Programme Area: Distributed Energy

Project: Micro DE

Title: Modelling the Cost Effectiveness and Hence Potential Uptake of Technologies

Abstract:

Please note this report was produced in 2010/2011 and its contents may be out of date. This deliverable is number 5 of 7 in Work Package 3. The report aims to identify the opportunities to develop micro DE and control technologies and quantify the potential impact on UK domestic energy use by 2040. It also addresses the impact of human interaction in the form of ‘comfort taking’, i.e. using micro DE technologies / improvements in building thermal efficiency to improve occupant comfort through higher internal temperature as opposed to reduction of energy consumption.

Context:

The project was a scoping and feasibility study to identify opportunities for micro-generation storage and control technology development at an individual dwelling level in the UK. The study investigated the potential for reducing energy consumption and CO2 emissions through Distributed Energy (DE) technologies. This was achieved through the development of a segmented model of the UK housing stock supplemented with detailed, real-time supply and demand energy-usage gathered from field trials of micro distributed generation and storage technology in conjunction with building control systems. The outputs of this project now feed into the Smart Systems and Heat programme.

WP 3.5.1 Modelling the cost effectiveness and hence potential uptake of technologies

and

WP 3.2.2 Human Factors modelling

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	Version: 11 September 2011

Micro Distributed Energy and Energy Services Management

Application to existing UK residential buildings

Preface

This report is one of seven reports presenting the findings and recommendations from the ETI Micro Distributed Energy project, a scoping and feasibility study to determine the opportunity for micro (household-scale) Distributed Energy (µDE) technology development. The project combined desk-top research and modelling with a small-scale field trial to assist with the understanding of the supply and demand of energy services in residential dwellings. This report utilises the Alpha (v6.1:Stock) µDE Model to obtain new insights into the current and future potential of technologies.

The background to the model development is important with regard to how much confidence should be put in the results output from the Alpha model. The µDE project is a pilot project and the original intention was to develop within the one year pilot a meta-model derived from existing models. Since the µDE project started, a 2-year project on Optimising Thermal Efficiency of English Housing (OTEoEH) was commissioned by ETI and it was decided that together the projects should develop a unified core model, rather than having different models for each project. This decision was taken after the µDE project had started; as such the model development had to be delayed to the latter half of the µDE project and it was agreed that only a constrained Alpha version of the model would be available for the conclusion of the µDE project, the fully functioning and tested version only being available at the end of the OTEoEH project.

It was not planned to undertake a further round of model testing and debugging as part of the Alpha model development, as all subsequent testing will be undertaken as part of the OTEoEH project. The Alpha model therefore has constrained functionality and does have bugs in it that have a significant impact on the modelled results. Some of these bugs have been fixed for subsequent scenarios modelling undertaken for ETI and incorporated into the final report; additional testing is being undertaken as part of the ETI- **O**TE**oEH** project, including comparisons against models used by EDF in France.

NOTE, FOR THE SCENARIOS MODELLED IN THIS REPORT THERE MAY BE SOME INCOMPATIBILITY BETWEEN THIS REPORT AND LATER ETI-µDE REPORTS IN RELATION TO ASSUMPTIONS ABOUT FUTURE COSTS AND PERFORMANCE THE RESULTS OF THIS REPORT SHOULD THEREFORE BE CONSIDERED AS INDICATIVE OF FINAL FUNCTIONALITY OF µDE MODELLING THAT WILL BE ACHIEVABLE AT THE END OF THE PROJECT. RESULTS DRAWN FROM THIS ANALYSIS SHOULD BE CONSIDERED AS PROVISIONAL AND REQUIRE ADDITIONAL CONFIRMATION ONCE THE FINAL TESTED VERSION OF THE MODEL HAS BEEN DEVELOPED AT THE END OF THE OTEOEH PROJECT. THE SCENARIO MODELLING UNDERTAKEN REPRESENTS TESTING OF THE SIXTH VERSION OF THE ALPHA MODEL. THE MODEL HAS NOT BEEN CALIBRATED AT THE STOCK LEVEL, AND SO NO SIGNIFICANCE SHOULD BE ATTACHED TO THE ABSOLUTE RESULTS. THE SCENARIO RESULTS, RELATIVE TO THE BASELINE FIGURES, ARE MORE ROBUST, BUT ARE LIKELY TO CHANGE AS FUTURE VERSIONS OF THE MODEL INTRODUCE NEW FUNCTIONALITY. IF SIGNIFICANT BUGS OR ERRORS ARE IDENTIFIED AT THE END OF THE OTEOEH PROJECT WHICH COULD INFLUENCE ANY OF THE CONCLUSIONS DRAWN FROM THE µDE SCENARIOS THEN THESE SCENARIOS WILL BE RE-RUN AT THE END OF THE OTEOEH PROJECT

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1 Introduction

The first version of the Alpha model was developed by BRE as an extension of its core BREDAM/SAP model, and delivered to UCL on 4 February 2011, and source code provided on 10 February 2011. UCL prepared in advance for this testing by developing spread sheet versions of SAP2009 and data sets of UK energy data prior to the delivery of the first version of the model at which stage a testing program was undertaken by a team led by Professor Tadj Oreszczyn from UCL (in alphabetical order: Ian Hamilton, Anna Mavrogianni, Eleni Oikonomou, Rokia Raslan, Andrew Smith, Catalina Spataru, and Andy Stone) (see “Draft report on WP3.1.1 and WP3.1.2 of micro µDE and WP1.3b of TE”, dated 19 February). Significant additional functionality was then included as well as the fixing of several bugs. Following discussion and prioritisation of feedback from UCL, BRE made agreed modifications, and a second version of the model (Alpha V2) was distributed by BRE on 11 March 2011. Additional bug-fixes, stock-handling and shell functionality were added by UCL in the subsequent week (Alpha V2: Stock). BRE delivered a third version of the model, Alpha V3 to UCL, and remaining bugs were fixed by UCL, to create the Alpha V6.1: Stock model used for this report.

The specification for this work-package stated in work package templates circulated to ETI on 25 January 2011 that:

> *“The actual cases to be modelled will be determined via discussions between all partners (including ETI) to scope the realistic future range of the above variables. UCL will then undertake modelling to assess the impact on uptake using the stock model, Markal and other calculations to help determine future CO_2 reductions. The number of variables will have to be significantly constrained to make this a manageable task within the timescale of the project. This will lead to a report detailing the potential impact of future technological development, changes in costs and government policies.”*

At the last project meeting UCL proposed the following nine scenarios to be modelled, see Figure 1, Table 1 . These scenarios were agreed by the Partners and covered a range of future scenarios compared to a Base Case (Now) of no µDE technologies installed in the current built stock.

Three levels of **PERFORMANCE** would therefore be assessed

1) Physical constraints – a 100% technology take up where physically possible (e.g. sufficient physical space for ground source heat pump and biomass), no other constraints, installing one technology at a time with optimistic performance assumptions modelled as per BREDEM 2009. Results presented by stock segmentation and technology.
2) Financially and performance constrained: assumes that µDE is only installed at those properties where an installed system would have a sufficiently short payback period.
3) No uptake - assumes that no µDE technologies have been installed.

Three time periods were to be investigated:

1) Now - stock size, levels of insulation, technological performance, costs and CO_2 factors are as is at present.
2) Green Deal - Efficient fabric i.e. thermal efficiency measures applied to every property in the stock; all other factors the same as Now. Measures are applied where physically possible across the stock: hot water tank insulation; loft insulation; floor insulation; new double-glazed windows. Note, no decarbonisation of the grid is assumed for this scenario.
3) 2040 Scenario - Fabric as Green Deal but technology performance improved in line with predictions for 2040. Also, electricity grid carbon intensity, fuel and µDE prices are all as per predictions for 2040.

Table 1 Nine scenarios

	Now	*Green Deal*	*2040*
Optimistic 100% uptake where physically possible	**Base case 100% uptake** 2010 scenario with µDE in properties where physical constraints allow (no financial constraints)	**Efficient stock 100% uptake** Green Deal scenario with thermal efficiency in the whole stock; and µDE in properties where physical constraints allow (no financial constraints)	**2040 100% uptake** 2040 scenario with thermal efficiency in the whole stock; and µDE in properties where physical constraints allow (no financial constraints)
Constrained financially	**Base case constrained** 2010 scenario with µDE in properties where financial and physical constraints allow	**Efficient stock constrained** Green Deal scenario with thermal efficiency in the whole stock; and µDE in properties where financial and physical constraints allow	**2040 constrained** 2040 scenario with thermal efficiency in the whole stock; and µDE in properties where financial and physical constraints allow
No uptake	**Base case** Base 2010 scenario	**Efficient stock** Green Deal scenario with thermal efficiency measures rolled out to the whole stock	**2040** Identical to TE-2010; except that prices are updated to 2040, to use as a benchmark for financial constraints in the £µDE-TE-2040 scenario

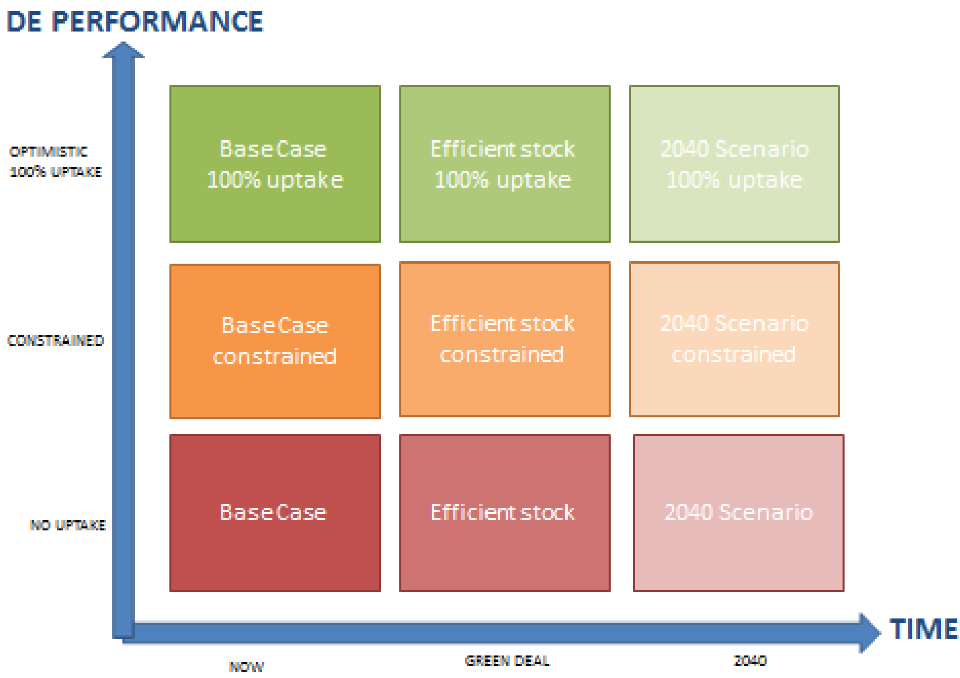

Figure 1 Scenario Matrix

Within the six scenarios that include µDE deployment (i.e. the orange and green scenarios above), each µDE technology is modelled independently; i.e. there are no combinations of µDE technology, and no changes to occupant behaviour. Two additional runs (Base scenario and Green Deal) were made with comfort take-back temperature algorithms, to assess the effect of those algorithms on the model. This final model run is in fulfilment of deliverable D3.2.2:

> *"**D3.2.2 Report the results of running the stock model** using standard internal temperatures across the whole stock and comparing these results to that utilizing a simple occupant behaviour model where the internal temperature is adjusted according to the efficiency of the property."*

The model scenarios have been developed further, see Section 2, in the light of the subsequent testing of the Alpha model and a fuller understanding of its specification. Indicative results of running the nine scenarios are presented in Section 3. Note, the full level of functionality required to produce the scenarios has required additional post processing of data generated by the Alpha model, with Excel (v2007 or later) spread sheets: these spread sheets therefore form part of the model . Future versions of the model may incorporate some of this functionality as part of the core code, rather than post-processing, but the Alpha version of the µDE model was never envisaged to have this functionality.

2 Scenarios

This section presents all the assumptions underlying the nine scenarios to be modelled and explains how the various inputs and assumptions were arrived at. The first part discusses the building stock input used for the scenarios, the second part explains how the constraints for different scenarios were arrived at and the last section lists the other assumptions utilized in the modelling, such as costs, carbon emissions factors, etc.

Note, the input assumptions have been selected to demonstrate the functionality of the model, rather than to identify the best scenario or to test a detailed future hypothesis.

2.1 Building stock and dwelling variants

The BRE-20 stock dataset, one of two stock datasets contained in the µDE Alpha v6.1:Stock model, contains 20 dwelling types which are thought to represent the English stock. The logic underlying their generation is presented in the ETI µDE project 'WP1.2 Segmentation of the UK Housing Stock' by *Raslan et al. 2010*. However, for the purpose of examining scenarios with potentially different uptake, 20 dwelling types were not considered sufficient to capture the full diversity of the stock, particularly given that the five types of flat would be excluded, as flats were taken to be physically constrained from µDE deployment. Therefore, building on work that UCL has undertaken as part of previous research projects, UCL has populated the µDE model with a second stock dataset, using 12,443 dwelling definitions based on the information from the **English Housing Conditions Survey (EHCS) 2007**. This is deemed to be a representative sample of the English non-flats housing stock as of 2007, i.e. it incorporates existing retrofit levels in older properties. The EHCS database also categorizes each property by its potential to receive various thermal upgrades, a useful field for assessing the potential "Green Deal" scenario. This dataset was prepared solely by the UCL Energy Institute from the DCLG dataset. The associated programming was also prepared solely by the UCL Energy Institute.

The input database used in the scenarios therefore contains 12,443 rows with the assigned **primary** known variables for each house that are directly derived by EHCS (e.g. age, type, dimensions, wall type, fuel type etc.) and the **secondary** variables that are needed for a full BREDEM calculation which are inferred by RdSAP tables as a function of the known variables. (As this was an Alpha run of the model, some variables have been estimated only roughly; further refinement of the stock data will be done as part of later runs: for this reason, and others, even base-scenario outputs will change in future model runs).

The frequency of each type of variant in the stock is then used to multiply up the energy statistics for each variant, to scale the sample up to the English stock.

Flats have been excluded from the scenario modelling due to increased technical constraints in the installation of the majority of µDE technologies and complexity of modelling different configurations (such as top/mid/ground floor, number of external walls, access stairwells). It is feasible that a proportion of blocks of flats would be serviced by communal/district heating/electric systems which are being investigated under the macro–DE ETI project.

2.2 Technology parameters

Table 2 shows the technology parameters modelled for each DE technology for 2010 and 2040.

Table 2 Technology parameters modelled

Note, some of the following parameters in this set of scenarios differ from values reported in other DE reports as this report pre-dated these.

Technology	Parameters	2010 value	2040 value
micro-CHP	Max thermal output (kW_{th})	5	
	Max electric output (kW_e)	1	2
	Heating regime	variable	
Biomass	Efficiency (useful heat out ÷ energy in, %)	63%	70%
	Responsiveness	0.75	0.6
	% of heating from secondary system	0%	
GSHP	Proportion of hot water from heat pump	100%	
	Responsiveness	Pipes in screed above insulation	
	Space heating	Underfloor heating	
	Heat pump	Ground to water	
ASHP	Proportion of hot water from heat pump	100%	
	Responsiveness	Radiators	
	Space heating	Radiators with load compensation	
	Heat pump	Air to water	
PV	Tilt	30°	
	Orientation	South	
	Peak power (kW)	4	
	Area (m^2)	20	
Solar thermal	Area (m^2)	4	
	Panel type	Evacuated tube	
	Orientation	South	
	Tilt (degrees from the horizontal)	45°	
Wind	Rotor height (metres)	12	
	Swept diameter	3	3.5
	Wind characteristics	Rural	

2.3 2010 constraints

In considering potential uptake of µDE technologies it is necessary to determine the constraints that will inhibit this uptake. In this report we detail these constraints and their impact on the total number of installations in the UK stock (as defined by the EHCS) and the total energy demand and CO_2 emissions.

Given the limited time and scope of the µDE project, the uptake of upgrade options of µDE is assumed to be a function of only:

1) **Technical constraints** according to crude assumptions made about the technical eligibility of houses; and
2) **Financial constraints** for a given payback period, for simplicity the period chosen was undiscounted savings over 10 years. This is approximately equal to 20 years of savings with an annual discount rate of 8%.

2.3.1 Technical Constraints

For each µDE technology a set of crude physical constraints were defined based on an understanding of the field trials and industry installation requirements. It should be noted that these constraints are basic and in some cases are conservative and others propitious. Therefore the results of these constraints should be seen as indicative and capable of being refined under more realistic considerations.

A set of technology-dependent factors for physical constraints have been specified for each of the technologies covered in the µDE project: photovoltaics, solar thermal, ground source heat pumps, air source heat pumps, micro-CHP, wind turbines and biomass. These constraints were predominantly dictated by broad assumptions on the access and space requirements of each technology, in conjunction with what dwelling-specific data is available in the EHCS. Future modelling of constraints can be significantly developed.

The factors of Physical Constraints are summarized in Table 3 .

Table 3 Physical constraints

µDE technology	Requirement to pass the eligibility criteria	Type of variable
Photovoltaics	Only 30% of the roof/footprint area can be used	Area value (m^2)
Solar thermal	Only 30% of the roof/footprint area can be used	Area value (m^2)
Ground source heat pumps	Presence of open plot of more than 145m^2 size	Binary (yes/no)
Air source heat pumps	No constraints	
Micro-CHP	Total space heating demand of >20 MWh/yr	Binary (yes/no)
Wind turbines (only stand-alone installations)*	Presence of plot of more than 315m^2 size AND Rural/semi-urban location	Binary (yes/no)
Biomass boiler	Availability of storage space in rear plot of more than 10m^2 size AND Rural/semi-urban location	Binary (yes/no)

* It was decided to include only stand-alone rural/semi-urban wind technologies due to the increased level of complexity in the uptake of roof wind turbines and the low wind speeds in urban areas.)

Take-up of the technologies is summarised below:

Table 4 Take up with physical constraints in the 2010 stock, with and without the Green Deal

		Green Deal
ASHP	100%	100%
biomass	16%	16%
GSHP	37%	37%
micro-CHP	56%	56%
PV	13%	13%
solar thermal	100%	100%
wind	11%	11%

Note, the same physical constraints apply for the Green Deal as the base case because the Green deal only impacts on the economic constraints and not the technical constraints, e.g. the Green Deal does not impact on the availability of roof space, etc.

The constraints for the µDE technologies are technical constraints based on either physical properties of the dwelling or property (i.e. available roof space or dwelling location) or demand constraints (i.e. minimum space heating demand). For the technical constraints based on physical limitations it is very much the case that individual dwellings may or may not be eligible, for example roof area available for solar technologies does not include whether the space is actually available or well oriented.

It will also be true that there are conflicting technologies or where the installation of one µDE negates the application of another. Thus, there are two types of conflicting technologies:

1) technologies competing for space, e.g. photovoltaics and solar thermal competing for roof space; and
2) technologies competing for output, e.g. micro-CHP and solar thermal competing for hot water generation.

However, no conflicts between technologies are taken into account at this stage, as all technologies are tested independently.

In addition, there have been no physical constraints defined for air source heat pumps; although this is unrealistic, such technical constraints will also be the function of individual properties characteristics (i.e. available external wall area, noise conditions). This means that heat pumps will always be chosen provided they meet the financial constraints. For solar technologies and air source heat pumps, constraints are factored in the next step of financial constraints.

