree day region, with a maximum adjustment of +3.7 ºC applied to the August temperature in the BRE Thames region and a minimum adjustment of +1.8 ºC applied to both Severn and South West regions throughout the first and last 4 months of the year. The average adjustment was 2.4 ºC.

### 6.4 Model assumptions

For these scenarios, the parameter was set in the model to require the estimation of energy use for space cooling. In these calculations, the SAP default value of 2 is set for the SEER (Seasonal Energy Efficiency Ratio) of the air conditioner. The model assumes that air conditioning uses only standard rate electricity, since the hottest part of any day is usually during peak hours. A further assumption made is that all the heat pumps installed are reversible, i.e. capable of both heating and cooling. In terms of the heat pump systems themselves, this assumption is reasonably plausible, since such systems are currently available [59] and it is also possible to convert existing systems. However, in the retro-fit installations involved in this study, the existing radiator distribution systems are not recommended for cooling use. Ochsner [17, p90] suggests that convection fans may be used for cooling and it is possible that these may be adopted over the 40 years to 2050, if cooling is found necessary.

The value for carbon dioxide emissions for electricity generation was reduced according to the current target for 80% reductions in carbon emissions by 2050, reducing from 0.517 $kgCO_{eq}$/kWh to 0.103 $kgCO_{eq}$/kWh. Additional 'zero-carbon' electricity was deemed to be supplied by roof-mounted photo-voltaic systems, the output of which was estimated as per section 6.5.

### 6.5 Photo-voltaic systems

Estimates were created of the possible output from photo-voltaic systems when deployed in parallel with heat pump systems. Output from roof-mounted photo-voltaic systems on each dwelling sample was estimated in the following stages:

The maximum output value (0.193 kWp/m2) from the RenSMART [60] comparison table of photovoltaic modules provided a standard value for the per-area output of the modules, assuming that this maximum value will become a typical value by 2050.

The monthly output of the system was estimated using the methods from the current draft SAP 2012 calculation [61] and supporting Technical Paper [62]. The relationship between solar output and annual solar radiation, peak output of the modules and overshading is provided by the Appendix M of SAP 2012:

$$AnnualOutput = 0.8 \times kWp \times S \times Z_{PV} \quad (1)$$

where kWp is the peak output of the system, S is the annual solar radiation in kWh/m$_2$ and $Z_{PV}$ is the overshading factor.

Appendix U of SAP 2012 relates $S_m$, monthly solar radiation, to orientation, tilt and month of the year, based on a factor converting horizontal radiation values to a given inclination, again for a given orientation and tilt, as follows:

$$S_m = 0.024 \times n_m \times S(orient, p, m) \quad (2)$$

and monthly output by:

$$Monthly\,Output = 0.8 \times kWp \times S_m \times Z_{PV} \quad (3)$$

Section U3.2 of SAP 2012 gives the derivation of S(orient, p, m) as follows:

$$S(orient, p, m) = S_{h,m} \times R_{h-inc}(orient, p, m) \tag{4}$$

and

$$R_{h-inc}(orient, p, m) = A \times \mathbf{cos}^2(\phi - \delta) + B \times \mathbf{cos}(\phi - \delta) + C \tag{5}$$

where:

$n_m$ = number of days in month $m$;

*orient* = orientation of the roof surface (N, NE, E, SE, S, SW, W or NW)

$p$ = tilt of the surface in degrees from horizontal (e.g. 0° is horizontal, 90° is vertical), 30º assumed;

$S_{h,m}$ = horizontal solar flux (W/m$^2$) for the month and heating degree days region.

$R_{h\text{-}inc}(orient, p, m)$ = factor for converting from horizontal to vertical or inclined solar flux in month $m$ for a given orientation *orient* and tilt $p$;

$\phi$ = representative latitude in degrees N for the heating degree region of the sample dwelling;

$\delta$ = solar declination for the applicable month in degrees;

$A$, $B$ and $C$ are further determined by a set of quadratic expressions in the sine of the tilt angle with coefficients determined by orientation [61Table U5].

The area of photovoltaic modules used to estimate output is determined by the area of the uppermost floor of the dwelling of which an arbitrary fraction (0.33) is deemed available for this purpose and the orientation of the system is determined by that assumed for the dwelling, with the further assumption that if the dwelling faces north, then the system can be installed on the south aspect of the roof.

Since output from these systems is available directly for consumption in the dwelling, and is independent of the dwelling occupants' behaviour, the estimates of their output are used unadjusted in calculations. Similarly, as minimal carbon dioxide emissions are attributable to their operation, estimates from the emissions calculation must be adjusted to reduce carbon dioxide emissions values by an amount equivalent to the photo-voltaic system output.

### 6.6 Life-cycle Analysis of heat pump systems

For GSHPs, Bennett [63] puts forward energy and carbon payback periods of 2.1 years and 6.0 years respectively compared with a gas-fuelled system, and embedded $CO_2$ of 500 kg $CO_2$(eq.). Johnson [64] in studying refrigerant leakage rates and their effects, found that, of life-time carbon emissions, electricity consumption contributed 80 − 83%, refrigerant 15 − 18% and the material in the pump itself 2 − 4% of emissions. This provided a lifetime's embedded CO2 equivalent value of between 4400 and 12000 kg $CO_2$(eq.) for heat pumps rated between 3.4 and 10.4 kw installed in the "Standard House Set", created by BRE for the Government consultation on the Renewable Heat Incentive [65] to provide examples of possible payments under the scheme. Johnson's estimates are, however, based on a fluoro-carbon refrigerant, R-410A, which has a global warming potential (GWP) of 1725, whereas commercial heat pumps using carbon dioxide (GWP = 1) are already available in the UK[66]. Making this refrigerant change would reduce the contribution from this source substantially and should be possible over the period to 2050, if not before.

**Table 7** contains entries for a limited range of dwelling floor areas in the "Standard Set", for which a linear relationship within dwelling type has been assumed between total floor area and emissions - in this case those for "Production and disposal", since emissions due to operation are calculated directly from consumption estimates and an existing distribution system is assumed. Since the basic components of an ASHP (compressor, evaporator, condenser and refrigerant) are the same as those in a GSHP, with only the collectors being significantly different, the same embedded $CO_2$ values are assumed for GSHP systems. For comparison, the EcoInvent database [67] provides a value of 0.6 tonnes of $CO_2$ for the embedded energy for a gas-fired central heating boiler. Estimates for embedded carbon emissions for each standard building and wall construction type combination are calculated as a linear function of the dwelling Total Floor Area.

**Insert - Table 7 Estimated life-time carbon emissions for heat pumps installed in BRE "Standard House Set" [64]**

### 6.7 Results for 2050

#### 6.7.1 Distribution of system types by dwellings

A summary of these are shown in Table 8, which also shows the 2020 equivalent installation scenarios for comparison.

The effect of the de-carbonisation of the electricity supply is to complete the shift of main heating systems using solid fuel to heat pumps, while, in the "centre" scenario at least, the remaining direct electric systems remain in place. This could be anomalous, since these systems are likely to have been replaced in the years following 2020. The 2050 Stretch scenario finds all forms of main heating systems virtually eliminated other than heat pumps (~85%) and gas central heating (~15%) but with consumption of other forms of energy remaining because of their use in secondary systems.

**Insert - Table 8 Summary of dwelling / heat pump assignments for 2050 scenarios**

### 6.7.2 Energy consumption

### 6.7.2.1 Annual effects

These results assume that, by 2050, space cooling will be required, and the "Business As Usual" results assume that conventional air condition equipment will be utilised for this.  Results for overall energy consumption and electricity consumption are shown in Figures 7  and 8 below.

These indicates that the substantial, "2050 Stretch", increase in heat pump installations has a correspondingly large effect on the consumption of mains gas, with a ~40% decrease in gas matching a 33% increase in overall electricity consumption and 46% increase in peak rate electricity. The net effect of the deployment of photovoltaic systems is extra output of 50 TWh, which reduces the net increase in electricity consumption to 10 TWh.

**Insert - Figure 7 Energy consumption up to 2050**

**Insert - Figure 8 Electricity consumption up to 2050**

Assuming the presence of space cooling, the effect of heat pump installations is to reduce estimated consumption for this purpose by some 6.2 and 15.4 TWh / annum for the “2050 Centre” and “2050 Stretch” scenarios, respectively, which to some extent mitigates against the 23 TWh and 63 TWh added overall by heat pump installations in these scenarios. The effect of the photo-voltaic systems is then to reduce the additions from heat pumps back down virtually to zero in the “2050 Centre” scenario and 4 TWh only in the "Stretch" scenario, making a very worthwhile contribution.

### 6.7.2.2 Monthly effects

These are illustrated by Figure 9 for the "2050 Stretch" scenario, indicating that it is possible that the output from photovoltaics would balance out not just the requirement for space cooling, but the entire system requirement for the four summer months.

**Insert - Figure 9 Monthly electricity consumption by system function -  "2050 Stretch" Scenario**

### 6.7.3 Estimates for carbon dioxide emissions

#### 6.7.3.1 Embodied carbon dioxide

These were estimated as per section 6.5 and the results are summarised in table 9, noting that if only one replacement gas boiler per household was necessary over the period to 2050, then there would be a net reduction in embedded carbon in heating systems with the higher numbers of installation. As the life of a gas boiler is put at 15 years [68], an ASHP at 15 years, and a GSHP at 20 • 25 years, the actual reduction could be higher than this estimate.

**Insert - Table 9 Estimated embedded carbon emissions to 2050**

### 6.7.4 Operational carbon dioxide emissions

These are summarised in Table 10. These estimates are compiled starting from the total value based on the BREDEM-8 estimates for the entire weighted EHS survey data using current emission estimates for electricity generation - line (1) in Table 10. This total is then re-calculated for 2050 based on the emissions estimated for the "de-carbonised" electricity supply and the changed energy requirements of the 2050 UKCP09 climate impacts as line (2), with the resulting reduction as line (3). The emissions reductions due to each installation scenario is calculated (lines 6 and 10) from the estimated emissions without heat pumps (lines 4 and 10) and with heat pumps (lines 5 and 11) and the overall reduction from 2006 to 2050 calculated in lines 6 and 12. These results show for the target emissions reduction of 80% to be approached, the adoption of domestic heat pumps is not only required to reach the levels indicated in the "2050 Stretch" scenario but must be accompanied by a corresponding 80% reduction on the carbon intensity of electricity generation. Further analysis of fuel use indicates that the main difference between the two scenarios is the far greater reduction due to the replacement of natural gas systems. However, while the '2050 Stretch' scenario apparently ensures that the UK reaches its target of 80% reduction in $CO_2$ emissions for the existing English housing stock, achieving this requires the installation of an extra 10 million heat pump systems over the '2050 Centre' scenario. The estimated cost of these $CO_2$ savings is between £107 and £234 per tonne., a high cost contributes to the anomalous position of heat pump heating systems, in that their status as low carbon technology is dependent on the availability of a low-carbon electricity supply and, in general, as the carbon intensity of the electricity supply reduces, the greater the effectiveness of these systems becomes at reducing carbon compared to a fossil fuel-fired system. However, as the carbon intensity of the electricity supply reduces, the difference in effectiveness in carbon emissions reduction between heat pump and direct electric systems reduces, even if the size of the heat pump COP is maintained. If a sufficiently large photovoltaic system is installed, as proposed here, the extra cost and complexity of installation of the heat pump system compared with, say, water-filled electric resistance radiators, becomes even more difficult to justify, since the value of the output from the photo-voltaics will go some way to defray the extra running cost of direct electric heating. The cost of more substantial energy efficiency improvements to the building fabric than were considered earlier in this study is likely to be similar to that of a heat pump system and this, too, would reduce running costs. While direct electric systems lack the capability to provide space cooling, it is by no means clear that this would be an absolute requirement, given the range of possible outcomes in the UKCP09 forecasts, where projections of summer temperature increases range from 1.2ºC to 7.6ºC under three different emissions scenarios [69]. Temperature changes at the low end of this range would probably eliminate the necessity for space cooling.

**Insert - Table 10 Carbon dioxide emissions 2020, 2050**

## 7 Discussions

### 7.1 Sample weights

The weights provided with the EHS database to gross-up the sample estimates to the housing stock are not calculated in a particularly transparent fashion. The calculation process is documented in the survey Technical Report [70] but not in way that indicates a relationship of the sample weight value to any of the factors affecting energy consumption. However, the Technical Report [70] contains chapters on "Using EHCS data to model Decent Homes Thermal Comfort" and "Heating and insulation", indicating that grossing-up using these weights is deemed valid for these characteristics.

### 7.2 Additions to, and improvements, in current housing stock

This study has deliberately omitted from the estimates any increase in energy consumption from additions and any reductions due to improvements. This is due to the range of variation, both in the numbers of new-build houses and in the possible government policies on building energy efficiency. On numbers, the size of the UK housing stock has increased steadily by slightly under 1% per annum over the 10 years from 1997 to 2006 - about 200,000 dwellings every year [28]. However, this steady increase covers up wider variations in the numbers of new-build houses built, which ranged from 54,000 to 410,000 p.a. over the same period. If the steady rate of increase continues to 2050, the UK housing stock will have increased from about 25 million to about 38 million dwellings, an increase of 50%. Increasing at the average of the more variable rate this estimate could reach some 43 million, 72% increase.

As far as the energy efficiency of additions to the housing stock is concerned, the UK government has recently downgraded the proposal[71] for all dwellings to reach a 'zero-carbon' standard by 2016, requiring all energy consumption, including appliance use, to be balanced by onsite generation using renewable sources, by removing the consumption for appliance use from that requirement. Thus, depending on the built form of the dwelling, emissions of between 10 - 14 kg$CO_{2(eq)}$/$m^2$/year would be permitted under the revised policy as against zero under the original [72, 73].

To date, policies and actions on the energy efficiency of the current stock have been limited in scope, being in the form of grants programmes for some forms of renewable energy systems, known as the Low Carbon Buildings Programme, under which only a few thousand installations were made [74] and the Decent Homes programme, a longer and much more complex programme attempting to alleviate fuel poverty (where household energy costs amount to greater than 10% of household income) amongst other forms of regeneration, both social and physical, within the social housing stock. Under the latter, improvements have been made to some 1.9 million homes with a further 168,000 remaining when the programme completed in 2010, though these may involve improvements to the washing and cooking facilities as well or instead of energy efficiency measures. The programme has been extended to 2015 in an attempt to complete it [75]. Another new programme, entitled the 'Green Deal' started in 2012 and consists of loan facilities to finance energy efficiency improvements with repayments via occupants' electricity bills but its take-up has been minimal. The current level of funding available for the programme, some £3bn, equates to £125 for each dwelling in the UK.

**Insert - Figure 10 Delivered energy consumption 1970 - 2006 [28]**

The idea that the gradual increase in energy consumption due to the increasing housing stock is balanced by an equally gradual improvement in the energy efficiency of the existing dwellings is confirmed by Figure 10, from the 2008 Domestic Energy Fact File [28], supporting the omission of new-build houses from this study.

## 8. Conclusions

A novel regression-based model for heat pump coefficient of performance, based on monitored data and results from heat pump standard testing, has been embedded within a BREDEM-8 dwelling energy model, enhanced with procedures to vary source/sink temperatures, to estimate space cooling and carbon dioxide emissions. The BREDEM-8 model was used to process an extract from the English House Survey to provide estimates of energy consumption for the sample dwellings, both with its original heating and with a heat pump, with source type determined by the plot size from the EHS sample. Data reduction techniques are employed to complete the parameters for the model, based on the age and built form of the dwelling. The individual sample estimates were grossed up with sample weights to obtain estimates for the whole stock for energy consumption and carbon dioxide emissions.

To examine the effects of heat pump installations on the UK electricity supply, two levels of scenarios were created for 2020, the first level based on the numbers of heat pump installations to be deployed by these dates, the second level based on the policy for applying the heat pump installations to houses. The deployment scenarios were derived from consultants' reports to the UK Government to define the possible financial effect of the proposed support for 'renewable heat", with installation numbers ranging from 560,000 in the "2020 Central" scenario to approximately 1.8 million in the "2020 Stretch".

The application scenarios analysed were: installation of heat pumps without any pre-conditions or dwelling enhancements; a similar policy but with limited improvements to roof and hot water insulation; the selection of sample dwellings where the weighted, estimated carbon emissions were highest; and the selection of dwellings with the highest emitting heating systems. The results analysis of these policy scenarios showed that, as the only scenario that had a substantial emissions reduction effect (~7.5% in "2020 Stretch"), the third scenario also caused a substantial increase in electricity consumption (23 TWh annually in "2020 Stretch"). The fourth application scenario was the only one that caused a reduction in overall electricity consumption and in carbon dioxide emissions in the "Centre" scenario. An analysis of peak electricity loads was carried out for application scenarios 1, 2, and 4, showing that, under scenario 4, the average January peak load would be subject to a negligible increase in 2020 with the other scenarios creating a circa 2 per cent increase. These results would indicate that if there are issues in maintaining the level of UK energy supply in 2020, then Scenario 4 would provide a better solution than the others.

A second set of analyses was carried out with scenarios to 2050, re-calculating energy consumption and carbon emission estimates based on monthly average temperatures "morphed" to those estimated for the UK CP09 predictions, reduced emissions from electricity generation matching those required by the UK Climate Change Act targets for 2050, and including space cooling and output from roof-mounted photo-voltaic systems. Deployment scenarios for heat pump systems were based on 80% adoption of gas central heating in dwellings between 1964 and 2010 and the application scenario used was that of scenario 4 above. Analysis of electricity consumption showed an increase of approximately 60 TWh in electricity consumption for space heating for the "2050 stretch" deployment scenario, a substantial increase on the ~63 TWH of 'business as usual", but also showed a reduction from 30 TWh to 15 TWh in consumption for space cooling. Estimates of embedded carbon showed a substantial reduction - about 32% - from heat pump systems compared with gas boilers and estimates of carbon emissions from operation showed that the UK target of 80% reduction is approachable under the "2050 stretch" scenario of about 15.6 million heat pump installations, but is dependent on the parallel decarbonisation of the UK electricity supply. Estimated output from photo-voltaic systems in the 'Stretch' scenario amounted to 50 TWh annually, balancing the electricity consumption in the summer months and reducing carbon emissions by an extra 1.5 to 3%.