2.3.2 Financial Constraints

In applying financial constraints we take an approach that assumes that technologies with an undiscounted payback period of more than 10 years (approximately equal to 20 years payback at an 8% discount rate) will not be taken up by homeowners.

This means that fewer properties have µDE measures, compared to the respective scenario where only physical constraints are made: they are an additional constraint, on top of the physical constraints. If the physical constraints do not allow installation, then no µDE is installed. The Net Value of a µDE measure is calculated for each property, based on the cost of a µDE installation, and the annual fuel savings: where physical constraints allow installation, and where ten years of fuel savings are at least equal to the installation cost, then µDE is installed.

The net value of the µDE technology is determined over the 10-year payback period using fuel cost (Table 6) and an estimated unit cost (Table 5) for each dwelling in the EHCS. The unit cost, in this report, includes the capital cost of the µDE technology as well as the installation costs.

Net Value_{10year} = (fuelcost*10year-unitcost)

Table 5 Unit costs (2011)

µDE	Unit Cost (£)
GSHP	£12,000
ASHP	£3,600
Solar Thermal (4m2)	£6,000
PV 4kw (20m2)	£13,000
Micro-CHP	£5,000
Biomass	£9,000
Wind	£16,000

Table 6 Fuel costs

Fuel	Fuel Cost (p/kWh)
Electricity	11.46
Gas	3.10
Oil	4.06
Solid	2.97
Biomass	5.45

Note some of these costs in nTable 5 and 6 may differ to other DE report costs in reports which were produced post this report.

The uptake in the face of financial constraints is determined based on cases where the net value over 10 years is *less* than the initial unit cost, therefore achieving a positive payback. The table below identifies the proportion of dwellings that take up each measure, in the 2010 stock, with physical and financial constraints.

Table 7 Take up with physical and financial constraints in the 2010 stock, with and without the Green Deal

		Green Deal
ASHP	4%	3%
biomass	0%	0%
GSHP	1%	1%
micro-CHP	30%	19%
PV	0%	0%
solar thermal	0%	0%
wind	0%	0%

2.4 2040 Uptake constraints

In this report we also describe a future scenario, in 2040, which aims to illustrate how the µDE Alpha model can consider changes in µDE technology (i.e. efficiency) and therefore the potential uptake against technical and financial constraints.

The take-up is as follows:

Table 8 Take up with physical and financial constraints in the 2040 stock

	Physical constraints	Physical & financial constraints
ASHP	100%	4%
biomass	16%	0%
GSHP	37%	1%
micro-CHP	56%	55%
PV	13%	0%
solar thermal	100%	0%
wind	11%	0%

2.4.1 Technical Constraints

In the 2040 scenario the technical physical constraints are unchanged. The changes in the µDE technology are largely through improvements in the efficiency of the unit. For example, biomass boilers seasonal performance is improved from 63% to 70%, and the responsiveness coefficient changes from 0.75 to 0.6.

2.4.2 Financial Constraints

In the 2040 scenario the financial constraints are changed to reflect potential improvements in production and installation costs and increases in current fuel costs. In the case of the unit cost we have taken a basic approach by assuming an overall 20% reduction in the total costs (capital and installation) of the µDE technologies (Note, zero *relative* inflation is assumed for capital and installation: that is to say, the prices are assumed to have the same proportions relative to each other, and to fuel prices, as in 2010). It may be that some technologies are substantially improved beyond this figure, but this scenario is meant to provide an illustration of future scenario building. We also assume average fuel prices have increased by 10% as compared to the 2010 prices. Again, this estimate is probably conservative. The following tables provide a breakdown of the unit and fuel costs (in 2010£).

Table 9 Unit costs by technology

µDE	Unit Cost (£)
GSHP	£9,600
ASHP	£2,880
Solar Thermal (4m2)	£4,800
PV 4kw (20m2)	£10,400
Micro-CHP	£4,000
Biomass	£7,200
Wind	£12,800

Table 10 Fuel costs

Fuel	Fuel Cost (p/kWh)
Electricity	12.61
Gas	3.41
Oil	4.47
Solid	3.27
Biomass	6.00

2.5 Model versions

In order to be able to run the scenarios and sensitivity tests, some changes were made to the code supplied by BRE. These changes are summarised here:

Excel pre and post processing to demonstrate potential future functionality of a full µDE stock model. It used 12,443 dwelling types derived by UCL from the DCLG EHCS dataset, and enabled scenarios to be modelled with different take ups of the µDE technologies. Technical changes are discussed in Appendix B.

µDE Alpha V3 contained some bug-fixes by BRE to problems that came up during the testing of the previous version

µDE Alpha V6.1:Stock is an implementation that UCL has produced with further bug fixes, and interface enhancements. This is the version that has been used to calculate the results presented here. It features a choice between two housing stock datasets; and an Excel post-modelling spreadsheet that imports results from the model, and calculates summary statistics.

2.6 Time varying assumptions

This section details the assumptions on technological characteristics, CO_2 emissions and prices for the modelled scenarios.

The following sections set out, by technology, tables showing the capital cost, unit cost, and efficiency. Earlier, Table 5 summarised the capital costs used in the model. The following section sets out the literature and spread of costs behind the costs used in the model.

2.7 µDE system prices

2.7.1 Solar Thermal

Table 11 Solar thermal characteristics and prices

	Solar Thermal Flat Panels	Solar Thermal Evacuated Tubes	Sources
Description	2 - 3 flat glazed collectors (area of ~ 2 m2 each) & 300 litres tank storage	Vacuum tubes	(Radulescu 2010)
Capital cost (installation plus equipment)	£3,400-5,100	£5,100-6,800	(Radulescu 2010)
	£3,500-5,500	£5,500-7,500	(ETSAP 2010)
	£4,800 (inc VAT@5%) typical system –m^2 not known	£4,800 (inc VAT@5%) typical system	(EST 2011b)
	£2,000-3,000 (base year: 2001-02)	£3,000- 4,500 (base year: 2001-02)	(Wolf 2001-02)
Average capital cost	£3,500-5,500	£5,500-7,500	
Unit cost	31% (=£1,085-£1,705)	31% (=£1,705-2,325	(Mahjouri & Nunez)
One-off cost	69% (=£2,415-3,795)	69% (=3,795-5,175)	
FIT/RHI	8.5[1]	8.5	(DECC 2011)
Efficiency	40%	50%	(Wolf 2001-02.) / (Philibert 2005)

[1]Although solar thermal microgeneration is not included in the FIT, the consultation period for the Renewable Heat Incentive (RHI) has begun. Kicking off in April 2011, this scheme will guarantee payment to homeowners who install solar hot water (DECC 2011).

2.7.2 Photovoltaics

Table 12 Photovoltaic characteristics and prices

	PV	Sources
Description	$10m^2$ of crystalline silicon modules	(Kwiatkoski 2010)
Capital cost (installation plus equipment)	£4,000-6,000 /kWp	(Kwiatkoski 2010)
	£4,000-4,500 /kWp	(ETSAP 2010)
	£4,500-8,000 /kWp	(EST 2011a)
	£5,000-6,500 /kWp (base year: 2001-02)	(Wolf 2001-02)
Average capital cost	£5,000 /kWp	
Unit cost	60% (=£3,000)	(Public Renewable Partnership)
One-off cost	40% (=2,000)	(Public Renewable Partnership)
FIT/RHI	41.3	(Ofgem 2010)
Efficiency	15%	(Kwiatkoski 2010) / (Strachan)

2.7.3 Biomass

Costs are provided by the Forestry Commission report (2006). In average the installation price ranges between £450 - £600 per kW_{th} installed, with domestic wood chip boilers costing approximately 10% more than a pellet boiler. Log boilers are generally cheaper with a 20 kW_{th} system suitable for a 3 or 4 bed property costing between £150 - £200 per kW_{th} installed.

Biomass heating systems are characterised by lifetimes between 15 and 20 years.

The operation costs vary as a function of (Mabilat and Schraube-Eifer 2010):

- wood fuel type;
- location;
- form (bag or bulk) and quantity;
- delivery distance;
- feedstock and supply chain; and
- quality.

Future costs - For the purposes of this study, it will be assumed that the efficiencies of biomass systems will remain constant in the future.

There are two key constraints for the installation of biomass heating systems:

- the availability of storage space (and, potentially, a buffer tank); and
- access to fuel supply.

Taking the above into consideration, it was decided to limit the uptake of biomass systems only to EHS dwelling variants that:

- have an accessible back plot area above 144 m^2;
- are located in a rural area

These characteristics can easily be assessed using the EHS data. Other issues such as listed buildings and the location outside areas of outstanding natural beauty and smokeless zones exceed the scope of the present modelling exercise.

2.7.4 Micro-CHP

A number of physical constraints in the uptake of micro-CHP technologies where identified during the ETI Constraints workshop November 2010 . Such site and integration issues are also mentioned by McKoen (2010):

- The micro-CHP units are much heavier than the boilers they replace; therefore weight can become an issue for attic mounted systems.
- The provision of an electrical connection may be a lengthy process in the UK.
- The installation of micro-CHP units is a complex procedure that can only be carried out by specially trained installers.
- Additional space and advanced control systems for the auxiliary boiler and hot water storage tank may be required.

Nonetheless, such eligibility issues cannot be assessed due to lack of relevant data in the EHS datasets.

In line with the Carbon Trust Micro-Accelerator project, the selection of technically eligible houses for the installation of micro-CHP units will be limited to the potential for carbon savings compared to base case carbon emissions produced against a reference gas condensing boiler that provides the same thermal demand.

Results from a field trial study carried out by the Carbon Trust (2007) indicated that the Stirling engine Micro-CHP systems (power-to-heat ratio = 1:10), should be targeted at houses with an annual heat demand above 20,000 kWh, such as dwellings built before 1920 or dwellings with a floor area of over 110m^2.

Further analysis demonstrated that for dwellings with heat demands less than 10,000 kWh/year there is no net benefit in annual carbon emissions between a micro-CHP heating system and an A-rated gas condensing boiler (Carbon Trust 2011).

Taking into account the above, it was decided to only model the uptake of micro-CHP units in houses with a calculated annual heat demand of more than 20,000 kWh under the base case scenario.

It needs to be borne in mind that the carbon savings calculations will largely depend on the assumed 'grid mix' and 'marginal plant' electricity carbon intensity factors as these are defined in the Carbon Trust report (2007).

System characteristics to be tested

In the µDE Alpha model, micro-CHP systems can be expressed as:

- heat output and peak power;
- heat output and ratio of heat to power; and
- peak power and ratio of heat to power.

With regard to modelling micro-CHP systems, McKoen (2010) suggests the comparison of systems of equivalent nominal thermal power as this determines their operation in a conventional temperature-controlled heating application. The following base case system characteristics are given for Solid Oxide Fuel Cell (SOFC), Proton Exchange Membrane Fuel Cell (PEM), Stirling engine, Internal Combustion Engine (ICE) and Rankine Cycle micro-CHP systems.

micro-CHP technology	Electric Efficiency	Thermal Efficiency	Global Efficiency	Thermal Capacity	Electrical Capacity
SOFC	40%	40%	80%	1 kW	1 kW
PEMFC	30%	55%	85%	1 kW	545 W
Stirling Engine	15%	75%	90%	1 kW	200 W
ICE	25%	60%	85%	1 kW	417 W
Rankine Cycle	8%	80%	88%	1 kW	100 W

Projections for the micro-CHP system efficiencies for 2030 are shown below (McKoen 2010).

Table 13 Micro-CHP characteristics and prices

micro-CHP technology	Electric Efficiency	Thermal Efficiency	Global Efficiency	Thermal Capacity	Electrical Capacity
SOFC	50%	40%	90%	1 kW	1250 W
PEMFC	35%	55%	90%	1 kW	636 W
Stirling Engine	15%	80%	95%	1 kW	188 W
ICE	25%	65%	90%	1 kW	385 W
Rankine Cycle	10%	80%	90%	1 kW	125 W

	Capital cost (£) per kW_e	Unit cost (£)
SOFC	40,000	40,000
PEMFC	20,000	10,909
Stirling Engine	5,000	1,000
ICE	3,000	1,250
Rankine Cycle	5,000	500

The cost of mature technologies like ICE is not expected to change whereas the cost of fuel cells is predicted to decrease dramatically (McKoen, 2010).

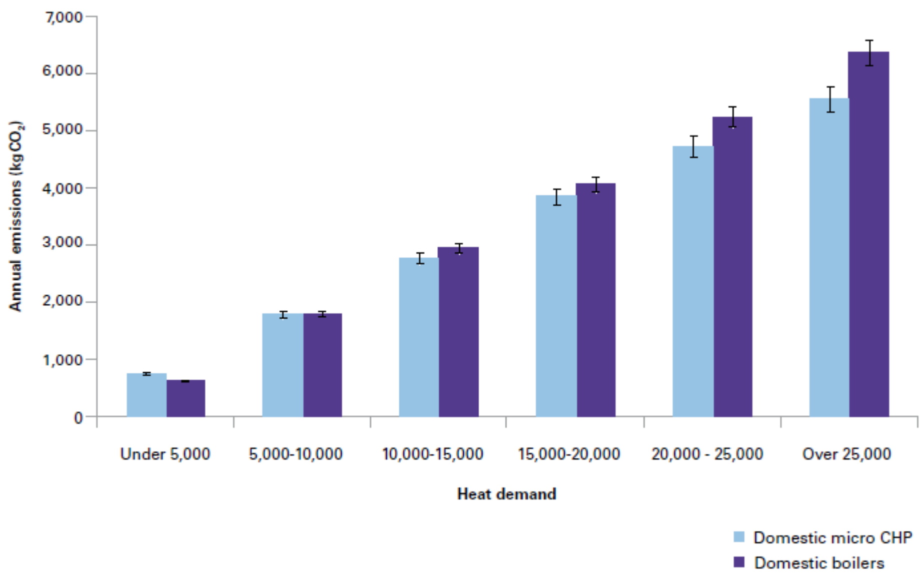

Figure 2 One forecast of relative uptake of boilers and micro-CHP

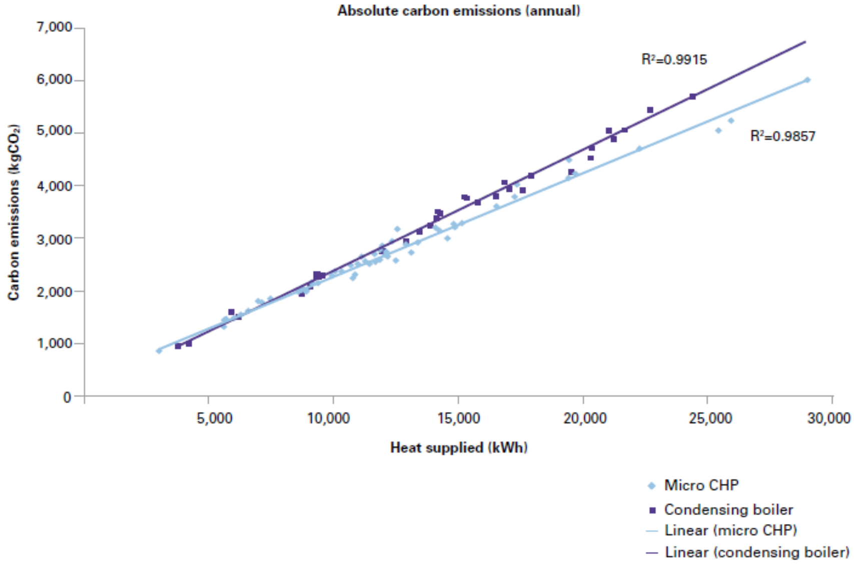

Figure 3 CO_2 emissions from different heating technologies

2.7.5 Wind Turbines

Table 14 Wind turbine characteristics

a-Required model inputs (based on <3 kW installation)[1]						B – Other INFO		
No. of Wind Turbines	Rotor Diameter (m)	Terrain	Hub Height (m)	Fixed Cost (£)	Unit Cost (£)	Power Output	Max Efficiency	Swept area (m2)
1	3.5	Rural	11	2000[2,3]	16,000[2]		42.4%	9.62

1. Proven 7 Wind turbine info at http://www.provenenergy.co.uk/our-products/

Technology lifetime assumed to be ~25years

2. Information at: http://www.bettergeneration.com/wind-turbine-reviews/proven-7-wind-turbine.html

3. The cost of the wind turbine itself accounts for approximately 75% of the total installation cost Sahin, A.D. (2004) Progress and recent trends in wind energy Progress in Energy and Combustion Science 30 (2004) 501–543.

2.7.6 Heat Pumps - GSHP & ASHP

The cost of GSHP installations depends on the installation of the ground pipe loops e.g. surface loops. Domestic systems (including ground loops) cost £400-£450 /kW before installation. This installed cost can rise to £1100/kW. A £900/ kW will be chosen to reflect the potential high installed costs. A 5kW unit will be modelled for providing the space-heating requirements for a medium demand house.

The capital cost of a GSHP, globally the same in France as in UK (BSRIA source), is mainly influenced by the installation cost of the ground collectors.

Table 15 Heat pump prices and characteristics.

	System type	Ground coil costs (£/kW)	Heat pump costs (£/kW)	Total system costs (£/kW)	Capital Costs (k£)	COP	CO_2 savings (kg CO_2/year)	CO_2 emissions (kg/kWh)
Sources		EST	EST	EST		GSHP Fact Sheet, ETI Project	GSHP Fact Sheet, ETI Project	
GSHP	Horizontal	250-350	350-650	600-1000		3.4 – 4.0	4787	0.1
	Vertical indirect	450-600	350-650	800-1250		3.8 – 4.5	5108	0.1
ASHP	Low temperature conventional heat pump				5 – 10	2.9		0.2
	High temperature				15- 20	3.4		0.2

(Source: EST, http://www.berr.gov.uk/files/file27558.pdf - Based on approximate calculations)

Typical systems can operate over very long periods, more than 20 years. The ground installation, when correctly installed, can operate for over 50 years without any maintenance. The current life time of the heat pump part is about 20 years. The heat pump itself does not need a lot of maintenance because of the absence of filters. A yearly check of the heat pump operation is the only precaution (estimation ~ 150 €/year) (Source: GSHP Fact Sheet, ETI Project).

2.7.7 Inputs to cost-of energy model

Table 16 . . .

Parameter	Value	Notes
Rated power	5 kW	This is a typical size system for a single residential application with 30% capacity factor*.
Lifetime	20 yrs	Heat pump lifetime is 15 – 20 years, but ground loops can last 50 years#.
Maintenance cost	5%	This is an estimate based on an annual maintenance check#.
Load factor	30%	This was based on domestic space heating requirements and best practice case study#. Produces 13.1 MWth per annum – sufficient to heat a medium demand house.
Coefficient of performance	3.16	Taken from case study#. A value of 2.8 is suggested as competitive against electrical heating**.

Energy input: The GSHP system is modelled with an electricity input of 50% Economy 7 and 50% standard tariff.

The efficiency for a specific installation will be dependent on the power required by the ground loop circulating pump and this should be kept as low as possible.

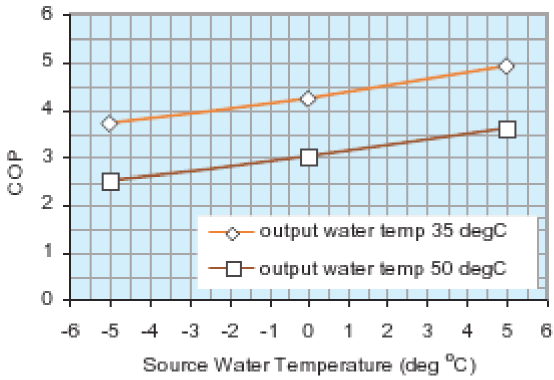

Figure 4 Coefficient of performance of typical small GSHPs

Source: *Energy Saving Trust*

The actual performance of the heat pump system is a function of the water temperature produced by the ground coil and the output temperature.

2.8 Installations to date

The table below lists domestic microgeneration renewables installations funded by Government programmes since 2002.

Table 17 . . .

Technology	Number of installations	Number of Installers	Total Installation Costs	Estimated annual turnover
Wind	165	29	£2,775,798	£925,266
Hydro	12	12	£344,512	£114,837
GSHP	500	28	£4,845,079	£1,615,026
Biomass	116	30	£777,139	£259,046
SWH	6,694	120	£24,660,834	£8,220,278
PV	1,301	56	£20,145,012	£6,715,004
TOTAL	**8,788**	**275**	**£51,101,864**	**£17,033,955**

Source: *Energy Saving Trust from 'Potential for Microgeneration Study and Analysis' Final Report Nov. 2005 by Element Energy*

The market is dominated by solar installations. This is mainly due to the mature nature of the SWH technologies and the generous support programmes which solar PV technologies have received since

2002. Heat pump installations have increased significantly since the launch of the DTI clearskies programme. The micro-wind sector is rapidly emerging since the development of cost effective turbines in the last 2-3 years.

RHI and FITS are capped in size and are designed to have a good rate of return and hence apply to our unconstrained financial case.

2.9 Internal temperature correction and "comfort taking" (D 3.2.2)

In addition to the 9 scenarios discussed above, which have all been modelled with constant internal temperature, a further modelling exercise that includes using an average internal temperature that is predicted based on the efficiency of the fabric and heat system has been undertaken using the relationship specified in WP 1.5.6, but described here also. This relationship, between the dwelling's fabric and heat system efficiency and the internal temperature is used in two ways: i) to predict the likely internal temperature experienced, thus a more realistic estimate of space heating demand; and, ii) as a result of the shape of this relationship, to take comfort taking (in the form of a temperature take back) into account when improvements to a dwelling's fabric are made.

2.9.1 Temperature take back

The introduction of take back is in the form of predicting the likely internal temperature of a dwelling based on the overall efficiency of the fabric and the heat system. This temperature take back means that dwellings with poor fabric and inefficient heating systems are more likely to have a colder internal temperature when the external temperature is low. The method implemented in this model is based on the work by Oreszczyn et al (2009) that uses an empiric relationship between the dwellings 'E-value'[2] and the internal temperature within the living room and bedroom standardised to periods with an external temperature of 5°C (Oreszczyn et al., 2006). The Warm Front analysis

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[2] An 'E-value' is the required energy consumption by the principal heating device to maintain a 1°C temperature difference between outside and inside during steady-state conditions ignoring incidental gains and ventilation heat losses. E-value = $(\Sigma U_i A_i)/\mu$, where Ui is the heat loss per square meter of surface area per degree Kelvin temperature difference between inside and outside (W/m2K) for the ith building element, Ai its surface area and μ the efficiency of the main heating device for the dwelling.

established a relationship between dwelling heat transfer characteristics ('E-value') and internal temperatures (standardised to an external temperature of 5°C) (see Figure 5). Changes in temperature resulting from changes in the heat transfer characteristics can thus be deduced. Here, we assume that an average of the standardised living room and bedroom temperatures provides a useful estimate of heating season average whole-house temperatures.

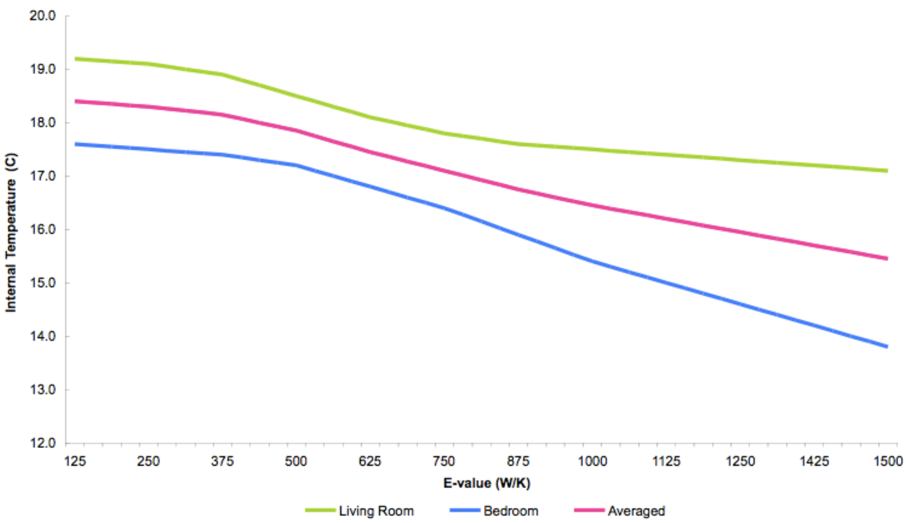

Figure 5 ...

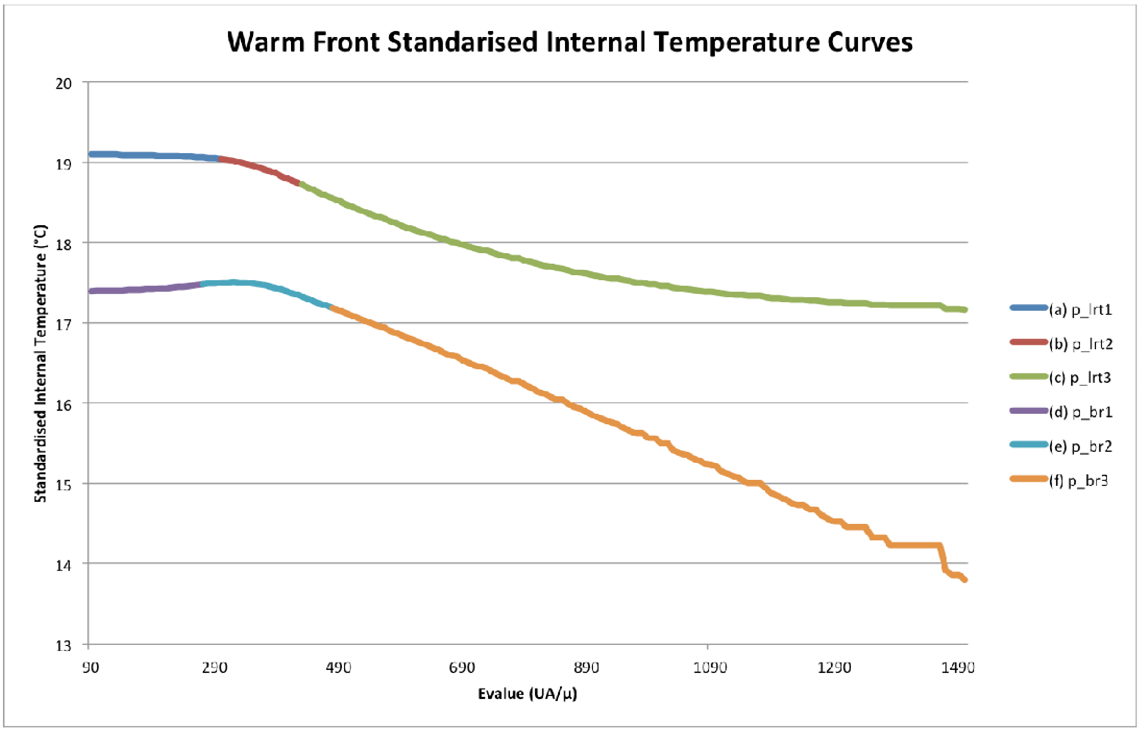

Figure 6 Warm Front Standardised Internal Temperature Curves

The process used here involved establishing a best-fit curve through the use of three segmented polynomials. The segmented curves were established using the Warm Front data, which is based on data for approximately 1400 dwellings, grouped into E-value bands. The bands were segmented into three curves that would provide a best fit to a 3-order polynomial, see as shown in figure 3 above.

In this report, we use the temperature relationship described above in order to add a further degree of sophistication when establishing the set point temperature, ultimately providing a temperature 'correction'. Two scenarios have been modelled, one with a standard internal demand temperature of 21 degrees and the other that uses the above curve to predict the likely internal temperature that is in line with the heat loss of the dwelling. The two scenarios are compared to determine the impact on energy and CO_2 savings. Further explanation is provided in WP 1.5.6.

3 Illustrative model outputs

Here we present the results from the nine µDE-uptake scenarios tested, and the results of the comfort-take-back algorithm. The following caveat appears at the start of this report, and is repeated here as context for the model outputs:

> THE RESULTS OF THIS REPORT SHOULD BE CONSIDERED AS INDICATIVE OF FINAL FUNCTIONALITY OF µDE MODELLING THAT WILL BE ACHIEVABLE AT THE END OF THE PROJECT. RESULTS DRAWN FROM THIS ANALYSIS SHOULD BE CONSIDERED AS PROVISIONAL AND REQUIRE ADDITIONAL CONFIRMATION ONCE THE FINAL TESTED VERSION OF THE MODEL HAS BEEN DEVELOPED. THE SCENARIO MODELLING UNDERTAKEN REPRESENTS TESTING OF THE SIXTH VERSION OF THE ALPHA MODEL. THE MODEL HAS NOT BEEN CALIBRATED AT THE STOCK LEVEL, AND SO NO SIGNIFICANCE SHOULD BE ATTACHED TO THE ABSOLUTE RESULTS. THE SCENARIO RESULTS, RELATIVE TO THE BASELINE FIGURES, ARE MORE ROBUST, BUT ARE LIKELY TO CHANGE AS FUTURE VERSIONS OF THE MODEL INTRODUCE NEW FUNCTIONALITY.

One of the key changes we can expect in future versions of the model is a significant change to the performance of air-source heat pumps which may be used for air-conditioning as well as heating: in the Alpha version of the model, no cooling is modelled (whether from an ASHP or any other source).

3.1 Illustrative outputs from scenarios

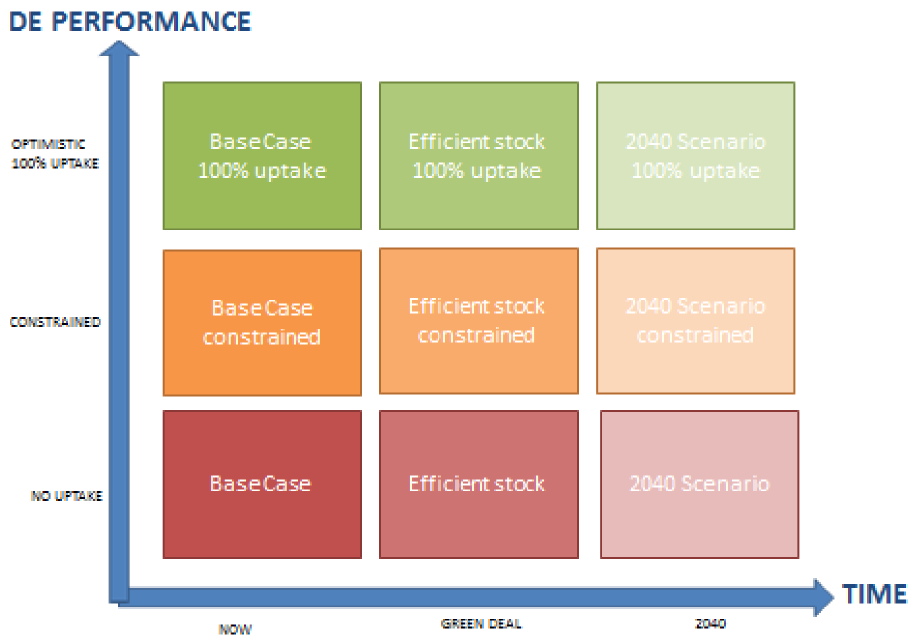

Figure 7 Scenarios

The following sections provides sample outputs from the above nine scenarios. The first section illustrates comparisons across the different µDE technologies; the second section illustrates specific outputs for a single µDE technology (here, biomass).

3.1.1 Comparisons across the different µDE technologies for an indicative scenario (Green Deal)

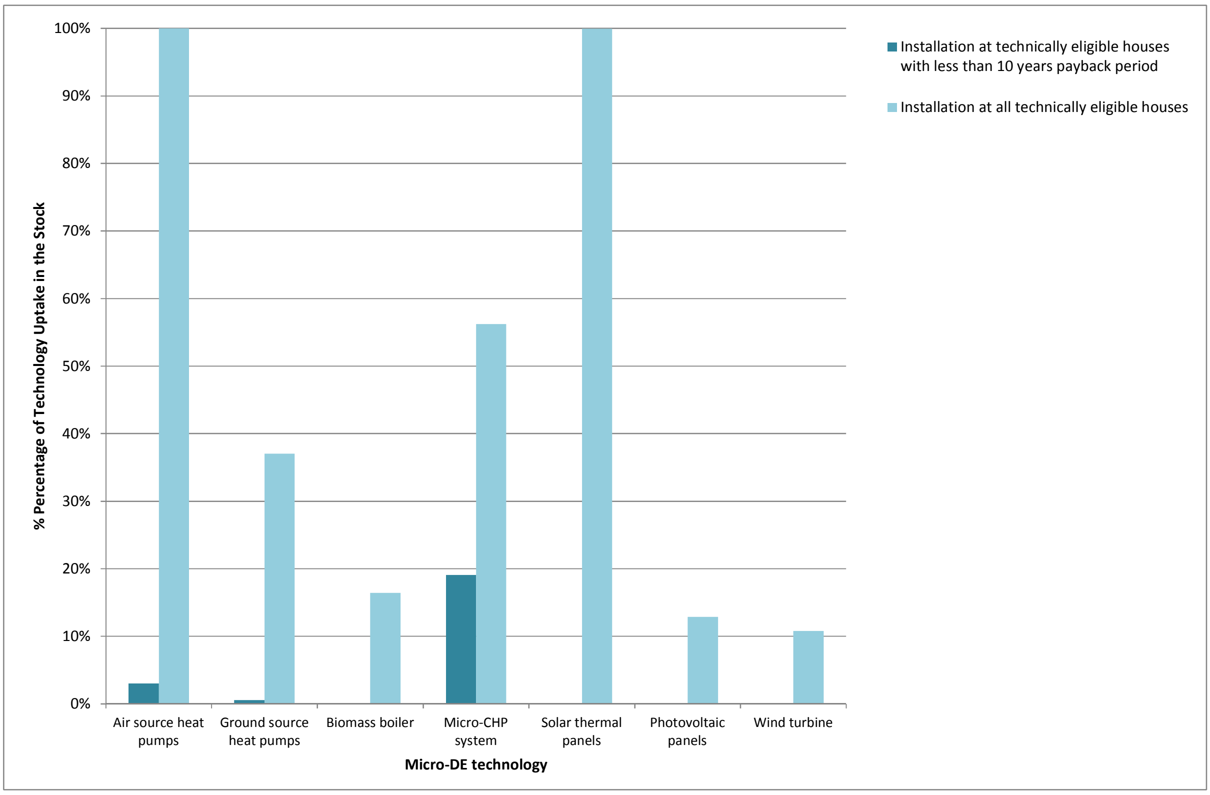

Figure 8 Uptake of each technology, when each is considered in isolation (i.e. no competition between technologies) for the 'Green Deal' Scenario

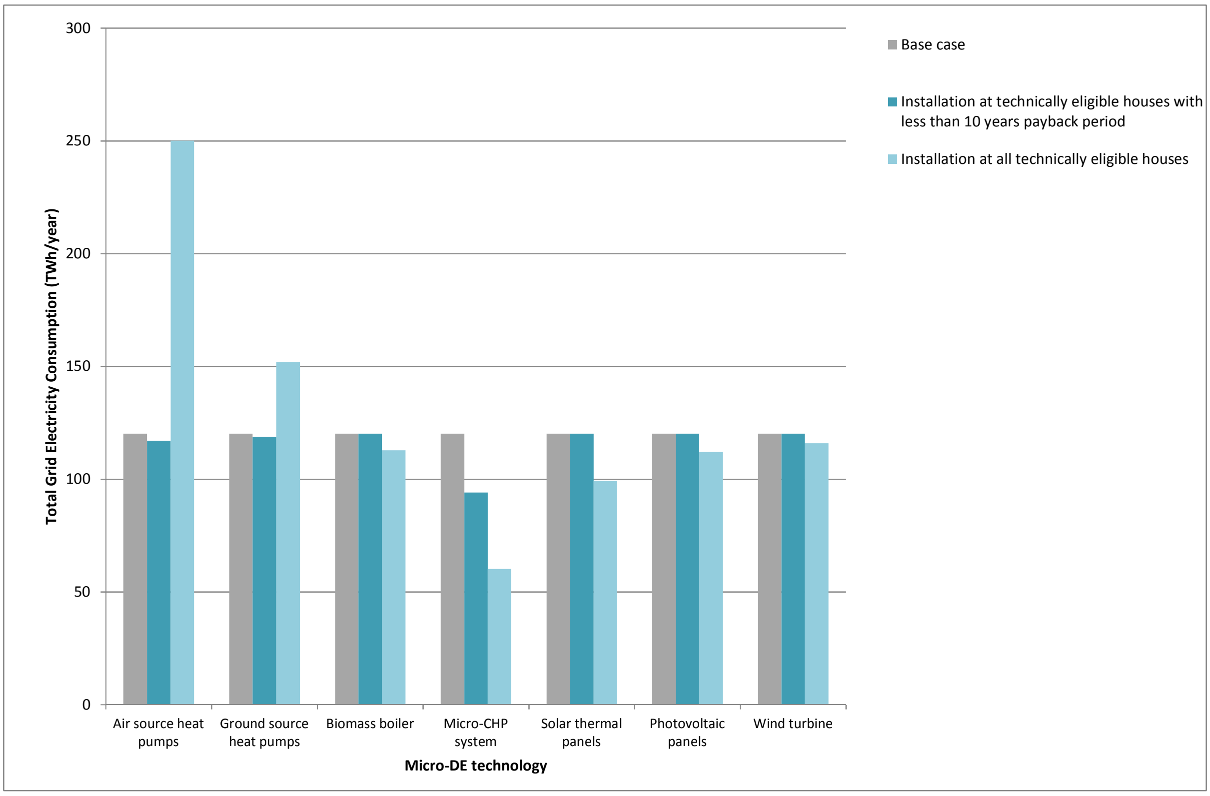

Figure 9 Impact on grid electricity consumption of each technology for the 'Green Deal' Scenario