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**Figure 1 Electricity consumption for 2020 application scenarios**

**Figure 2 Standard (peak) rate electricity consumption for 2020 application scenarios**

**Figure 3 $CO_2$ emissions reductions for 2020 application scenarios**

**Figure 4 Percentage change in energy consumption due to Scenario 4**

**Figure 5 Energy consumption for Scenario 4 - Fuel / technology replacement**

**Figure 6 Relative emissions of heat pump systems compared with fuel-burning systems**

**Figure 7 Energy consumption up to 2050**

**Figure 8 Electricity consumption up to 2050**

**Figure 9 Monthly electricity consumption by system function - "2050 Stretch" Scenario**

**Figure 10 Delivered energy consumption 1970 - 2006 [28]**

Highlights
Describes a study of possible effects of domestic heat pumps on the UK electricity supply
employs a standard dwelling energy model within a disagreggated housing stock model
estimates electricity consumption for scenarios of installations at 2015, 2020 & 2050
replacing high $CO_2$ heating systems reduced both electricity consumption & emissions.
in 2050, replacing some 80% of gas-fired systems would meet UK emission target

# Table 1 Comparison between grossed-up enhanced BREDEM estimates and Table 3.7 [52]

| | 1<br>EHS Flat/house ratio by TFA | 2<br>Table 3.7 values (Flats & houses) (GWh) | 3<br>B8 estimates (includes houses only) (GWh) | 4<br>Variation (-ve) | 5<br>Estimated energy consumption - flats (GWh) | 6<br>Estimated energy consumption - Houses (GWh) | 7<br>Adjustment factor |
|---|---|---|---|---|---|---|---|
| **Solid fuel** | 0.053 | 7,678 | 12,144 | 58.2% | 408 | 7,270 | 0.599 |
| **Gas** | 0.088 | 359,898 | 444,713 | 23.6% | 31,644 | 328,254 | 0.738 |
| **Electricity** | 0.428 | 123,569 | 101,760 | (17.6%) | 52,873 | 70,695 | 0.695 |
| **Oil** | 0.000 | 35,631 | 39,558 | 11.0% | 9 | 35,622 | 0.901 |
| **Total** | 0.109 | 526,775 | 598,174 | 13.6% | 45,660 | 441,842 | 0.739 |

**Table 2 NERA scenarios for heat pump installations 2015, 2020**

Table C.5

**Summary of ASHP Growth Scenarios**

| | | Domestic sector | | Non-domestic sector | |
|---|---|---|---|---|---|
| | **Year** | **Units thousand** | **Heat output TWh** | **Units thousand** | **Heat output TWh** |
| Stretch growth scenario | | | | | |
| | 2015 | 81 | 1 | 9 | 3.1 |
| | 2020 | 720 | 9.3 | 80 | 28 |
| Central growth scenario | | | | | |
| | 2015 | 59 | 0.8 | 7 | 2.3 |
| | 2020 | 270 | 3.5 | 30 | 11 |
| Higher growth scenario | | | | | |
| | 2015 | 88 | 1.1 | 10 | 3.4 |
| | 2020 | 410 | 5.3 | 46 | 16 |

Table C.8

**Summary of GSHP Growth Scenarios**

| | | Domestic sector | | Non-domestic sector | |
|---|---|---|---|---|---|
| | **Year** | **Units thousand** | **Heat output TWh** | **Units thousand** | **Heat output TWh** |
| Stretch growth scenario | | | | | |
| | 2015 | 140 | 1.7 | 15 | 5.3 |
| | 2020 | 1,100 | 14 | 120 | 42 |
| Central growth scenario | | | | | |
| | 2015 | 100 | 1.3 | 12 | 4.1 |
| | 2020 | 290 | 3.7 | 32 | 11 |
| Higher growth scenario | | | | | |
| | 2015 | 160 | 2 | 17 | 6.1 |
| | 2020 | 440 | 5.6 | 48 | 17 |

## Table 3 UK Targets for carbon intensity of electricity generation

| Date | Carbon intensity $kgCO_2/kWh$ | Source |
|---|---|---|
| 2008 (five year rolling average) | 0.55 | (Defra and DECC, 2010) |
| 2020 | 0.3 | (Committee on Climate Change 2010), to be achieved if current government ambitions on renewable energy and other low carbon sources are met. |
| 2030 | 0.052 | (Committee on Climate Change 2010). medium investment strategy (0.04 - 0.13 kgC02/kWh with high to low investment range) |
| 2030 - 2050 | Falls to around 0.01 | Markal modelling on behalf of CCC, (Committee on Climate Change 2010) |

Source: Fawcett, 2011.

**Table 4 Summary of application scenario / dwelling assignments**

| | 2020 | | |
|---|---|---|---|
| | Centre | High | Stretch |
| No of ASHP installations (000's) | 270 | 410 | 720 |
| No of GSHP installations (000's) | 290 | 440 | 1,100 |
| **Application scenarios 1 & 2: Heat pumps only and heat pumps plus insulation improvements** | | | |
| Average floor area ($m^2$) | 95 | 92 | 93 |
| Average SAP rating | 47.9 | 47.9 | 48.1 |
| Tenure | | | |
| Private rented | 7.50% | 8.50% | 7.50% |
| Housing association (RSL) | 5.20% | 5.20% | 5.00% |
| Local authority | 6.40% | 6.40% | 6.00% |
| Owner occupied | 80.90% | 80.00% | 80.80% |
| **Application scenario 3: Targetted on high CO2 emissions** | | | |
| Average floor area ($m^2$) | 198 | 184 | 157 |
| Average SAP rating | 31 | 33 | 36 |
| Tenure | | | |
| Private rented | 3.20% | 4.30% | 4.40% |
| Housing association (RSL) | 0.60% | 0.40% | 0.40% |
| Local authority | 0.00% | 0.10% | 0.10% |
| Owner occupied | 96.10% | 95.10% | 95.00% |
| **Application scenario 4: Technology / fuel replacement** | | | |
| Average floor area ($m^2$) | 79 | 94 | 114 |
| Average SAP rating | 34 | 33 | 35 |
| Tenure | | | |
| Private rented | 8.70% | 9.20% | 9.60% |
| Housing association (RSL) | 12.90% | 10.10% | 6.60% |
| Local authority | 8.20% | 6.70% | 4.40% |
| Owner occupied | 70.20% | 74.00% | 79.50% |

# Table 5 Estimated changes to electricity demand and load for January

| | Change in energy demand<br>2020 Stretch | | | Change in power load<br>2020 Stretch | | |
|---|---|---|---|---|---|---|
| | Heat pumps only | + improved insulation | Fuel / tech replace | Heat pumps only | + improved insulation | Fuel / tech replace |
| | | GWh | | | GW | |
| **Electricity** | | | | | | |
| **Std tariff** | **2,385** | **2,361** | **1,684** | **3.21** | **3.17** | **2.26** |
| Off-peak 7-hour | -14 | -20 | -1,531 | -0.02 | -0.03 | -2.06 |
| Off-peak 10-hour | 205 | 139 | 439 | 0.28 | 0.19 | 0.59 |
| 24-hour- heating tariff | -1 | -1 | -14 | 0.00 | 0.00 | -0.02 |
| **All electricity** | **2,575** | **2,478** | **578** | **3.46** | **3.33** | **0.78** |

**Table 6 Deployment scenarios for 2050**

| | Year | GSHP Units (000s) | ASHP Units (000s) | Total Units (000s) |
|---|---|---|---|---|
| Stretch growth scenario | | | | |
| | 2050 | 5,550 | 10,000 | 15,550 |
| Central growth scenario | | | | |
| | 2050 | 1,600 | 3,900 | 5,500 |

**Table 7 Estimated lifetime carbon emissions for heat pumps installed in BRE "Standard House Set" [64]**

| Heat-pump footprints, solid-wall construction, 15 year lifetime | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Consumptions | | | Footprint | |
| | | | | | | | Production and disposal | |
| Property | | Heat pump definition | | Power | Leakage | | Refrigerant | |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| Type | Area | Capacity | R410A | | Operating | End of life | Leaks | Prod'n |
| | m$^2$ | kW | kg | kWh/ lifetime | kg/ lifetime | | kg CO$_2$e/ lifetime | |
| **Flat** | 42 | 5 | 1.5 | 48,090 | 1.4 | 0.8 | 4545 | 493 |
| | 61 | 5.6 | 1.7 | 53,227 | 1.5 | 0.9 | 5128 | 557 |
| | 89 | 6.4 | 1.9 | 59,500 | 1.7 | 1.1 | 5840 | 634 |
| **Mid-terrace house** | 63 | 5.9 | 1.8 | 54,976 | 1.6 | 1 | 5327 | 578 |
| | 79 | 6.3 | 1.9 | 58,798 | 1.7 | 1 | 5761 | 625 |
| **End terrace house** | 63 | 8.9 | 2.7 | 79,092 | 2.4 | 1.5 | 8064 | 875 |
| | 79 | 9.7 | 2.9 | 85,806 | 2.6 | 1.6 | 8826 | 958 |
| **Semi-detached bungalow** | 64 | 7.2 | 2.2 | 65,897 | 2 | 1.2 | 6566 | 713 |
| | 74 | 7.7 | 2.3 | 69,306 | 2.1 | 1.3 | 6953 | 755 |
| **Detached bungalow** | 67 | 8.5 | 2.5 | 75,956 | 2.3 | 1.4 | 7708 | 837 |
| | 78 | 9 | 2.7 | 80,135 | 2.4 | 1.5 | 8182 | 888 |
| | 90 | 9.5 | 2.9 | 84,366 | 2.6 | 1.6 | 8662 | 940 |
| **Semi-detached house** | 77 | 9.5 | 2.9 | 84,189 | 2.6 | 1.6 | 8642 | 938 |
| | 89 | 10.1 | 3 | 88,782 | 2.7 | 1.7 | 9164 | 995 |
| | 102 | 10.7 | 3.2 | 93,418 | 2.9 | 1.8 | 9690 | 1,052 |
| **Detached house** | 90 | 14.3 | 4.3 | 122,755 | 3.9 | 2.4 | 13,019 | 1,413 |
| | 104 | 15.3 | 4.6 | 130,227 | 4.1 | 2.5 | 13,867 | 1,506 |
| | 120 | 16.3 | 4.9 | 138,180 | 4.4 | 2.7 | 14,770 | 1,604 |