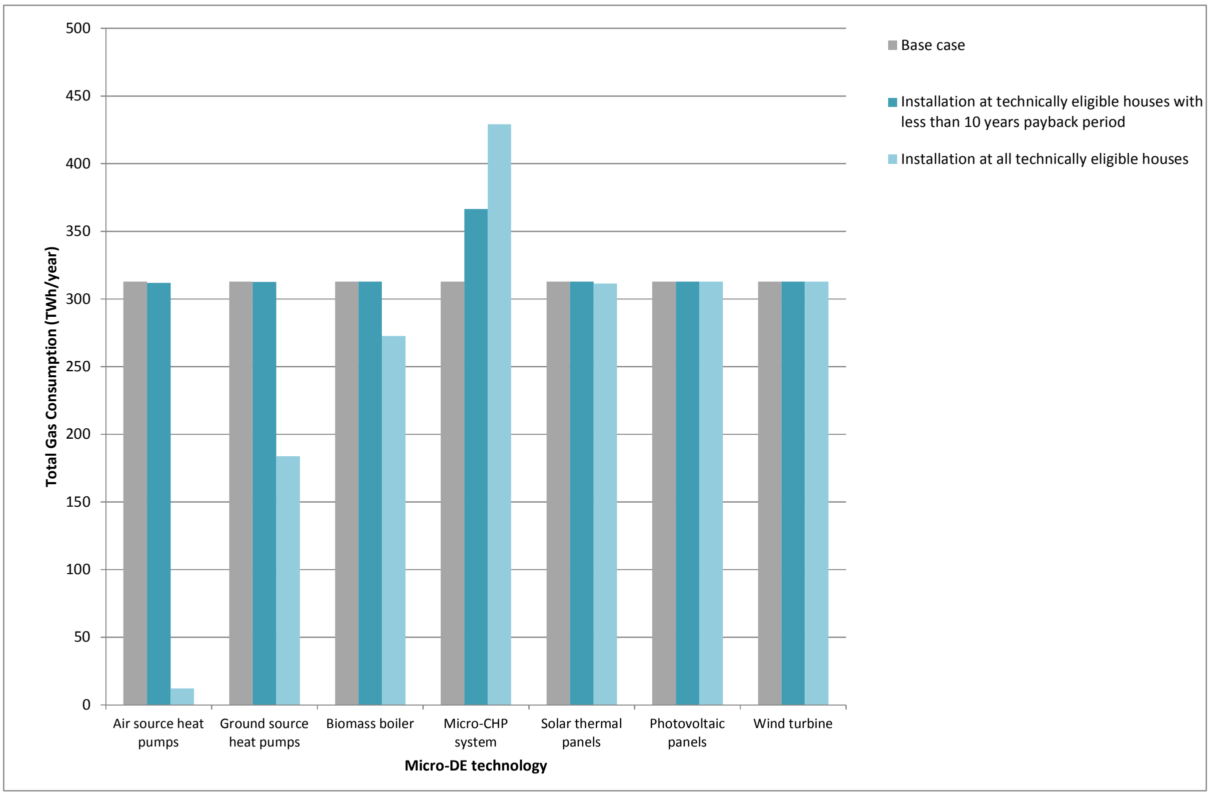

Figure 10 Impact on gas consumption of each technology for the 'Green Deal' Scenario

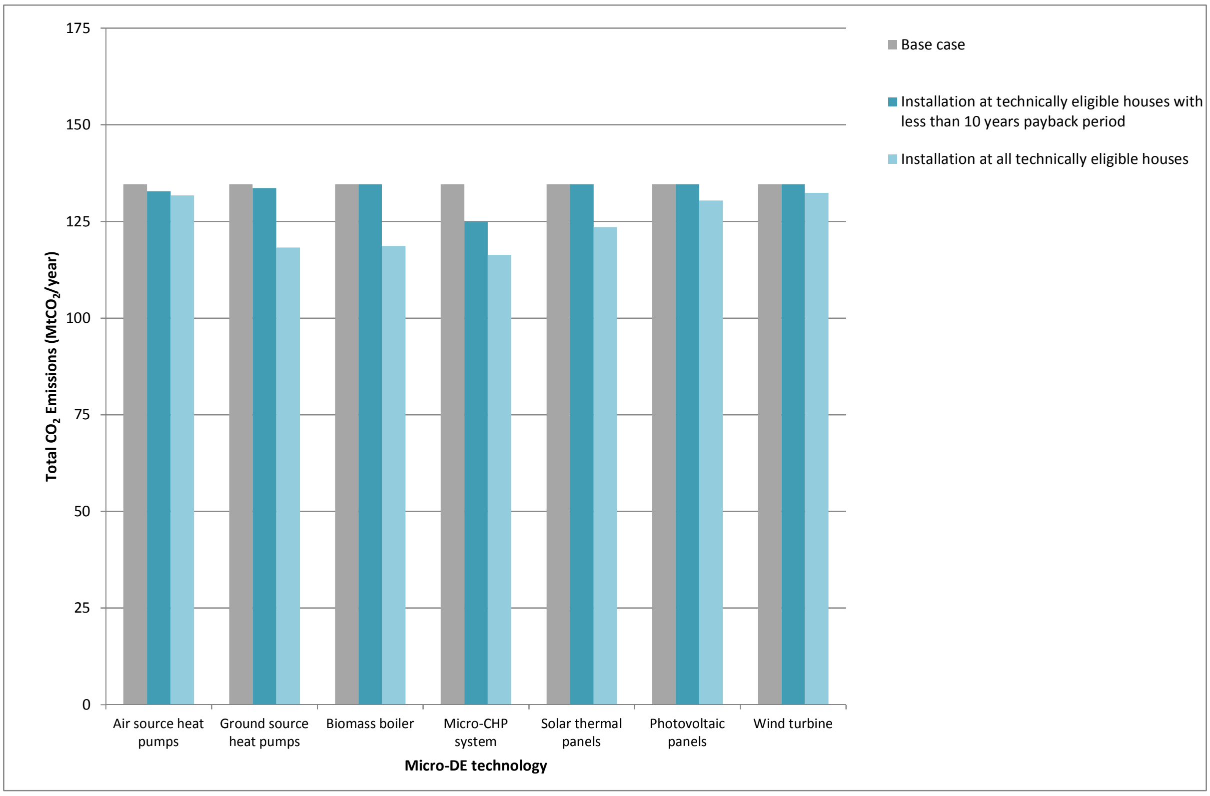

Figure 11 **Impact on CO_2 emissions of each technology for the 'Green Deal' Scenario**

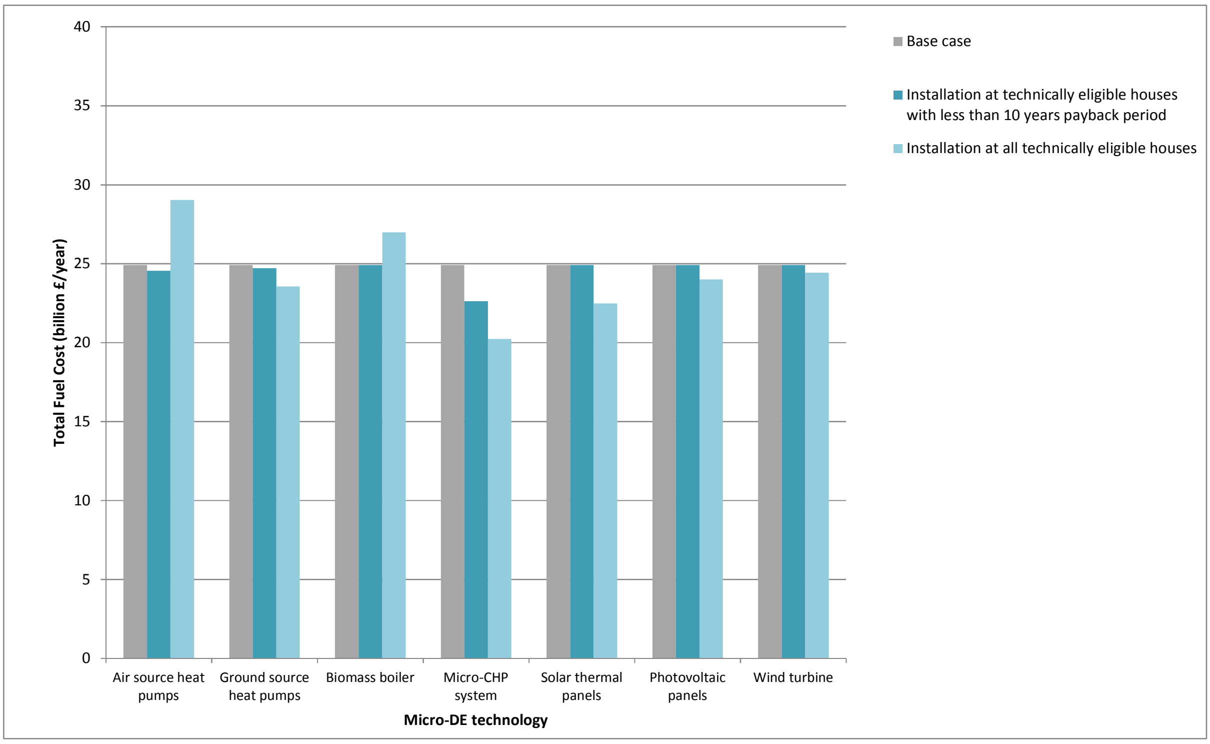

Figure 12 **Total fuel cost for each generation technology for the 'Green Deal' Scenario**

3.1.2 Specific outputs for a single µDE technology – ground source heat pump

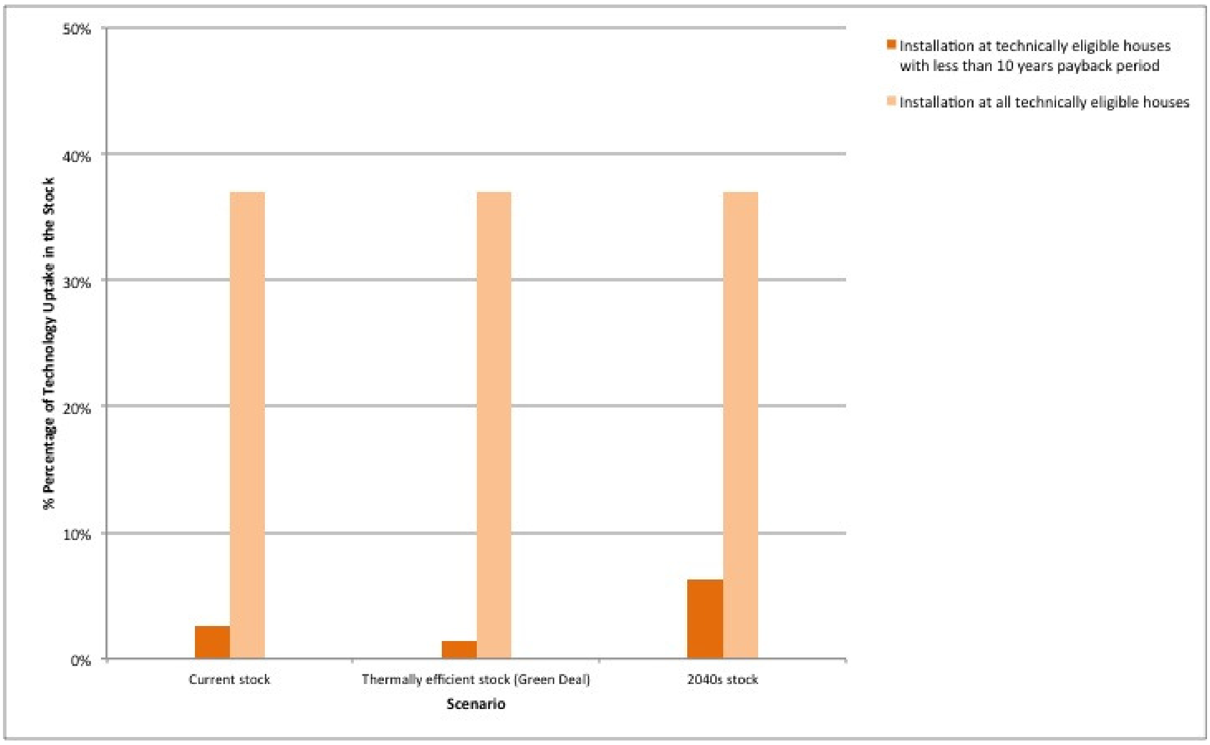

Figure 13 Uptake of ground source heat pumps

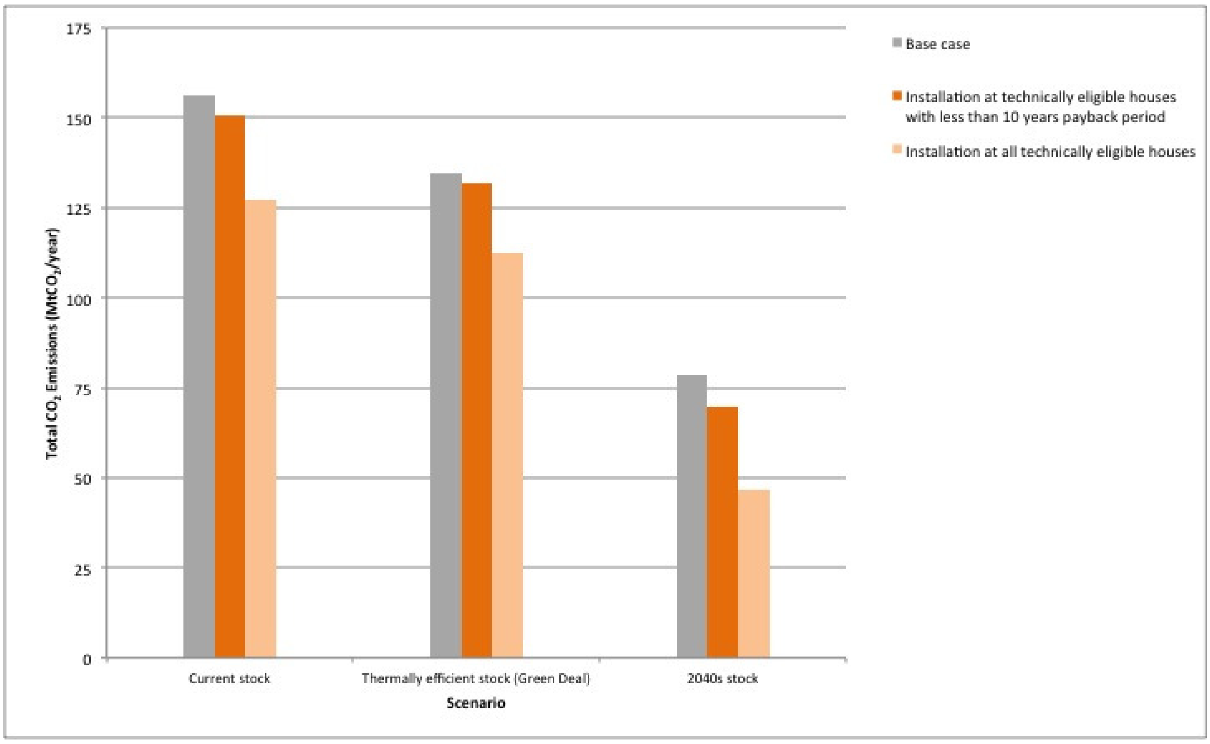

Figure 14 Impact on CO_2 emissions of ground source heat pump uptake

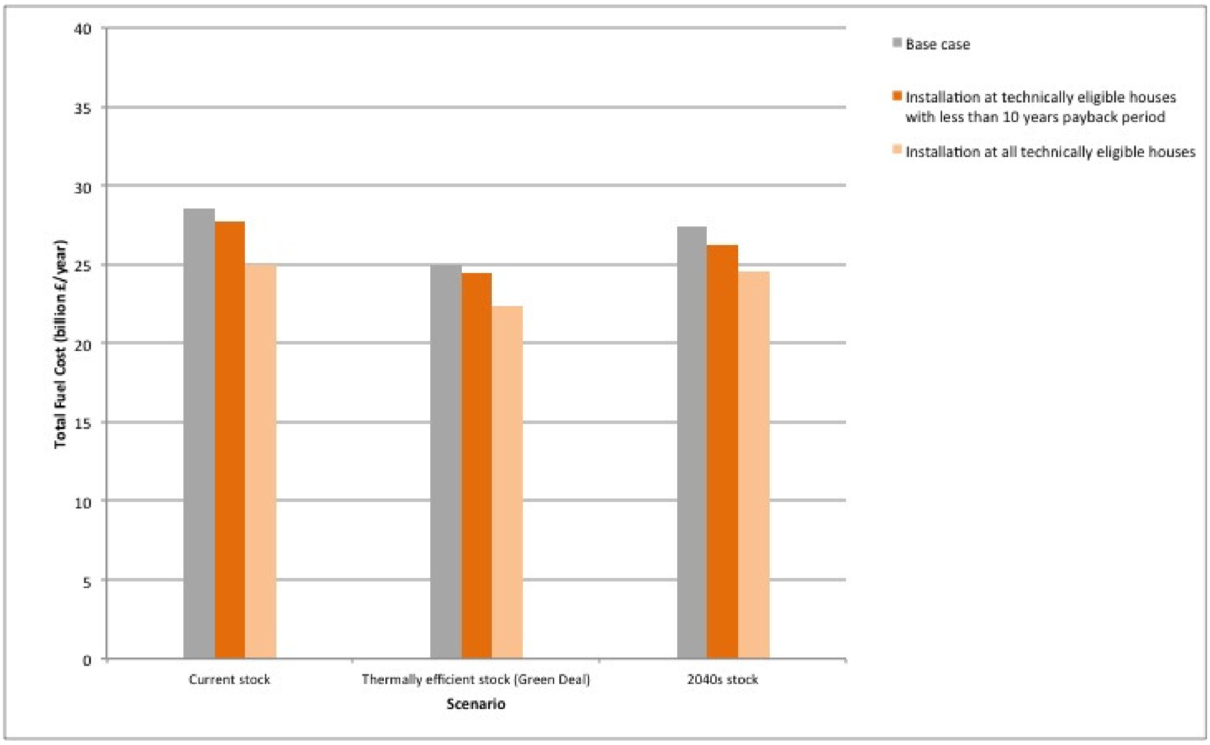

Figure 15 **Total fuel cost of domestic ground source heat pumps**

3.2 Illustrative outputs from temperature correction

All the scenario runs above are modelled without the temperature algorithm (used to determine the likelihood of comfort-taking). To illustrate the functionality of this temperature and dwelling (fabric and heating system efficiency), two additional scenarios were run using the temeprature algorithm: the base scenario, and the Green Deal scenario. These scenarios were chosen to isolate the effects of the algorithm from any effects of, or unexpected interactions with, µDE technologies. Hence, neither of the results illustrated below include any µDE uptake.

Because the comfort-taking algorithm is different from the basic BREDEM/SAP algorithm for internal temperature, then energy consumption and CO_2 emissions change in the base case, as well as in other scenarios. Therefore, the base case was re-run with the comfort-taking algorithm, to use as a benchmark.

Table 18 Energy savings (GW) from the Green Deal, with and without comfort-taking

Energy(GW)	Base	Green Deal	Savings
Without temperature correction	67	56	16%
With temperature correction	63	51	19%

Table 19 CO_2 savings (MT) from the Green Deal, with and without comfort-taking

CO_2 (MT)	Base	Green Deal	Savings
Without temperature correction	147	127	14%
With temperature correction	139	117	16%

The results of the run, shown above in Table 18 and Table 19 , illustrate the effect of using this algorithm. Note that the space heating energy demand and CO_2 emissions without the temperature correction are higher than with the correction. The reason for this is due to the lower internal temperature than is typically used in BREDEM. Secondly, the results show higher savings in case of temperature correction between the Base and Green Deal, this is due to the location of the stock along the temperature curve pre and post Green Deal and the 'saturation' point after which no more temperature is taken.

It should be noted that these comfort-taking results are preliminary and will be further investigated in the OTEoEH project.

Some evidence of comfort-taking associated with the installation of heat pumps was found in the small scale field trial. In a few households occupants reported heating their homes for longer and to higher temperatures since the installation of their heat pumps. It is recommended that future field trials look for further evidence of this type of comfort-taking as a result of the installation of µDE heating systems.

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Appendix A Sensitivity analyses and test results

As this report was being finalised, minor bugs were found in the modelling of the baseline, and of solar thermal performance. The results presented here were calculated with the Alpha v5.1 model; the relative changes between v5.1 and v6.1 are very small, and the results presented below continue to be representative of the *relative* performance of different parameters, though runs with Alpha v6.1 will produce slightly different *absolute* values.

A.1 Solar thermal

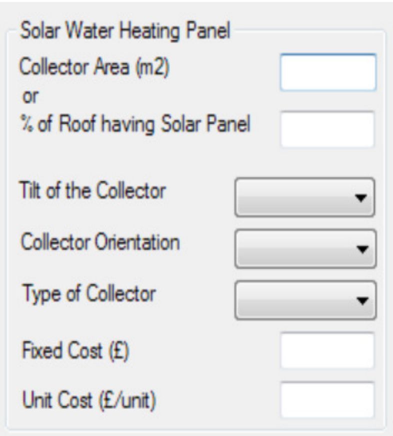

Figure 16 Snapshot of the BRE model interface (solar water heating section)

The available parameters to test with regard to Solar Water Heating Panels (Figure 16) are type of collector, collector area, tilt, orientation, fixed and unit cost. In the µDE Alpha-V6.1:Stock version, the model allows the user to either input the desired collector area or instruct the program to calculate this as a fraction of the roof area for each house. This information is used to calculate the panel's performance and accounts for this in the Domestic Hot Water (DHW) energy consumption (kWh/year), which in turn affects the total energy consumption (kWh/year) and the associated CO_2 emissions ($kgCO_2$/year). Fixed cost (£) and unit cost (£/unit) are only used for the calculation of costs. The sensitivity of solar thermal in terms of type (section A.1.1), area (section A.1.2), orientation (section A.1.3) and tilt (section A.1.4) was tested by looking at the energy used for DHW. The results were consistent for evacuated tubes and flat panels, both regarding the heat output (e.g. Figure 17) and the carbon emissions due to DHW (e.g. Figure 18).

A.1.1 Solar thermal collector type

Allowed value range: evacuated tubes / flat panels

The installations of five square metres of solar thermal evacuated tubes and flat panels (45° tilt, South oriented) were compared with the base case (standard building with no collectors) and found to significantly decrease the carbon emissions for DHW. As expected the domestic hot water carbon emissions were lower with evacuated tubes compared to the flat plates as a result of the reduced collector heat loss due to the vacuum providing better performance (Figure 17, Figure 18).

A.1.2 Solar thermal collector area

Allowed value range: any

The sensitivity of results with regard to collector area was tested by varying the area between 0 m^2 and 100 m^2. The roof areas of the 15 BRE test cases (excluding flats) range from 36 m^2 to 107 m^2. Increasing the area of both solar thermal evacuated tubes and flat panels (45° tilt, south oriented) was found to decrease the carbon emissions for DHW (Figure 19 - Figure 22). The decrease in DHW carbon emissions becomes smaller as the area becomes larger. The model allows the input of values exceeding the roof area, however the results remain the same after the solar collector area exceeds the roof area. Thus, regardless of the input, the solar collector area can only be as big as the roof area of each house type.

The use of solar collector area equal to a 'Percentage of Roof having Solar Panel' was tested for percentages up to 30% and the results presented similar trends to the above (Figure 23 - Figure 26). However, this option cannot be easily exploited as it depends on the different roof areas of the 15 archetypes. Therefore, it would not allow drawing specific conclusions about the optimum collector area or comparing with other widely available datasets.

A.1.3 Solar thermal collector orientation

Allowed value range: South / SE (SW) / E (W) / NE (NW) / North

The efficiency of solar thermal (45° tilt, 5m^2 area) decreases as the orientation changes from South (best) to North (worst). Results look reasonable and are similar both for solar thermal evacuated tubes and flat panels (Figure 27 - Figure 30).

A.1.4 Solar thermal collector tilt

Allowed value range: 0° / 30° / 45° / 60° / 90°

Five square metres of solar thermal, facing south, present the best yearly performance with a tilt of 45°and 60° (with only slightly different efficiencies) followed by a 30° tilt. Vertical and horizontal panels give the worst performance. The results are similar both for solar thermal evacuated tubes and flat panels (Figure 31 - Figure 34). Because the installations modelled are domestic, the hot-water storage available is equivalent to only a day or two's use; hence there is no inter-month storage. This means that usable monthly heat output (which is what is graphed here) is capped at monthly hot-water demand; so even where the installation could in theory produce more hot water, that heat is discarded and not counted.

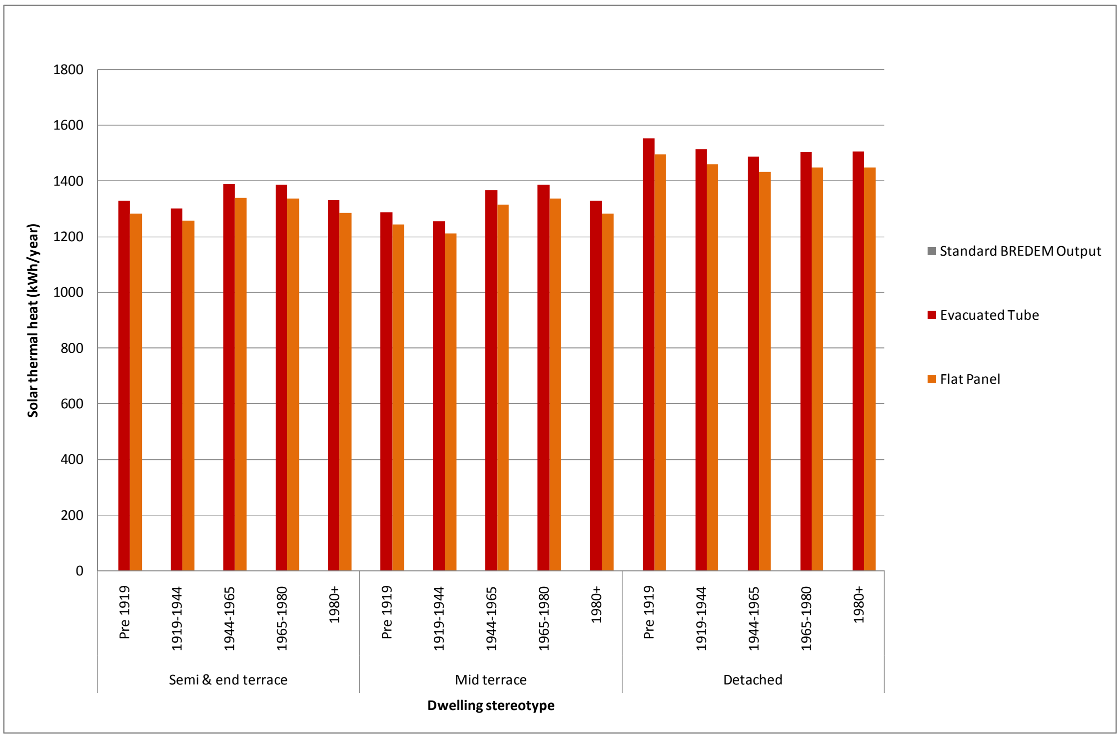

Figure 17 **Solar thermal: modelled impact of different technologies on heat output**

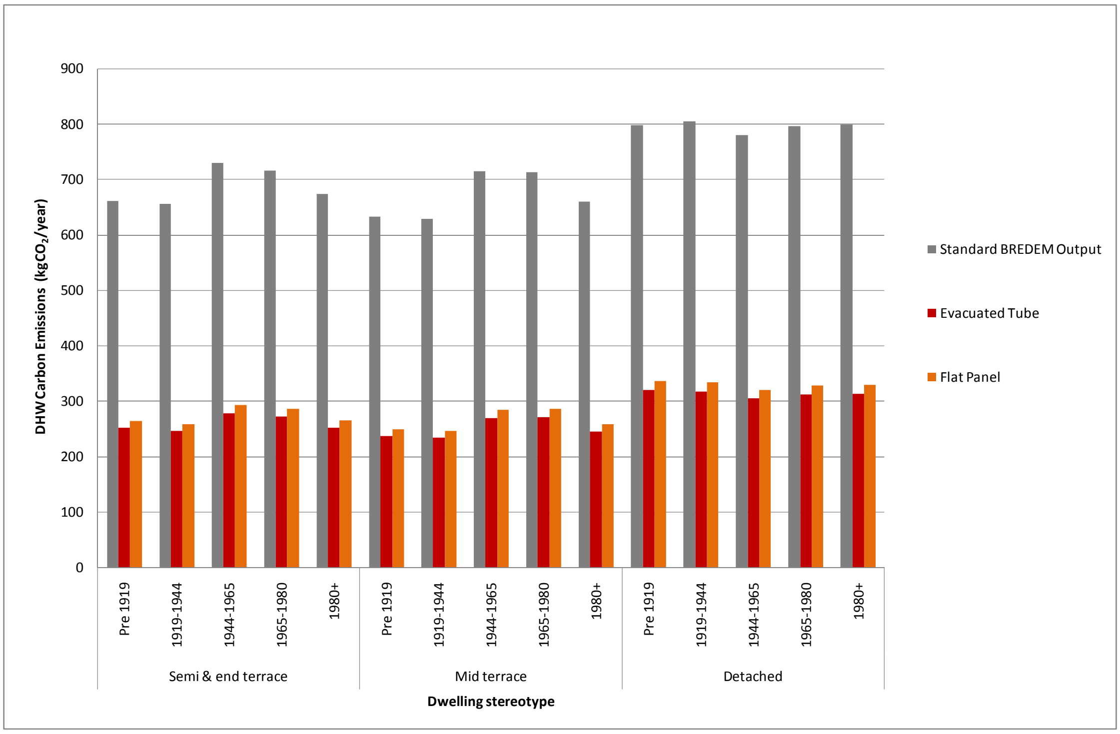

Figure 18 Solar thermal: modelled impact of different technologies on DHW CO_2 emissions

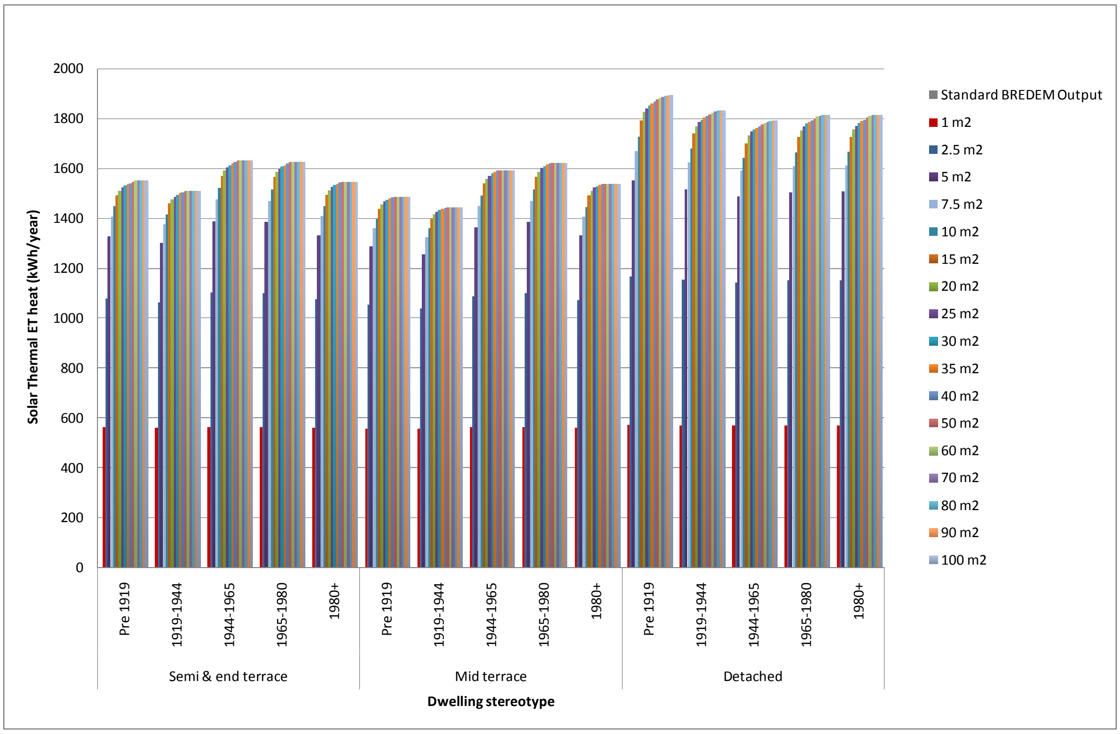

Figure 19 Solar thermal evacuated tubes: modelled impact of collector area on heat output

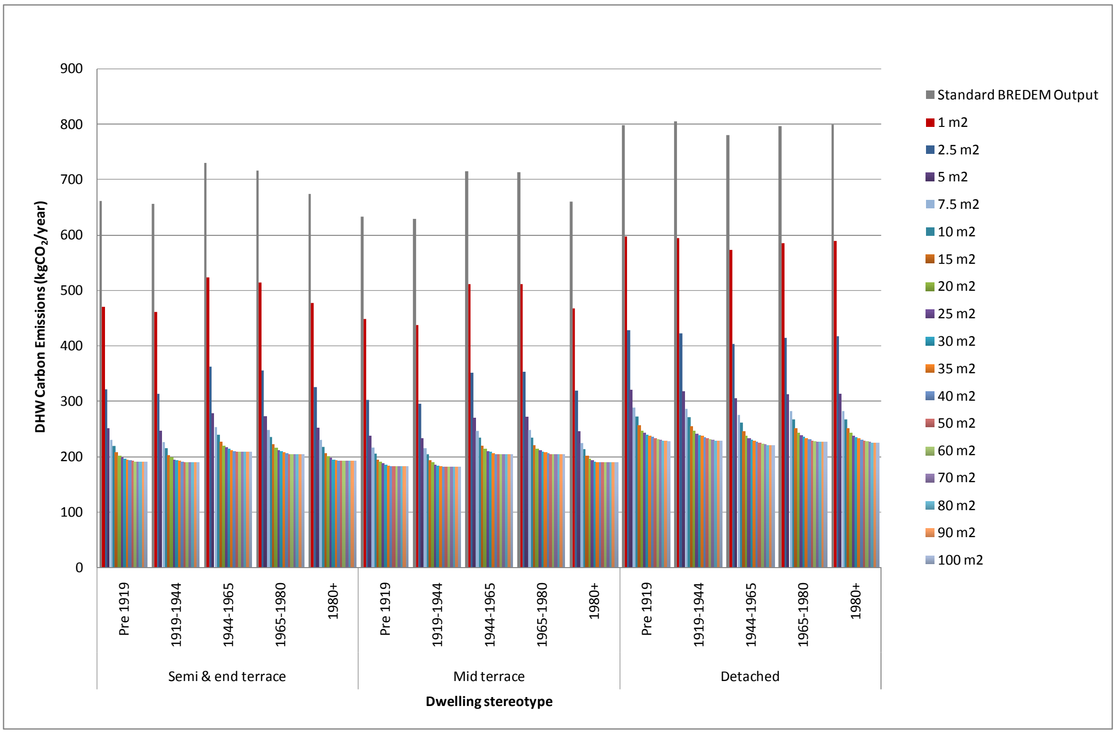

Figure 20 Solar thermal evacuated tubes: modelled impact of collector area on DHW CO_2 emissions

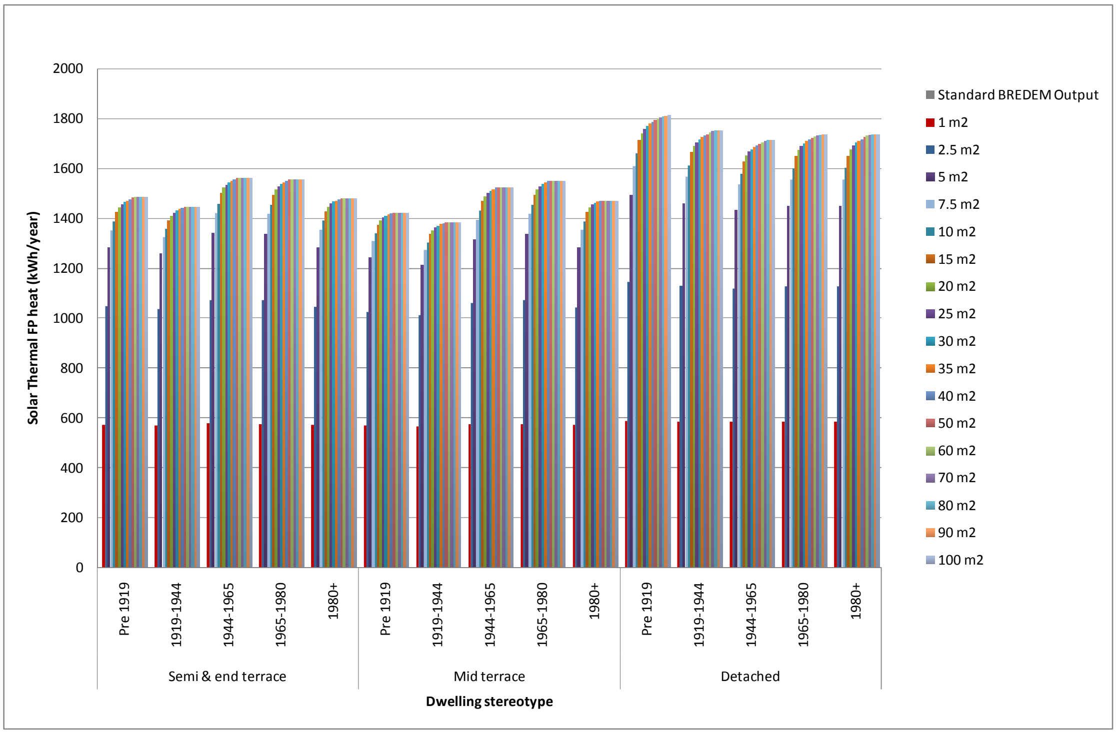

Figure 21 Solar thermal flat panels: modelled impact of collector area on heat output

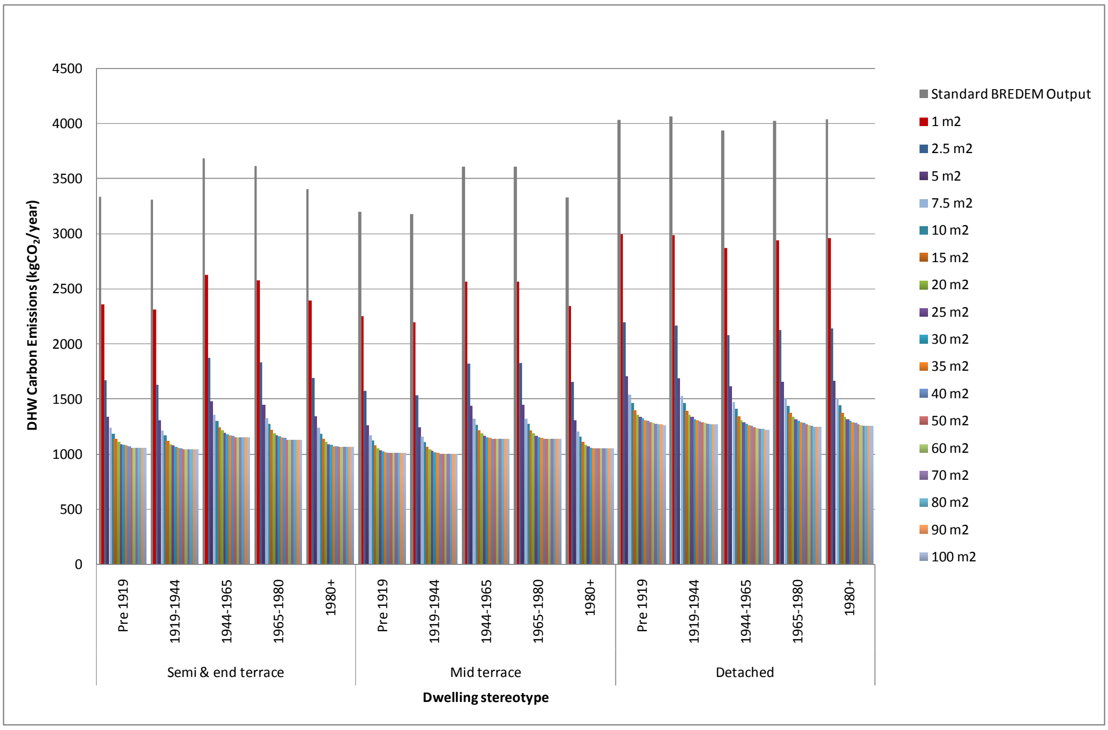

Figure 22 **Solar thermal flat panels: modelled impact of collector area on DHW CO_2emissions**