**Table 8 Summary of dwelling / heat pump assignments for 2050 scenarios**

| Summary of dwellings in scenarios | 2020 | | 2050 | |
|---|---|---|---|---|
| | Centre | Stretch | Centre | Stretch |
| No of ASHP installations (000's) | 211 | 639 | 3,900 | 10,000 |
| No of GSHP installations (000's) | 190 | 960 | 1,600 | 5,550 |
| Technology / fuel replacement | | | | |
| Average floor area ($m^2$) | 107 | 116 | 120 | 94 |
| Average SAP rating | 35 | 34 | 42 | 48 |
| Tenure | Percentage of scenario total | | | |
| Private rented | 15.4 | 12.6 | 5.7 | 8.4 |
| Housing association (RSL) | 9.4 | 7.1 | 1.9 | 3.4 |
| Local authority | 6.6 | 5.4 | 1.5 | 2.3 |
| Owner occupied | 68.6 | 74.9 | 90.8 | 85.8 |
| **Original fuel for main heating system** | Percentage of this fuel type in EHS weighted sample | | | |
| 01 mains gas | 87.8 | 87.8 | 68.3 | 15.2 |
| 02 bulk LPG (propane or butane) | 0.4 | 0.4 | 0 | 0 |
| 03 bottled gas (propane) | 0.3 | 0.3 | 0 | 0 |
| 04 heating oil | 5.1 | 1.4 | 0 | 0 |
| 05 house coal | 0.6 | 0 | 0 | 0 |
| 06 anthracite | 0.2 | 0 | 0 | 0 |
| 07 manufactured smokeless fuel | 0.6 | 0 | 0 | 0 |
| 08 wood logs | 0.1 | 0.1 | 0.1 | 0.1 |
| 11 wood chips | 0.1 | 0.1 | 0.1 | 0.1 |
| 13 standard tariff | 3 | 9.9 | 29.9 | 84.6 |
| 14 Off-peak 7-hour | 1.3 | 0 | 1.3 | 0 |
| 15 Off-peak 10-hour | 0.3 | 0 | 0.3 | 0 |
| 16 "24-hour"- heating tariff | 0 | 0 | 0 | 0 |
| Total dwellings in scenario | 560,000 | 1,820,000 | 5,500,000 | 15,550,000 |

**Table 9 Estimated embedded carbon emissions to 2050**

CO2 Emissions: embedded (Ktonnes)

| | Effects to 2020 | | Effects to 2050 | |
|---|---|---|---|---|
| | Centre | Stretch | Centre | Stretch |
| Gas boiler replacement | 241 | 959 | 3,300 | 9,330 |
| Heat pump + refrigerant | 392 | 1,044 | 2,325 | 6,282 |
| Net emissions | 152 | 85 | -975 | -3,048 |

**Table 10 Carbon dioxide emissions 2020, 2050**

$CO_2$ Emissions (variation for technology / fuel replacement)

| Deployment Scenario | | | Total emissions (Ktonnes) | Emissions reduction (Ktonnes) | Percent change | Cumulative Emissions reduction (Ktonnes) | Percent change |
|---|---|---|---|---|---|---|---|
| | 1) | Total estimated CO2 emissions based on EHS survey - 2006 values | 151,350 | | | | |
| | 2) | Total estimated CO2 emissions based on EHS survey - 2050 values | 74,856 | | | | |
| | 3) (1) - (2) | Reduction due to lower emissions from electricity generation | | | | 76,494 | 50.5% |
| 2050 Centre | 4) | BAU | 30,060 | | | | |
| | 5) | Effect of heat pumps | 9,863 | | | | |
| | 6) (4) - (5) | CO2 reduction due to scenario | | 20,197 | 27.0% | 96,690 | 63.9% |
| | 7) | Reduction due to PV output | 2,278 | | | | |
| | 8) (4)-(5)-(7) | Total reduction due to scenario | | 22,475 | 30.0% | | |
| | 9) (8) + (3) | Total CO2 reduction to 2050 | | | | 98,968 | 65.4% |
| 2050 Stretch | 10) | BAU | 65,199 | | | | |
| | 11) | Effect of heat pumps | 22,210 | | | | |
| | 12) (10)-(11) | CO2 reduction due to scenario | | 42,989 | 57.4% | 119,483 | 78.9% |
| | 13) | Reduction due to PV output | 5,053 | | | | |
| | 14) (12)-(13) | Total reduction due to scenario | | 48,042 | 64.2% | | |
| | 15) (10) + (3) | Total CO2 reduction to 2050 | | | | 124,536 | 82.3% |

**Figure 1**

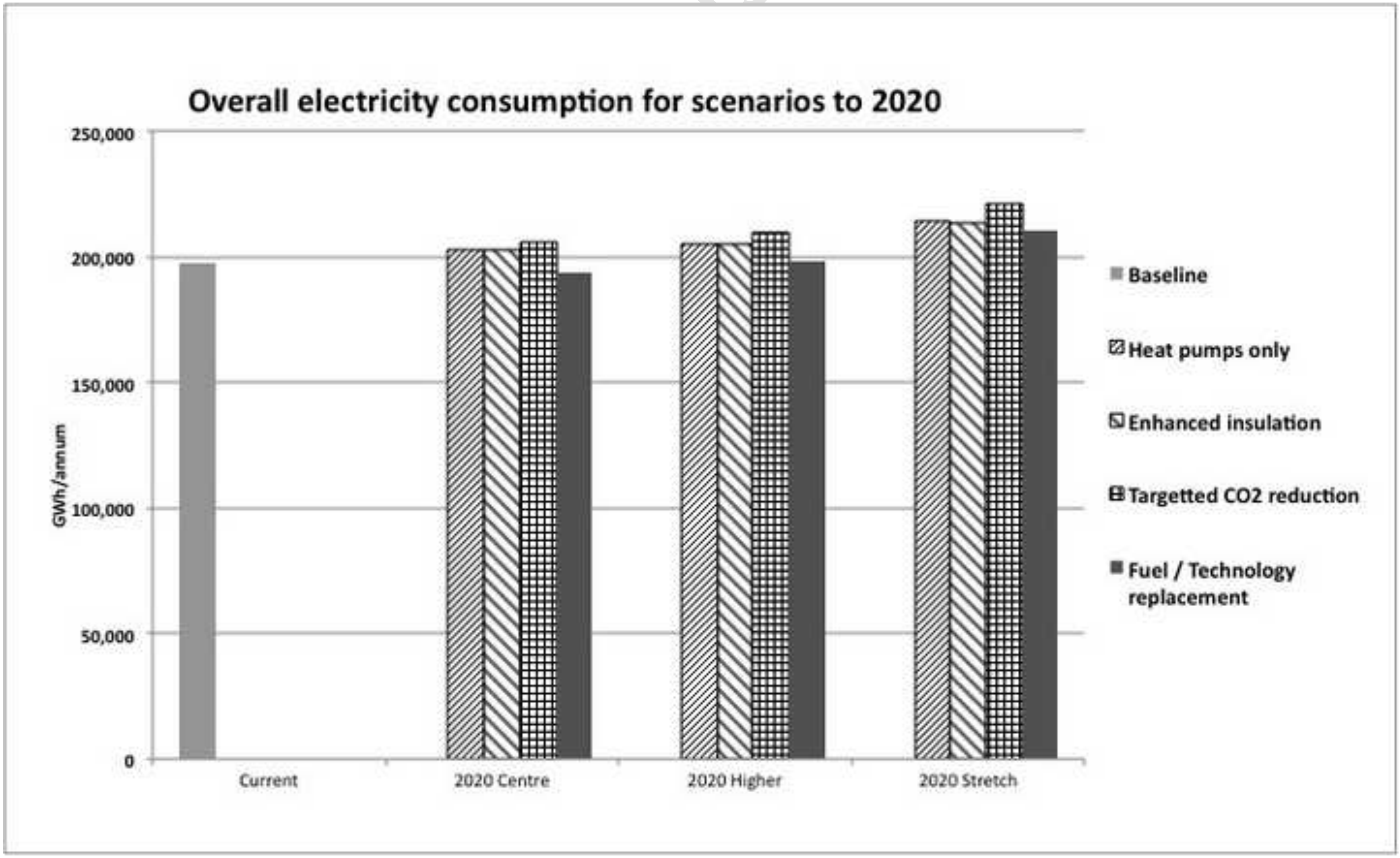

Overall electricity consumption for scenarios to 2020
GWh/annum
250,000
200,000
150,000
100,000
50,000
0
Current
2020 Centre
2020 Higher
2020 Stretch
Baseline
Heat pumps only
Enhanced insulation
Targetted CO2 reduction
Fuel / Technology replacement