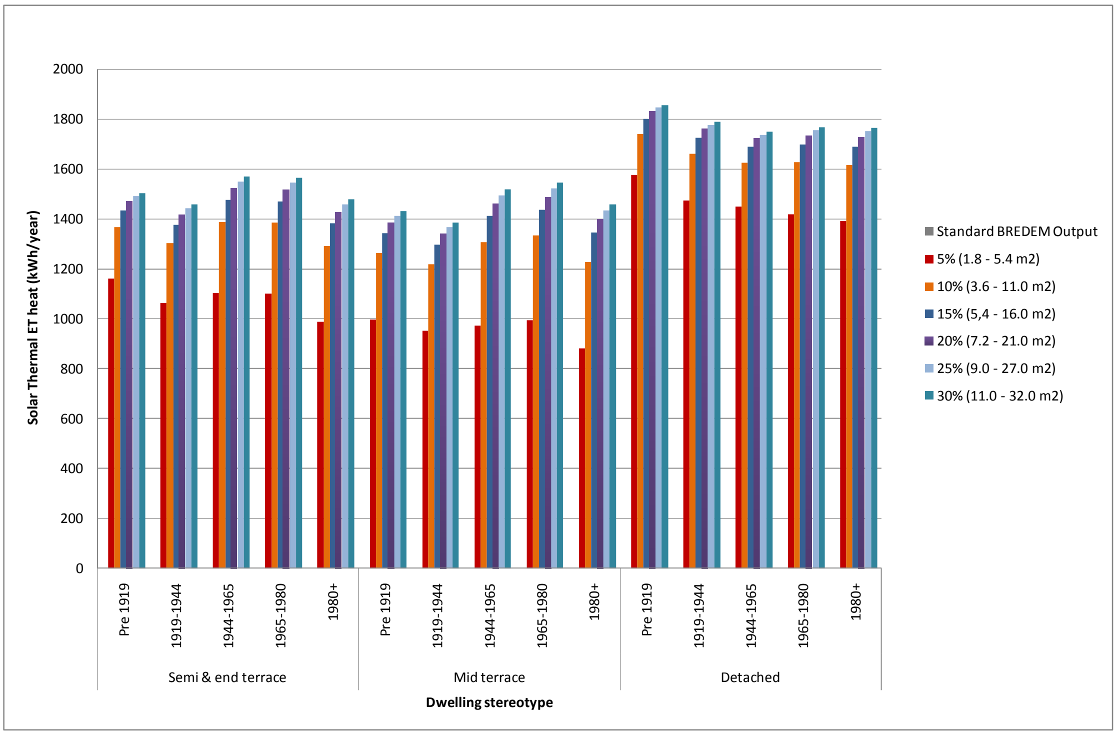

Figure 23 **Solar thermal evacuated tubes: modelled impact of collector area as a roof area fraction on heat output**

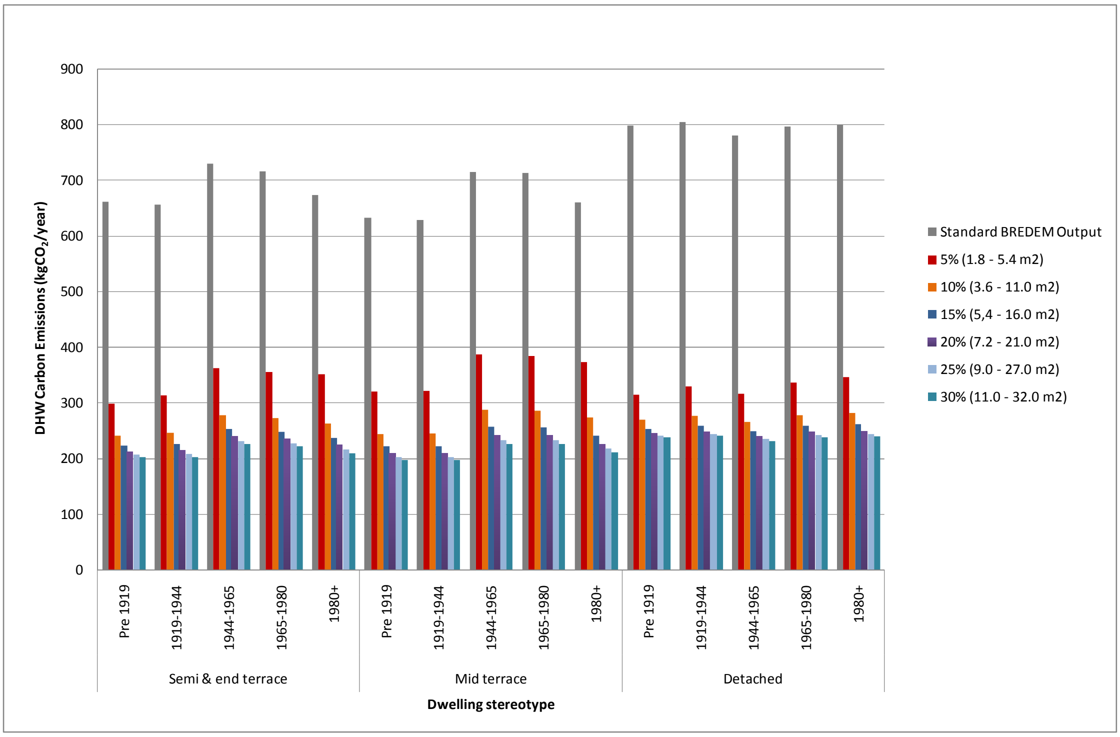

Figure 24 Solar thermal evacuated tubes: modelled impact of collector area as a roof area fraction on DHW CO_2emissions

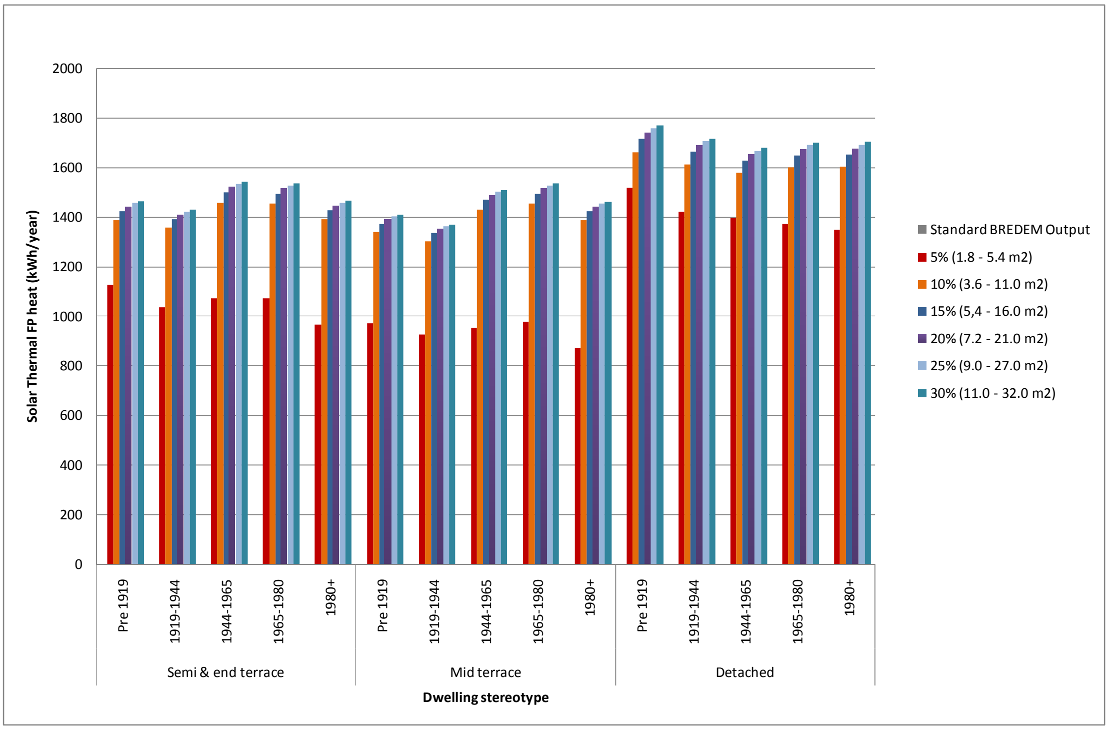

Figure 25 Solar thermal flat panels: modelled impact of collector area as a roof area fraction on heat output

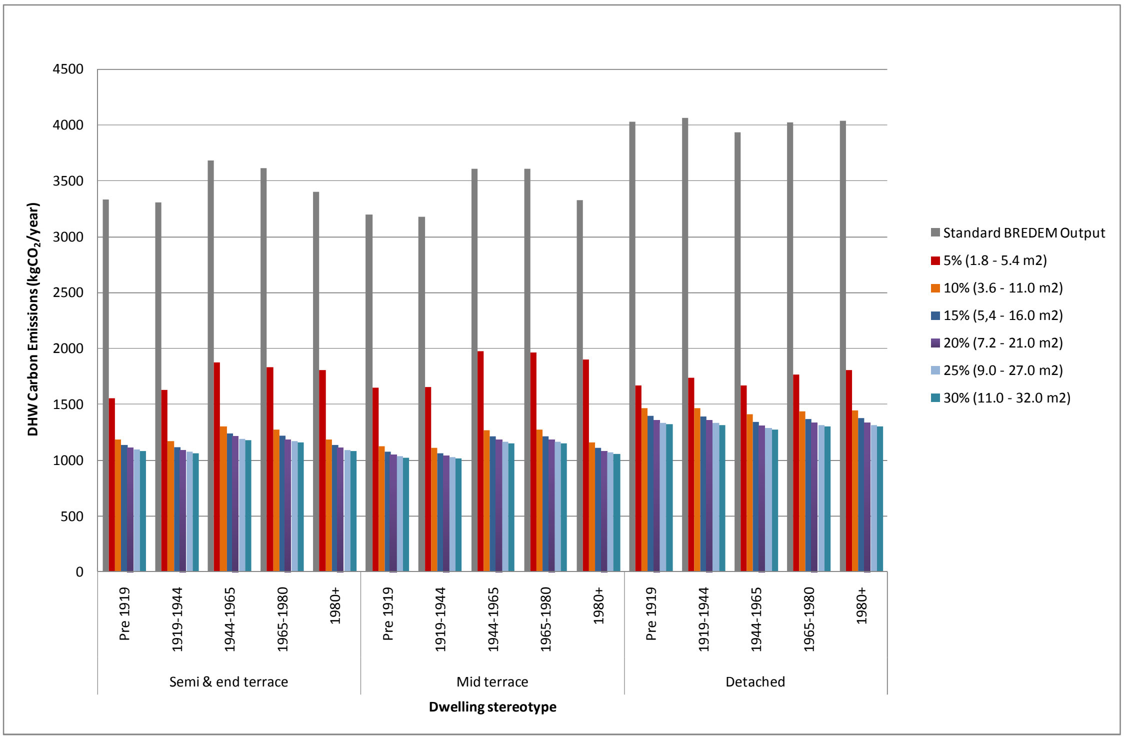

Figure 26 **Solar thermal flat panels: modelled impact of collector area as a roof area fraction on DHW CO_2 emissions**

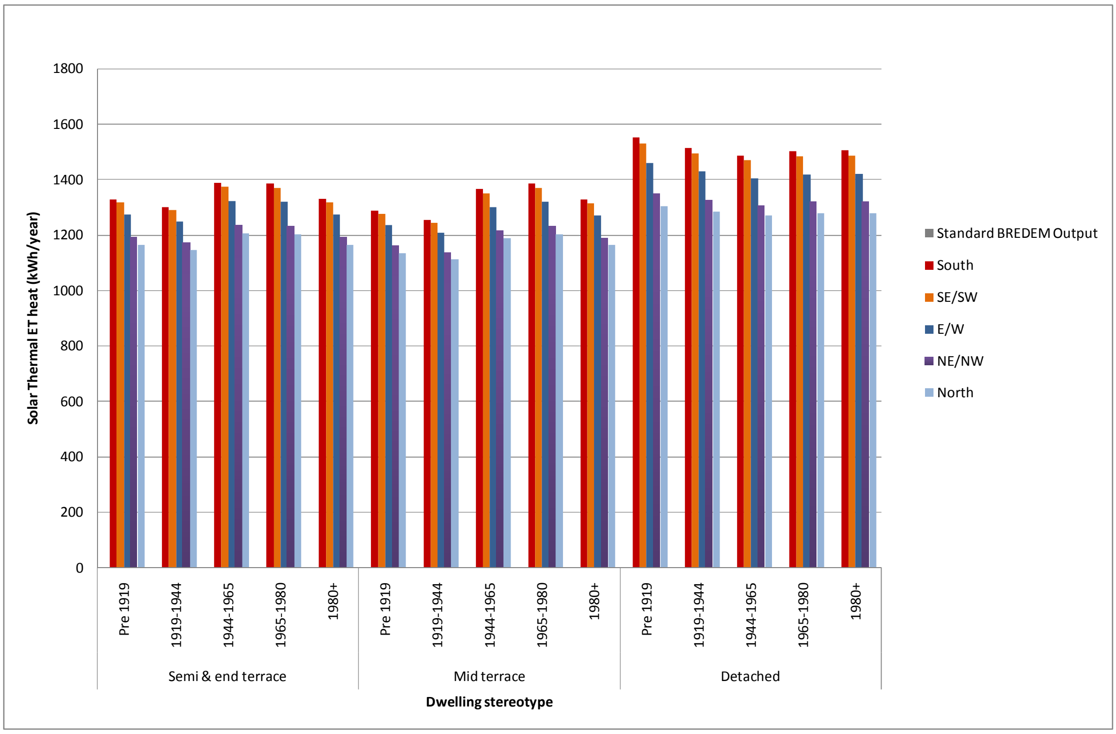

Figure 27 **Solar thermal evacuated tubes: modelled impact of orientation on heat output**

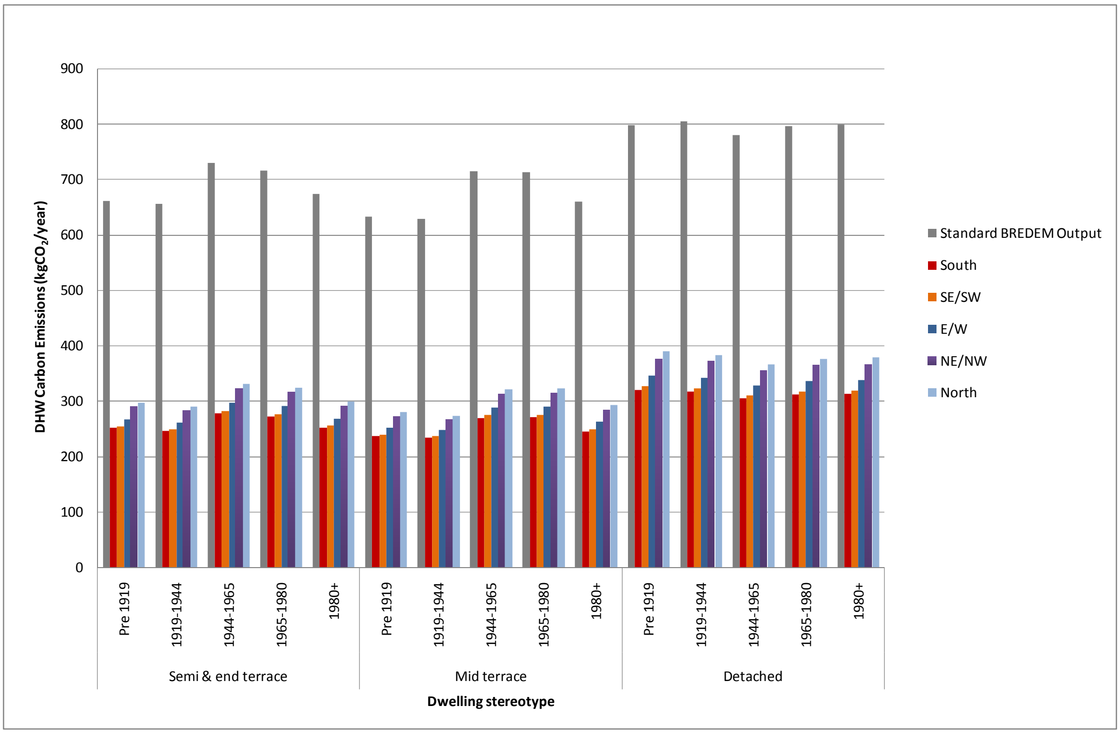

Figure 28 **Solar thermal evacuated tubes: modelled impact of orientation on DHW CO_2emissions**

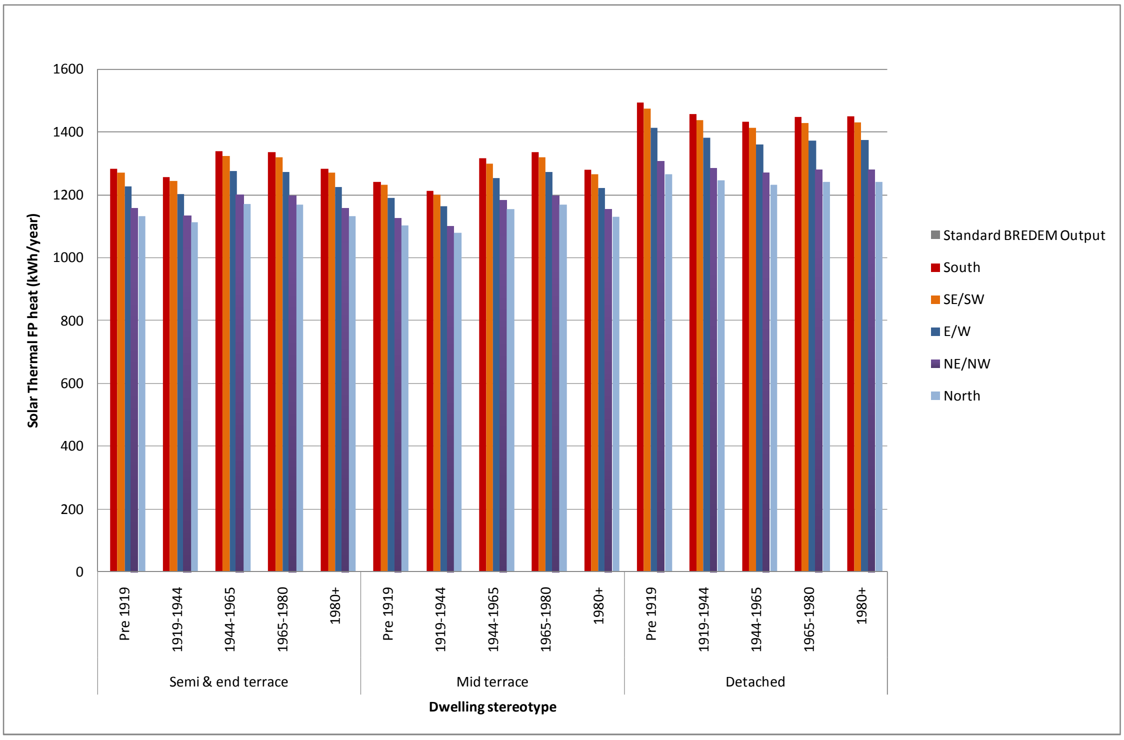

Figure 29 **Solar thermal flat panels: modelled impact of orientation on heat output**

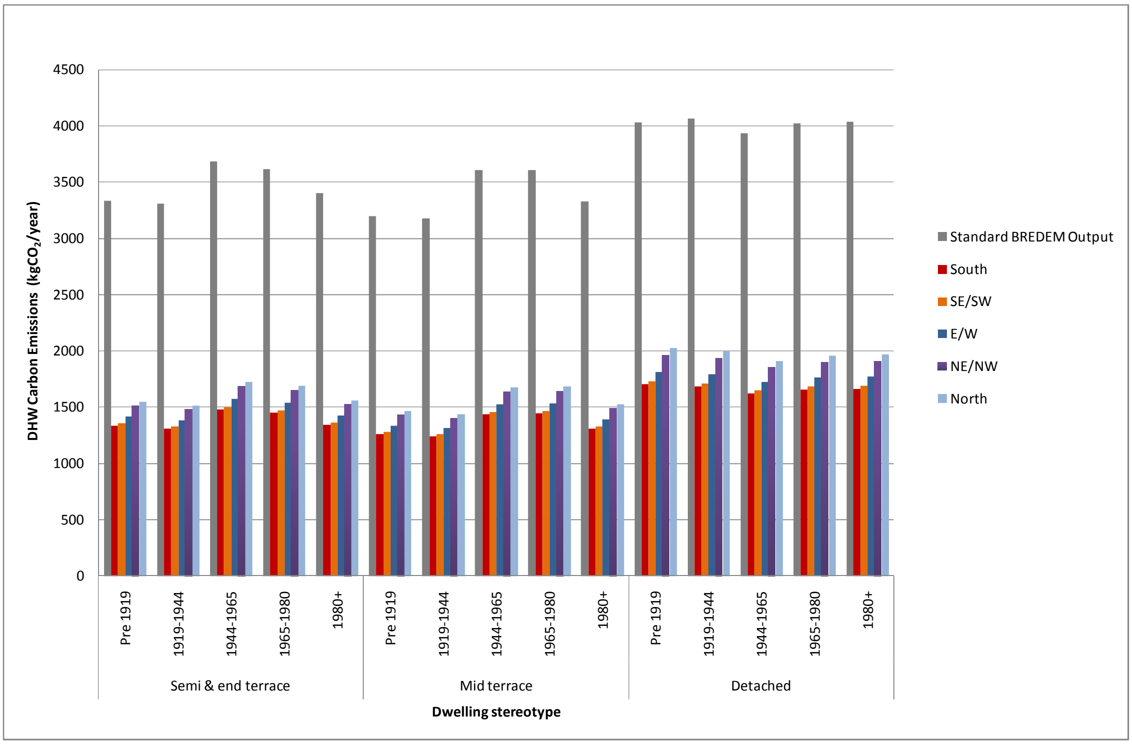

Figure 30 **Solar thermal flat panels: modelled impact of orientation on DHW CO_2emissions**

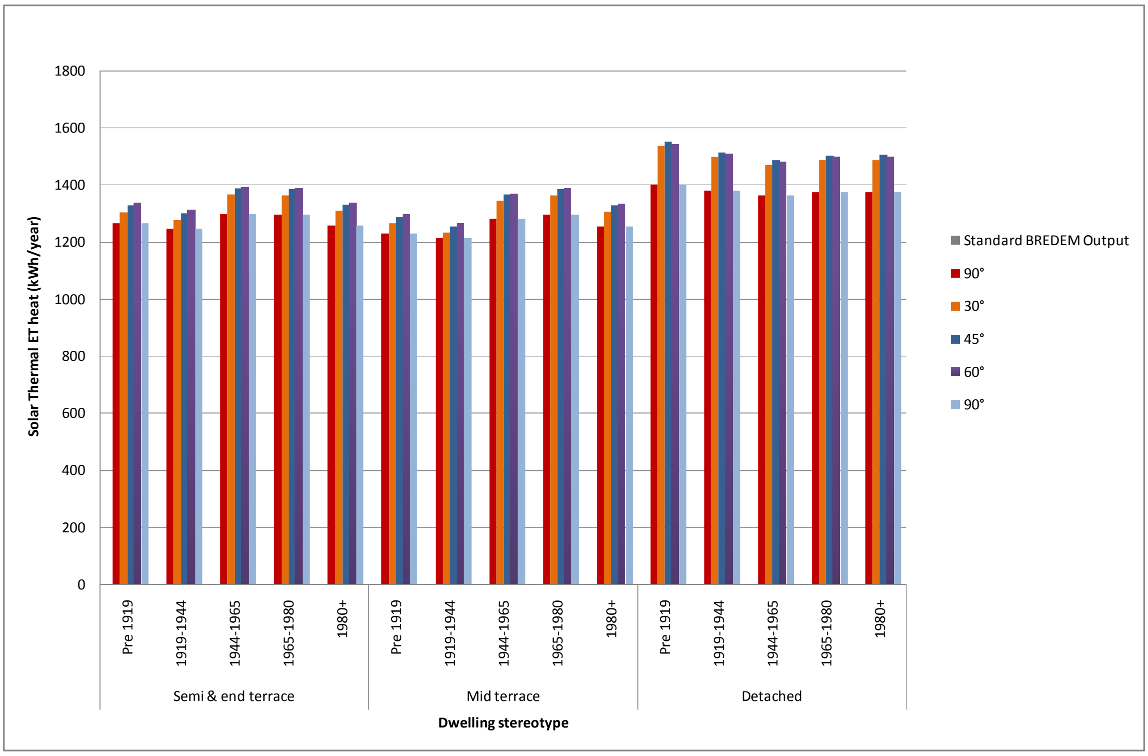

Figure 31 **Solar thermal evacuated tubes: modelled impact of tilt on heat output**

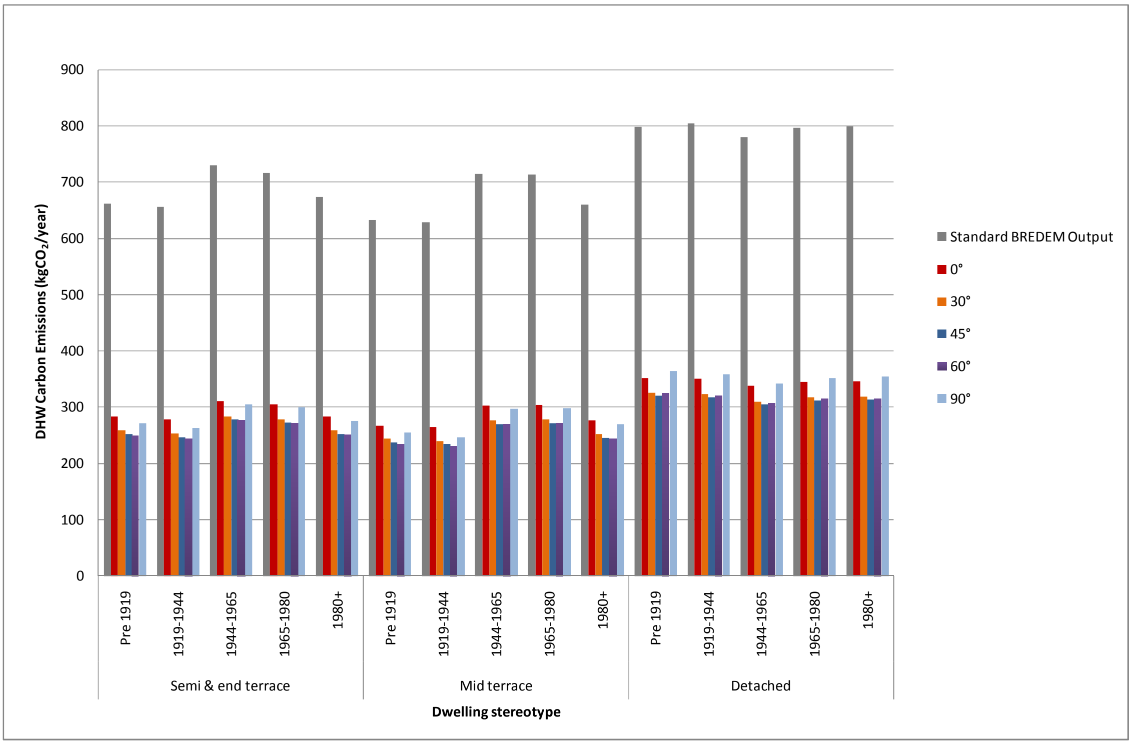

Figure 32 **Solar thermal evacuated tubes: modelled impact of tilt on DHW CO_2 emissions**

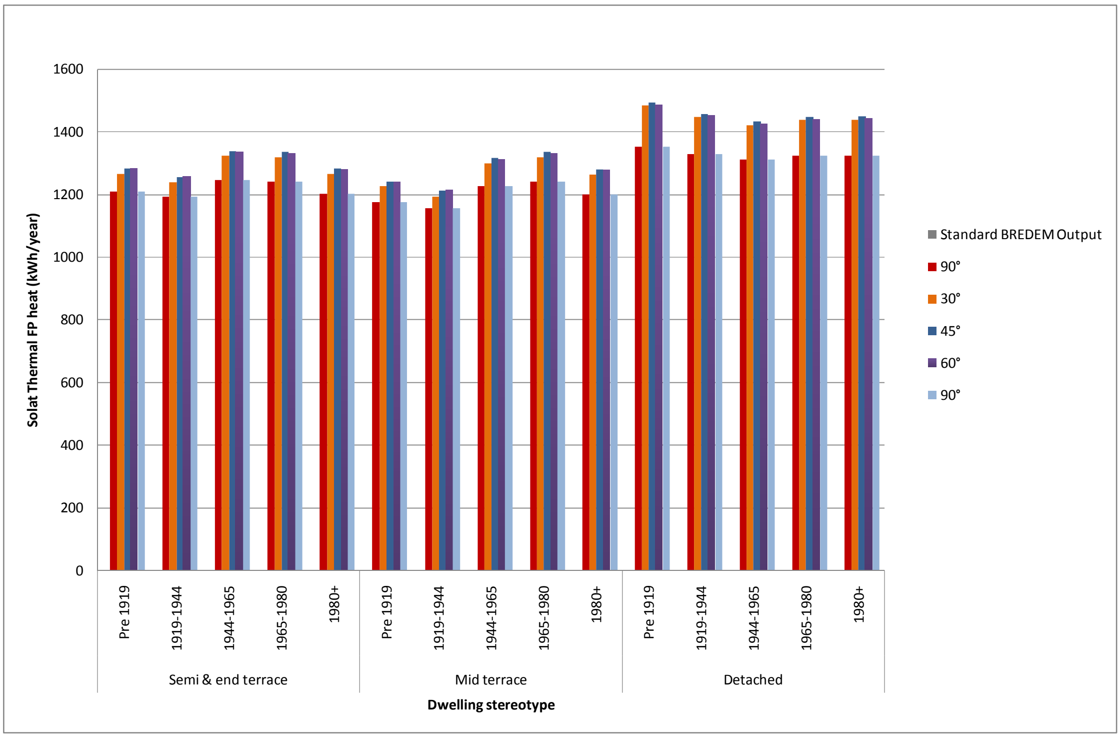

Figure 33 **Solar thermal flat panels: modelled impact of tilt on heat output**

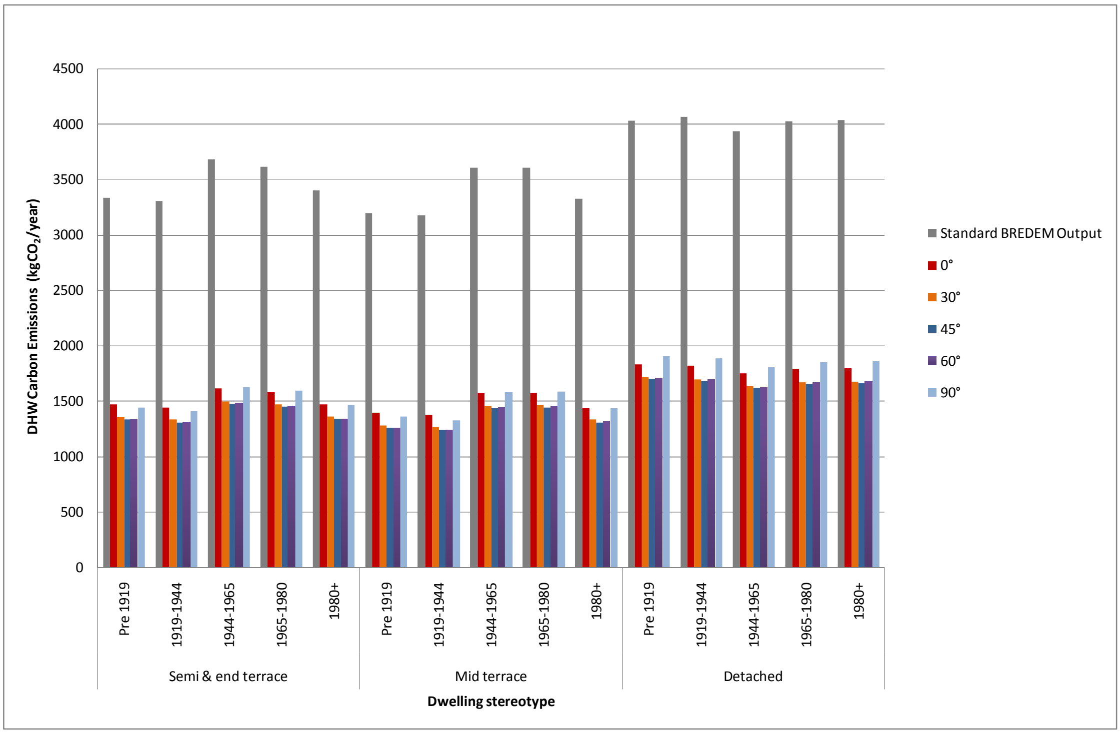

Figure 34 **Solar thermal flat panels: modelled impact of tilt on DHW CO_2 emissions**

A.2 Solar PV

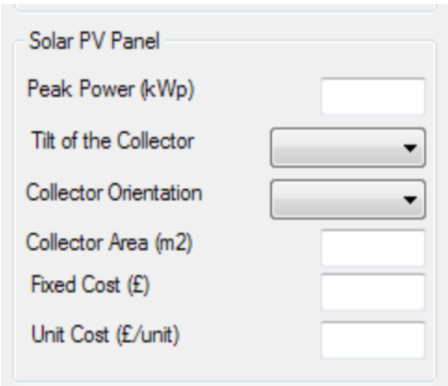

Figure 35 **Snapshot of the BRE model interface (solar PV section)**

The PV interface (Figure 36) allows for the following parameters to be tested: tilt of collector, collector orientation and peak power (kW_p), which are used to calculate the electricity generated and the associated CO_2 emissions saved. Collector area is specified as well but, together with fixed cost (£) and unit cost (£/unit), is only used to calculate total costs. Different types of Solar PV can be accounted for by adjusting the Peak Power (kWp). The sensitivity of solar PV in terms of peak power (section A.2.1), orientation (section A.2.2) and tilt (section A.2.3) was tested by looking at the energy spent for electricity. The results are consistent between electricity production (i.e. Figure 36) and CO_2 emissions (i.e. Figure 37).

A.2.1 Solar PV peak power

Allowed value range: any

Varying the peak power of solar PVs between 1 kWp and 10 kWp increases linearly the energy output; at approximately 5 kW_p the electricity production meets or exceeds the dwelling stock demand, which is a sensible finding (Figure 36, Figure 37). For this scenario, smaller and newer dwellings tend to produce more electricity than needed and thus become net exporters of electricity.

A.2.2 Solar PV collector orientation

Allowed value range: South / SE (SW) / E (W) / NE (NW) / North

The efficiency of a solar PV system (45° tilt, 5m^2 area) decreases as the orientation changes from South to North (worst) (Figure 39 Figure 39). Results for PVs look reasonable and present identical trends with solar thermal evacuated tubes and flat panels.

A.2.3 Solar PV collector tilt

Allowed value range: 0° / 30° / 45° / 60° / 90°

Solar PVs tested in different tilts show different trends in energy reduction in comparison with Solar Thermal. In particular, a PV installation of 5 kWp peak power, facing south, clearly performs best during the year at a tilt of 30° (Figure 40, Figure 41). The second best performance for PVs is at 45° with 60° and 0° coming next. The worst performance is given at 90° while solar thermal performs worst when horizontal.