Figure 2

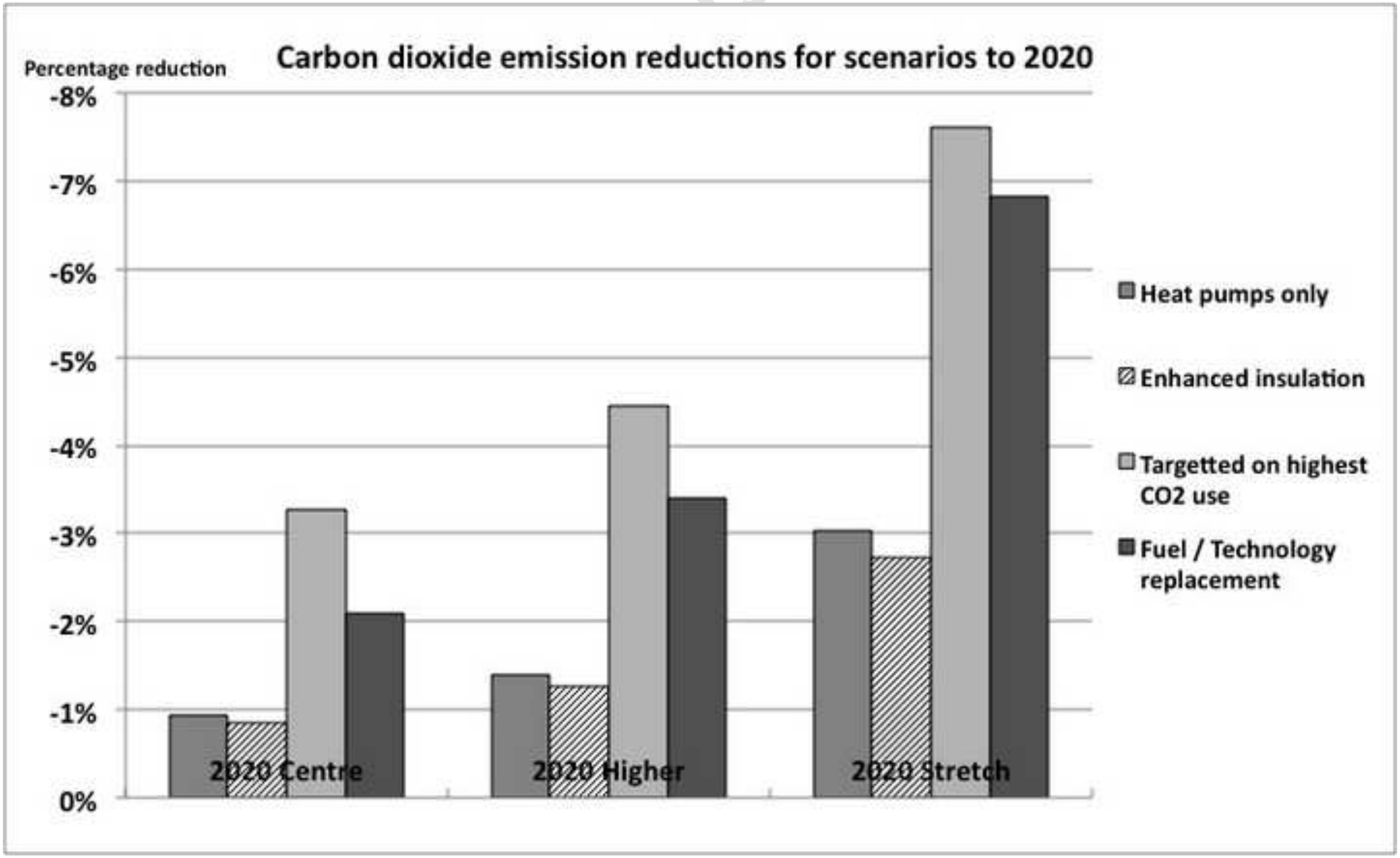

Percentage reduction
Carbon dioxide emission reductions for scenarios to 2020
-8%
-7%
-6%
-5%
-4%
-3%
-2%
-1%
0%
2020 Centre
2020 Higher
2020 Stretch
Heat pumps only
Enhanced insulation
Targetted on highest CO2 use
Fuel / Technology replacement

**Figure 3**

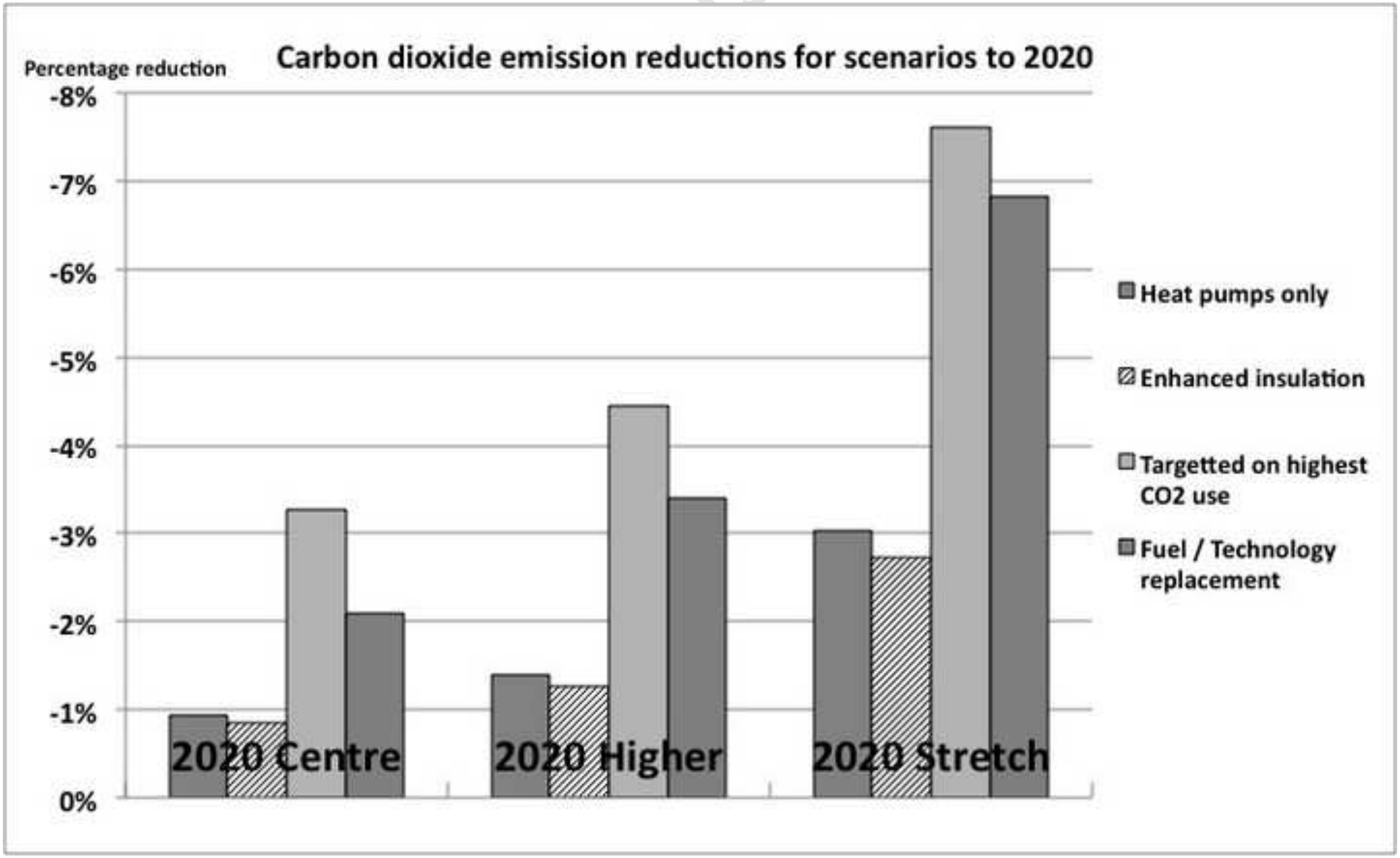

Carbon dioxide emission reductions for scenarios to 2020
Percentage reduction
-8%
-7%
-6%
-5%
-4%
-3%
-2%
-1%
0%
2020 Centre
2020 Higher
2020 Stretch
Heat pumps only
Enhanced insulation
Targetted on highest CO2 use
Fuel / Technology replacement

Figure 4

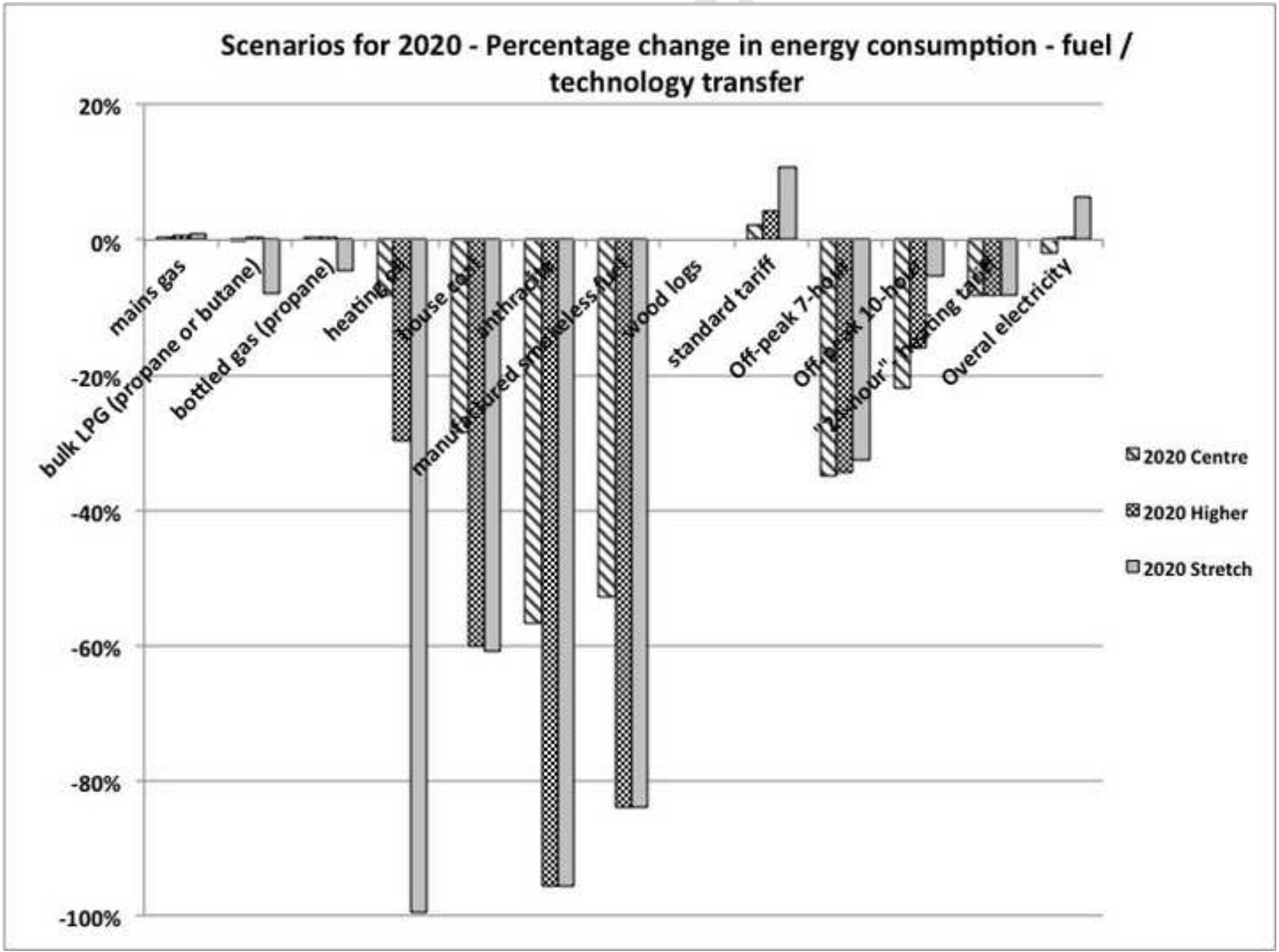
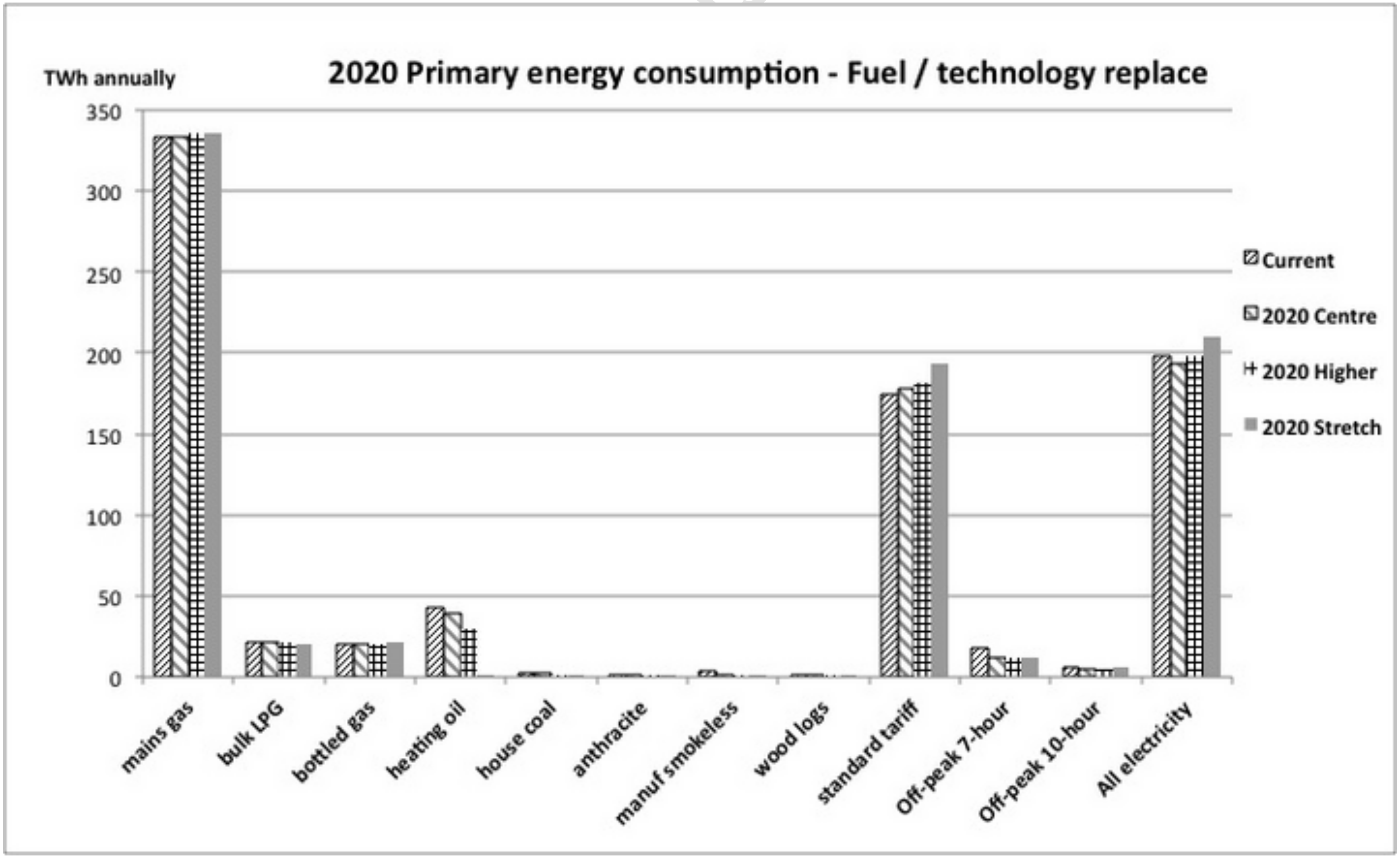

Scenarios for 2020 - Percentage change in energy consumption - fuel / technology transfer
20%
0%
-20%
-40%
-60%
-80%
-100%
mains gas
bulk LPG (propane or butane)
bottled gas (propane)
heating oil
house coal
anthracite
manufactured smokeless fuel
wood logs
standard tariff
Off-peak 7-hour
Off-peak 10-hour
"24-hour" heating tariff
Overal electricity
▧ 2020 Centre
▩ 2020 Higher
▢ 2020 Stretch

**Figure 5**



TWh annually
2020 Primary energy consumption - Fuel / technology replace
350
300
250
200
150
100
50
0
mains gas
bulk LPG
bottled gas
heating oil
house coal
anthracite
manuf smokeless
wood logs
standard tariff
Off-peak 7-hour
Off-peak 10-hour
All electricity
▨ Current
▧ 2020 Centre
⊞ 2020 Higher
■ 2020 Stretch

**Figure 6**

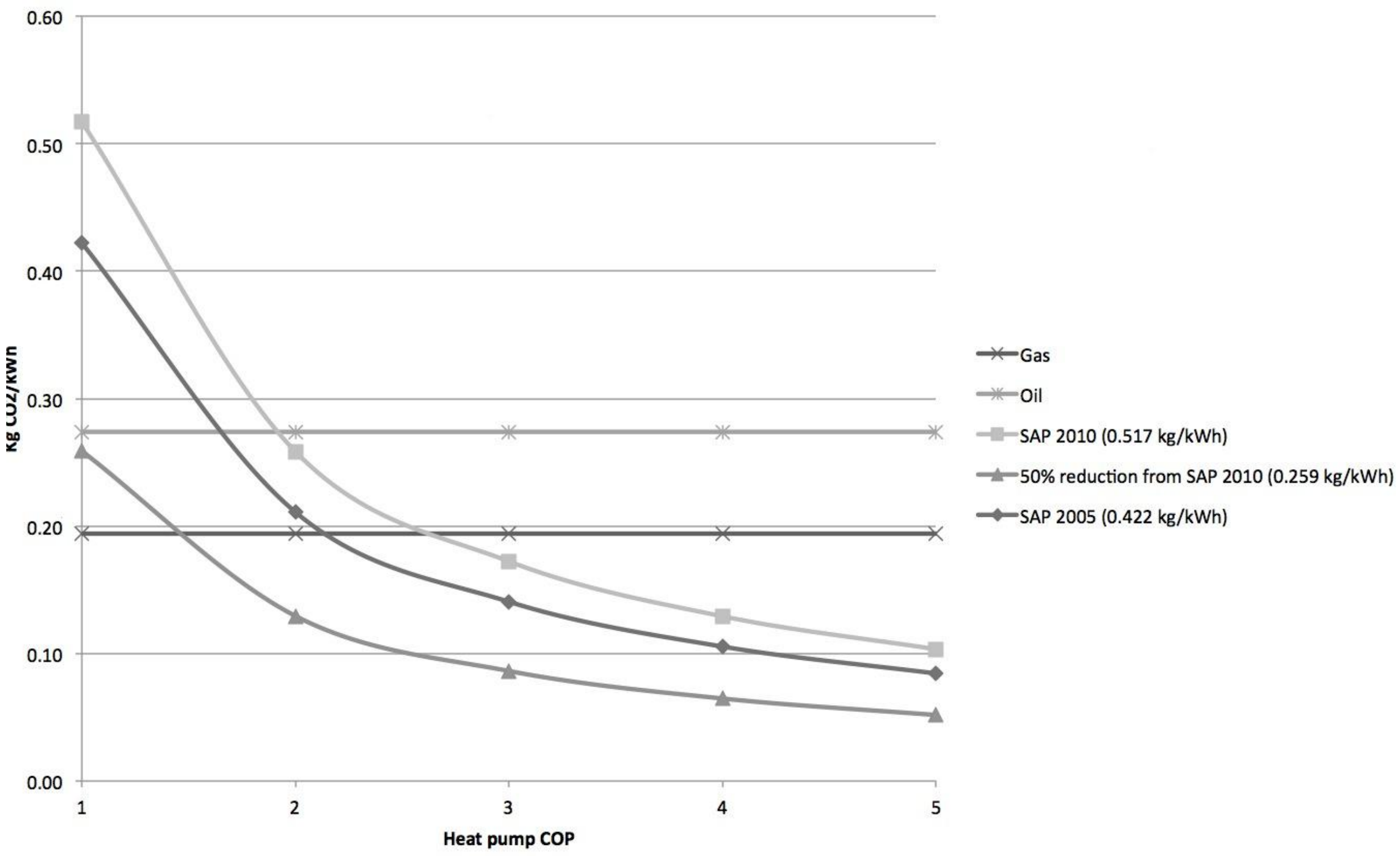

0.60
0.50
0.40
0.30
0.20
0.10
0.00
kg CO2/kWh
1
2
3
4
5
Heat pump COP
Gas
Oil
SAP 2010 (0.517 kg/kWh)
50% reduction from SAP 2010 (0.259 kg/kWh)
SAP 2005 (0.422 kg/kWh)

**Figure 7**

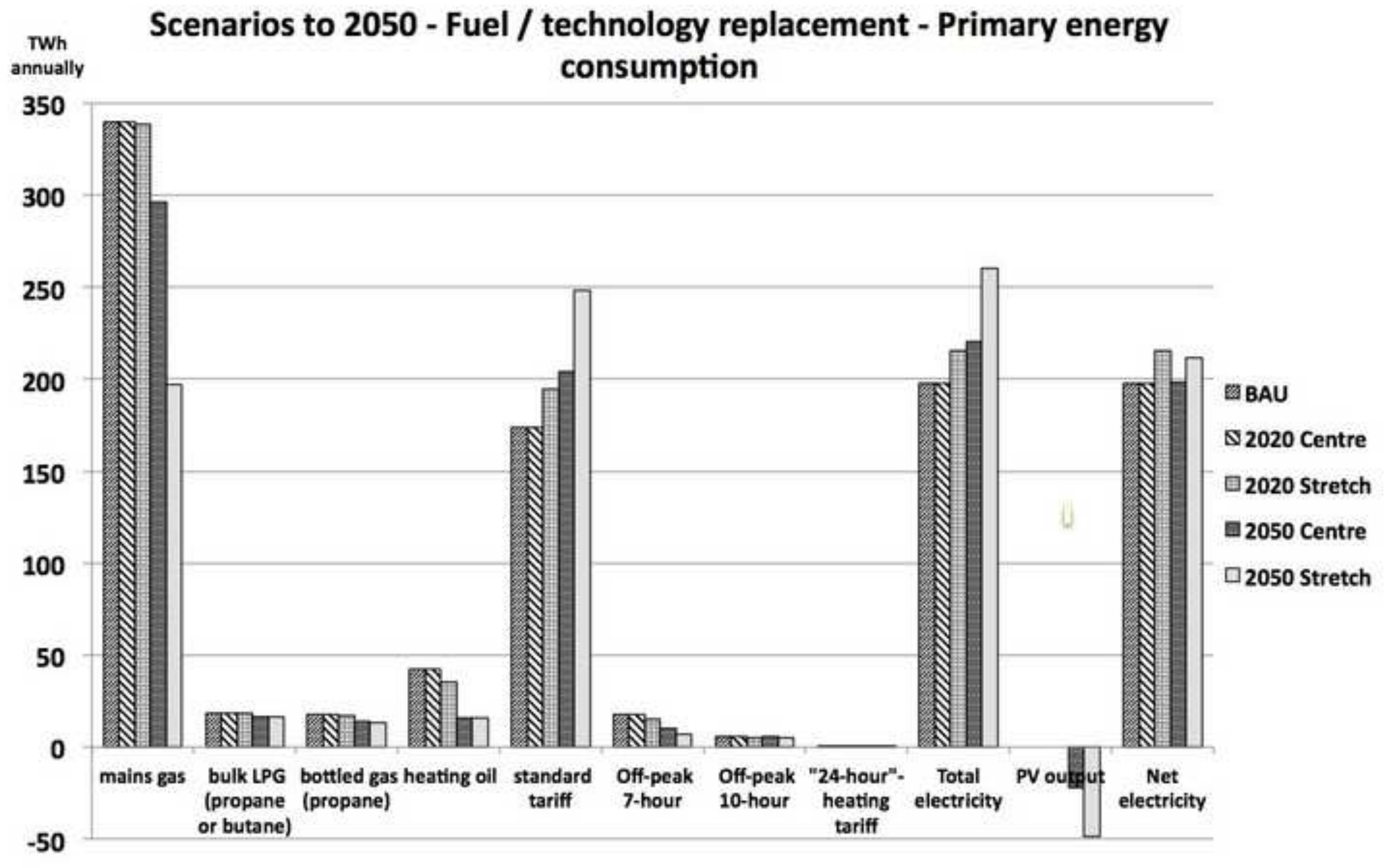

Scenarios to 2050 - Fuel / technology replacement - Primary energy consumption
TWh annually
350
300
250
200
150
100
50
0
-50
mains gas
bulk LPG (propane or butane)
bottled gas (propane)
heating oil
standard tariff
Off-peak 7-hour
Off-peak 10-hour
"24-hour"-heating tariff
Total electricity
PV output
Net electricity
BAU
2020 Centre
2020 Stretch
2050 Centre
2050 Stretch

**Figure 8**

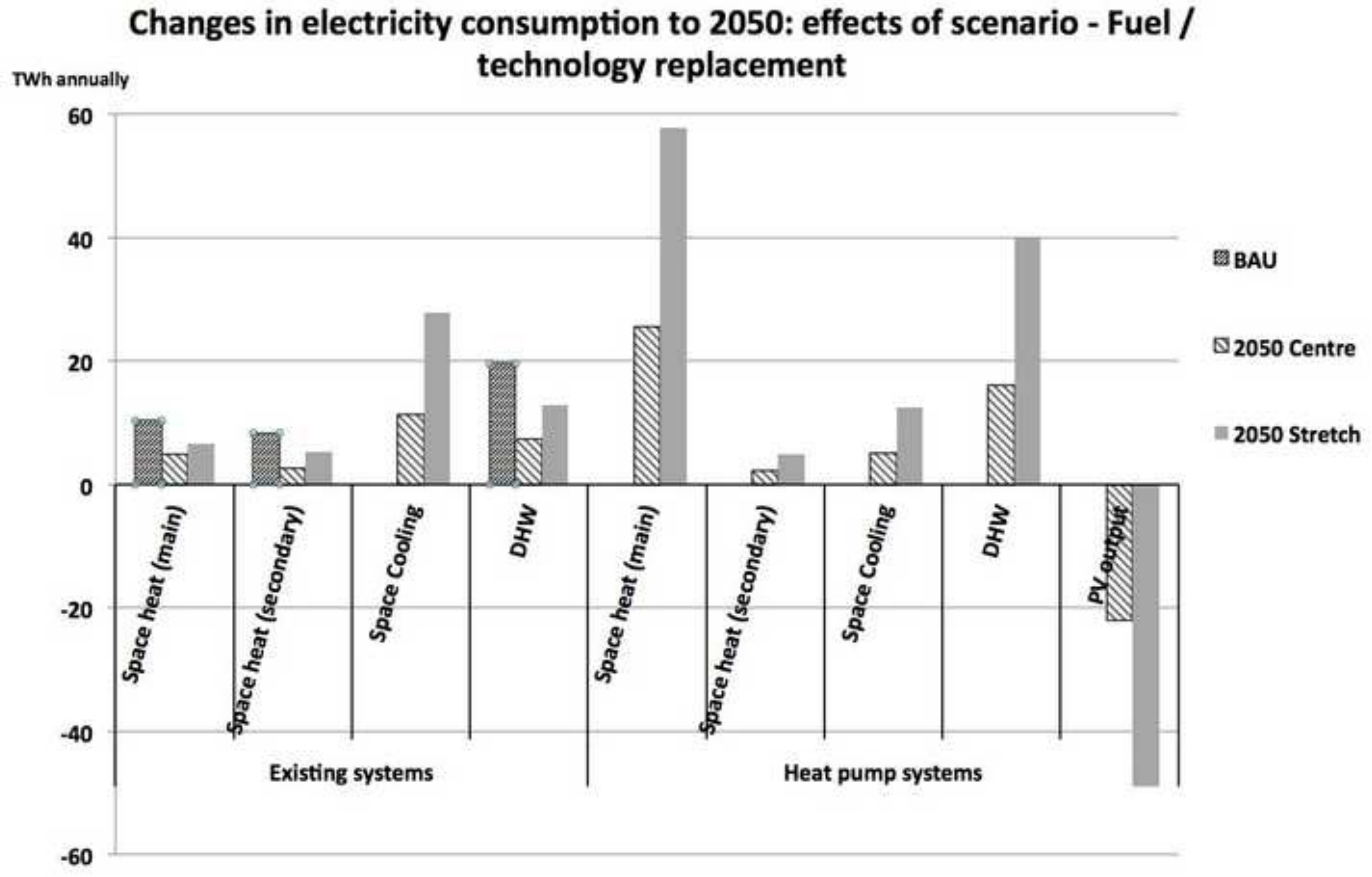

Changes in electricity consumption to 2050: effects of scenario - Fuel / technology replacement
TWh annually
60
40
20
0
-20
-40
-60
BAU
2050 Centre
2050 Stretch
Space heat (main)
Space heat (secondary)
Space Cooling
DHW
Space heat (main)
Space heat (secondary)
Space Cooling
DHW
PV output
Existing systems
Heat pump systems

**Figure 9**

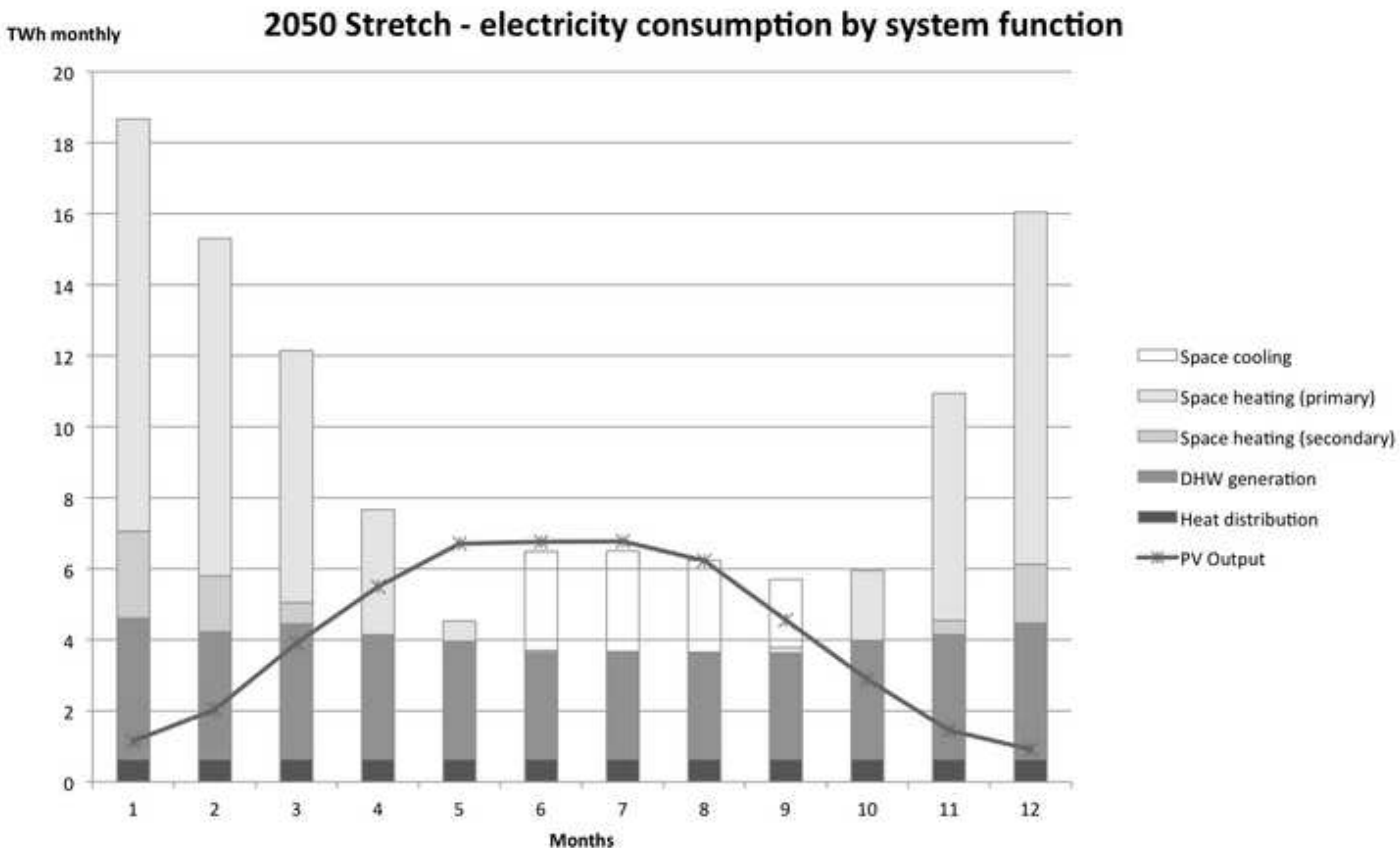
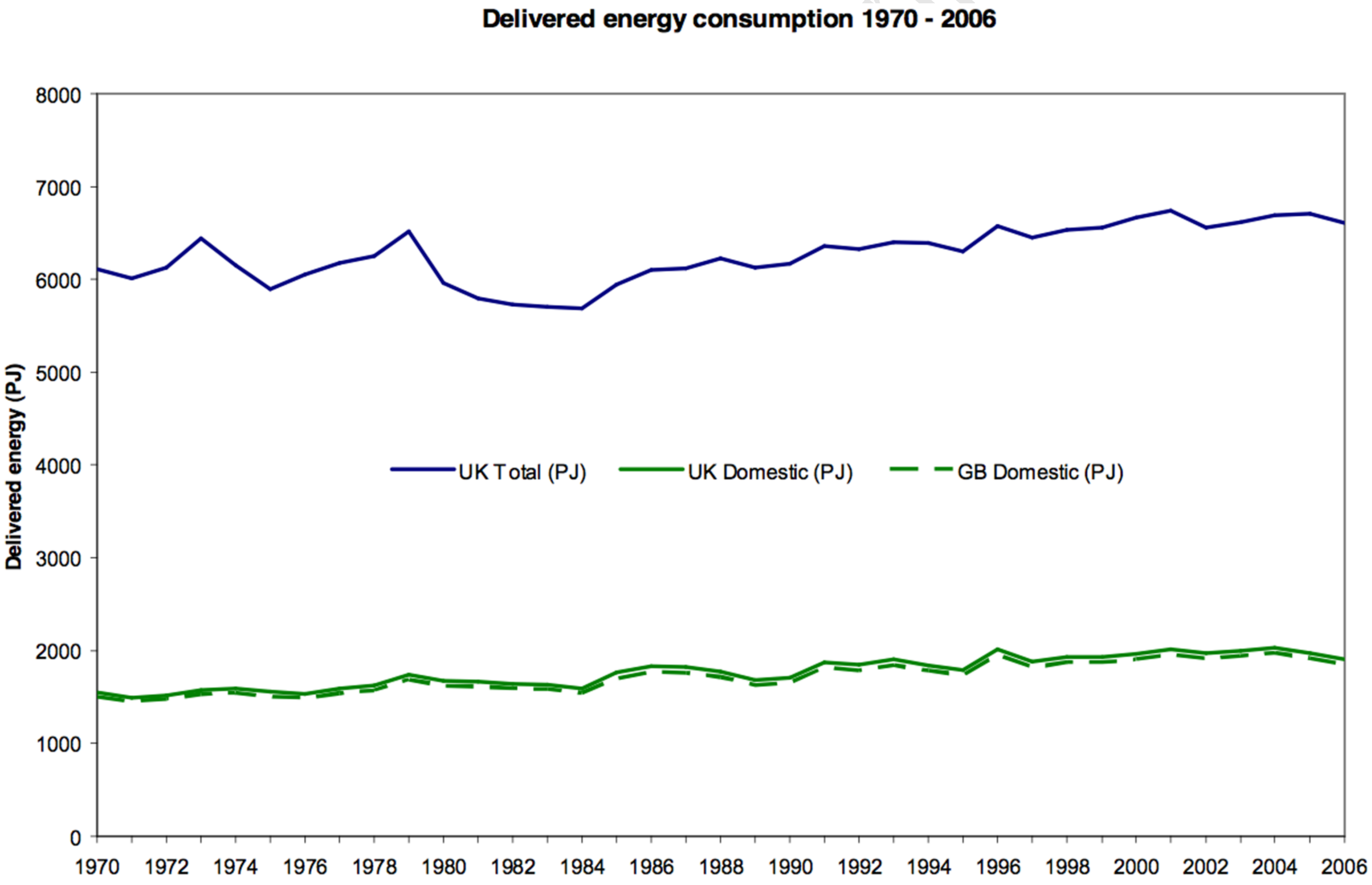

2050 Stretch - electricity consumption by system function
TWh monthly
20
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
11
12
Months
Space cooling
Space heating (primary)
Space heating (secondary)
DHW generation
Heat distribution
PV Output

Figure 10


Delivered energy consumption 1970 - 2006
Delivered energy (PJ)
0
1000
2000
3000
4000
5000
6000
7000
8000
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
UK Total (PJ)
UK Domestic (PJ)
GB Domestic (PJ)