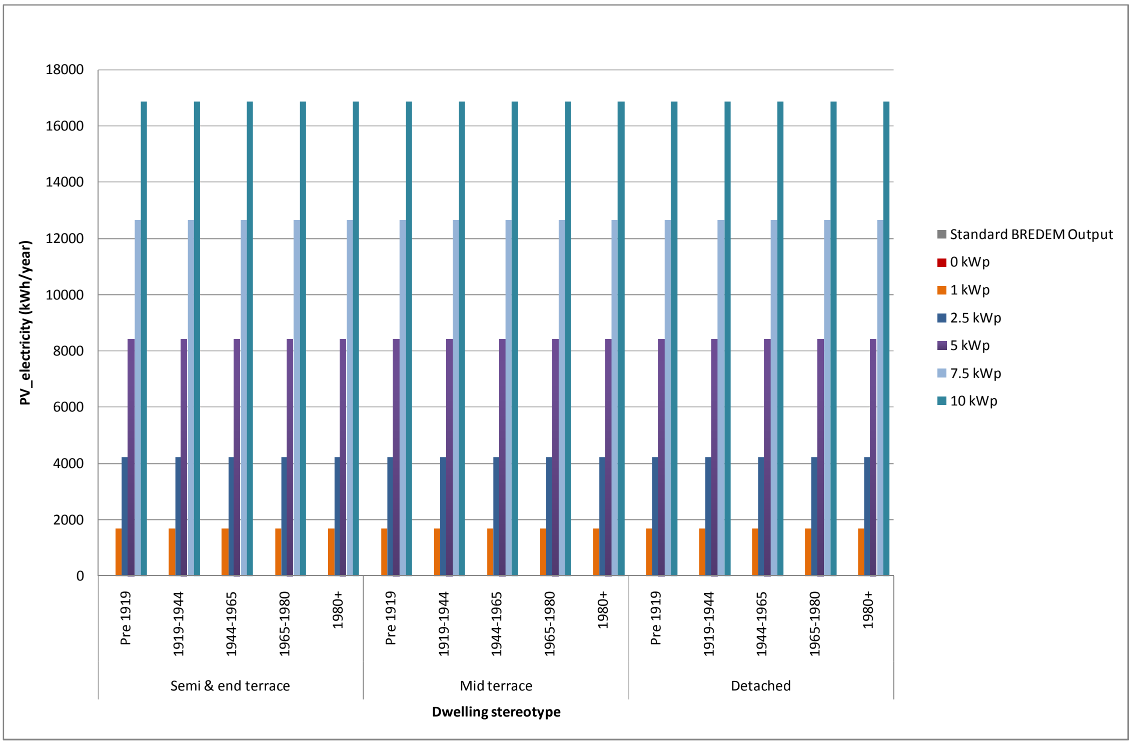

Figure 36 PV: modelled impact of peak power on electricity production

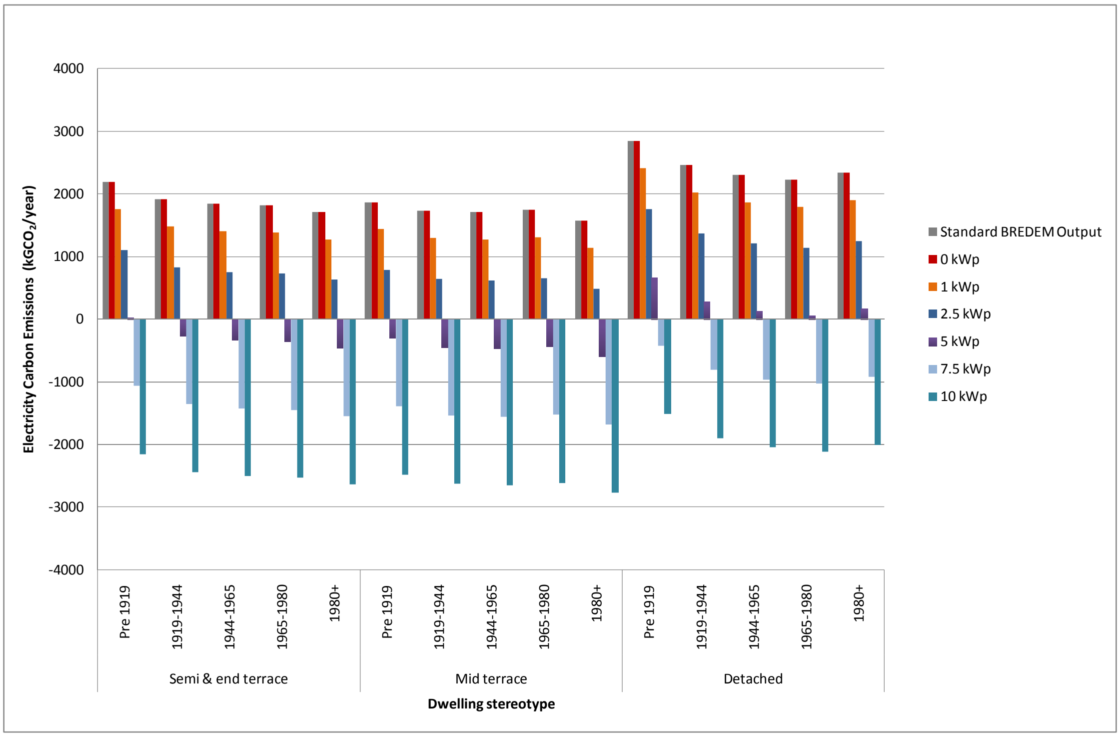

Figure 37 PV: modelled impact of peak power on CO_2 emissions

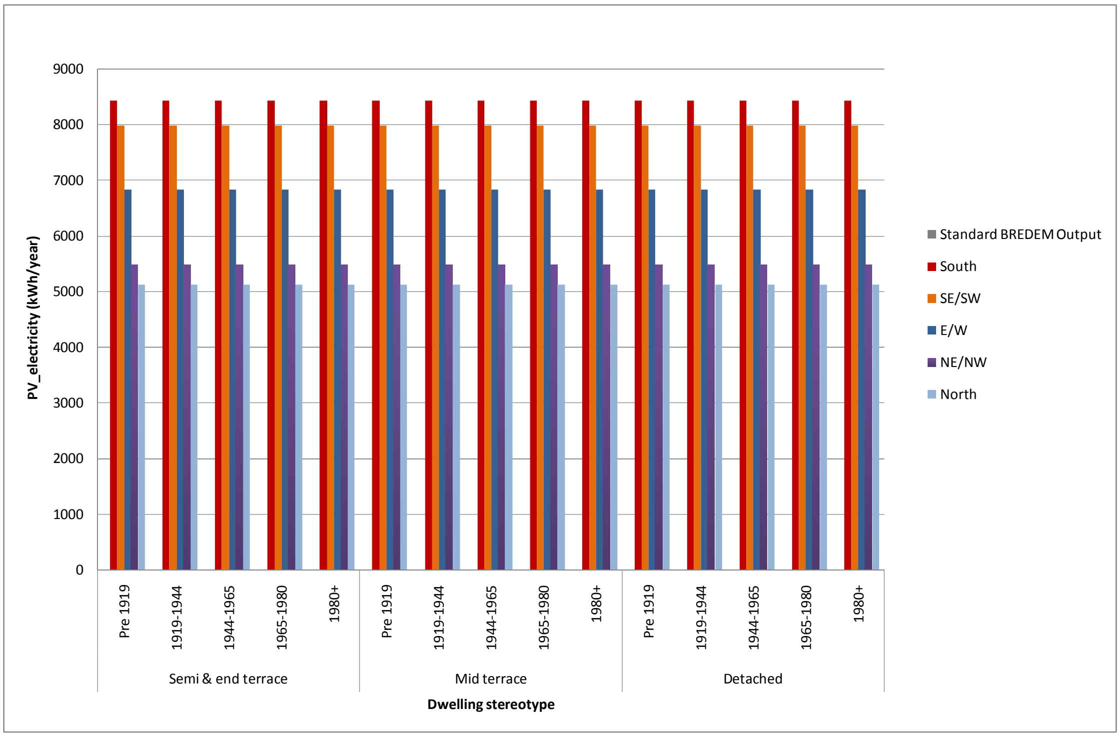

Figure 38 **PV: modelled impact of orientation on electricity production**

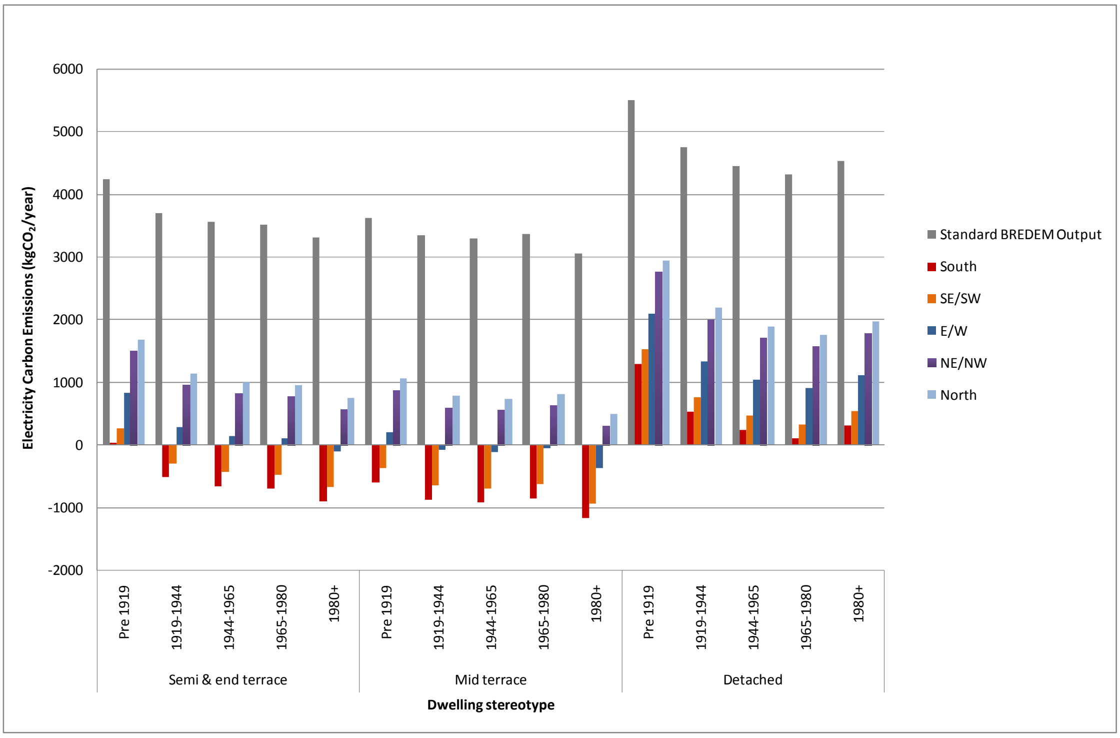

Figure 39 **PV: modelled impact of orientation on CO_2 emissions**

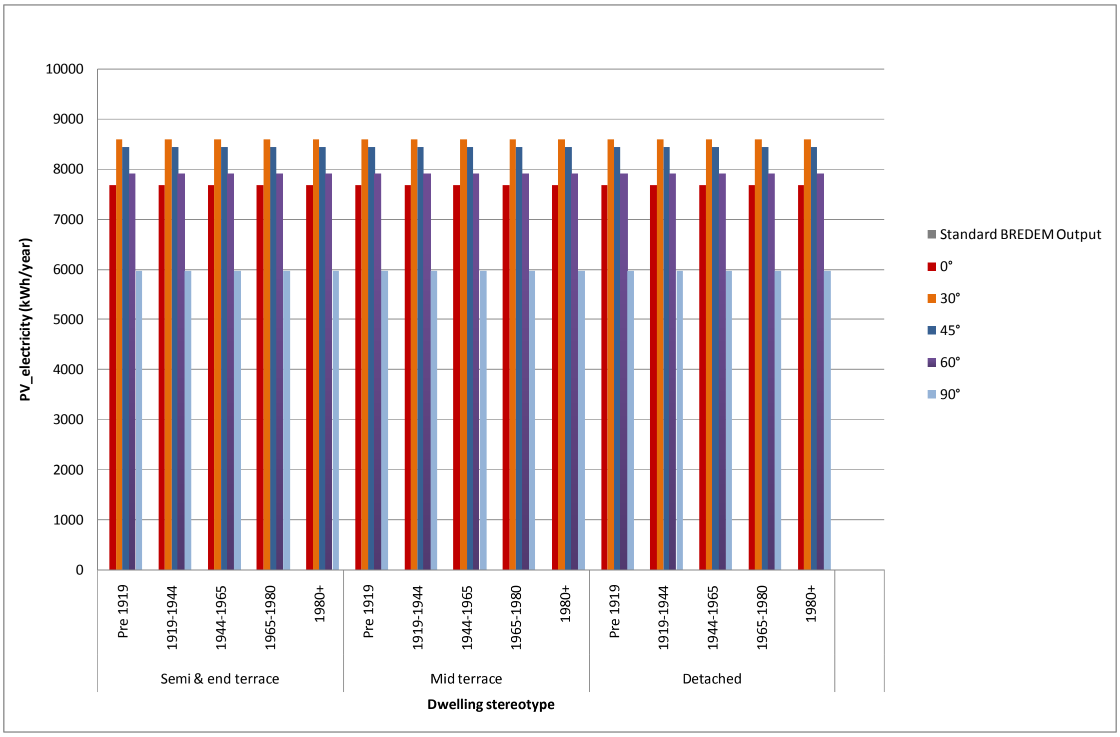

Figure 40 PV: modelled impact of tilt on electricity production

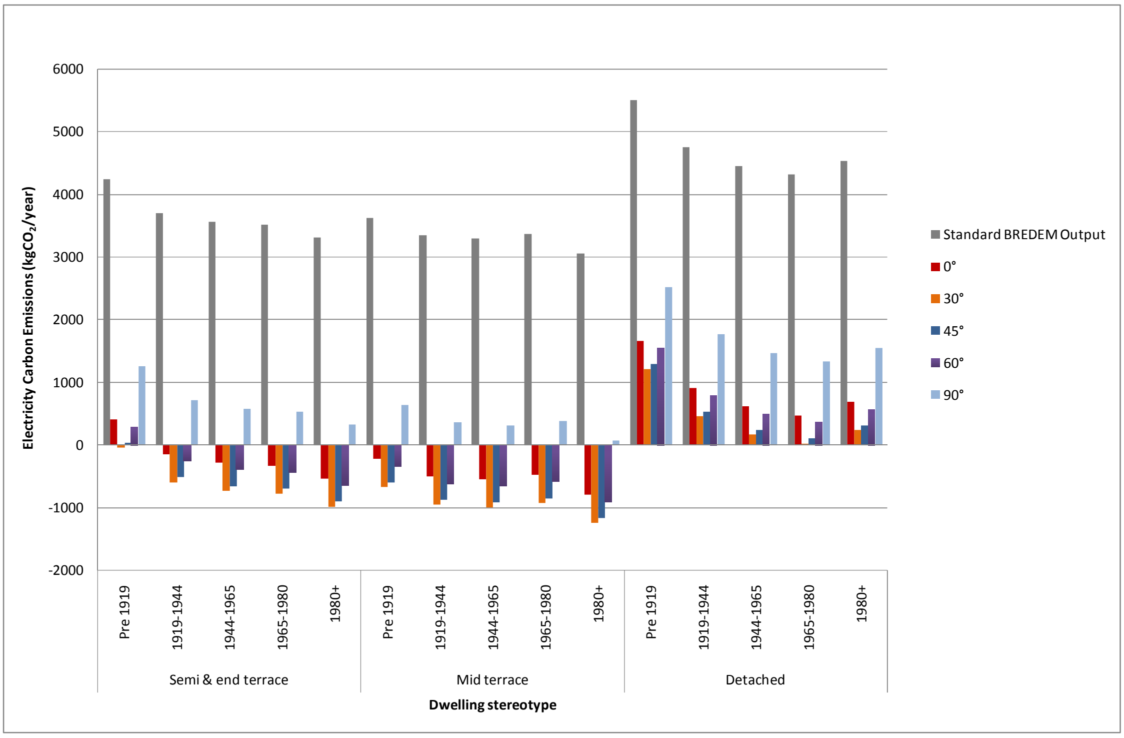

Figure 41 PV: modelled impact of tilt on CO_2 emissions

A.3 Small wind turbines

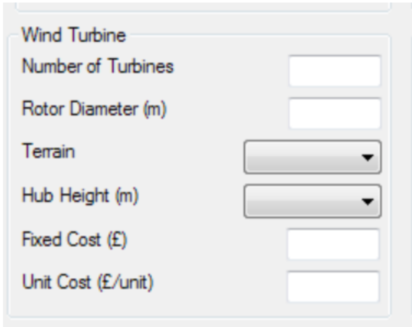

Figure 42 Snapshot of the BRE model interface (wind turbine section)

The testing strategy developed for the micro wind turbine component of the ETI model was originally based on the input data derived from actual wind turbine installations described in the EST report “Domestic small-scale wind field trail report” (EST 2009). The rationale behind this approach was to:

- attempt to test typical “real world” micro wind turbine installations; and
- enable the comparison of modelled results with monitored data available in the aforementioned study.

However after an initial set of model runs, it was determined that the current limitations of the model would not allow this testing strategy to be implemented. The main limitations affecting testing can be summarised as follows.

- There is no facility to input turbine power (in W or kW) – a crucial variable in the calculation of the overall effect of micro wind turbines.
- Modelling is restricted to the hard-coded pre-specified input fields such as “wind turbine height”. These can currently be overridden, but in this case no calculation of energy demand reduction takes place.

For the testing of the µDE Alpha V2 model, the strategy adopted aimed to test various height variations of a mast mounted wind turbine installation selected after the consideration of the relevant technological parameters.

Accordingly, the following hub height cases were used:

Table 20 Test cases for wind turbines

Case	Number	Blade diameter (m)	Height (m)	Terrain	Fixed cost (£)	Unit cost (£)
1	1	3.5	0	Rural	2000	16000
2	1	3.5	2	Rural	2000	16000
3	1	3.5	7	Rural	2000	16000
4	1	3.5	12	Rural	2000	16000

Notes:

1 Inputs such as blade dimensions and costs based on selected mast-mounted installation (Proven 7 wind turbine, 3.5 diameter, 3kW)

2 Tested heights are limited to those pre-specified in the model

3 Only a rural terrain setting was considered for the testing

These cases, in addition to a base case with no micro wind turbines, were run in the ETI model. The comparative results are illustrated in the graphs below (Figure 43, Figure 44). Additional tests with increasing unit numbers of 12m high wind turbines (Figure 45, Figure 46) and varying rotor diameters (Figure 47, Figure 48) showed no apparent irregularities.

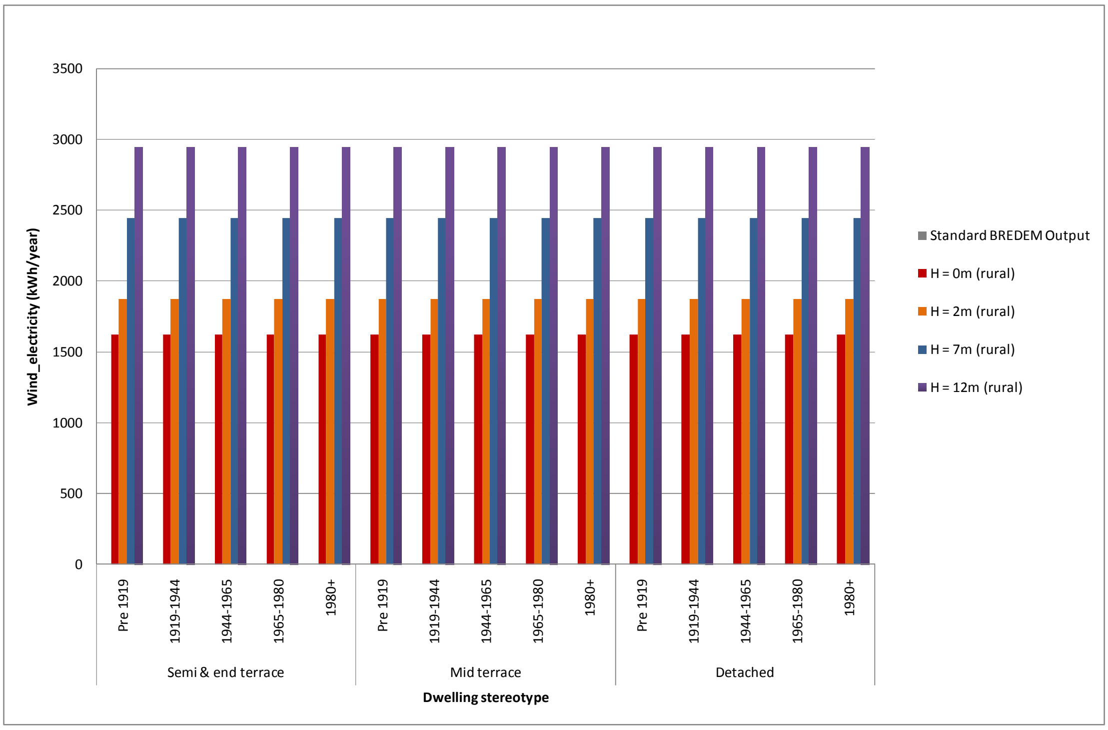

Figure 43 **Wind turbines: modelled impact of rotor height on electricity production**

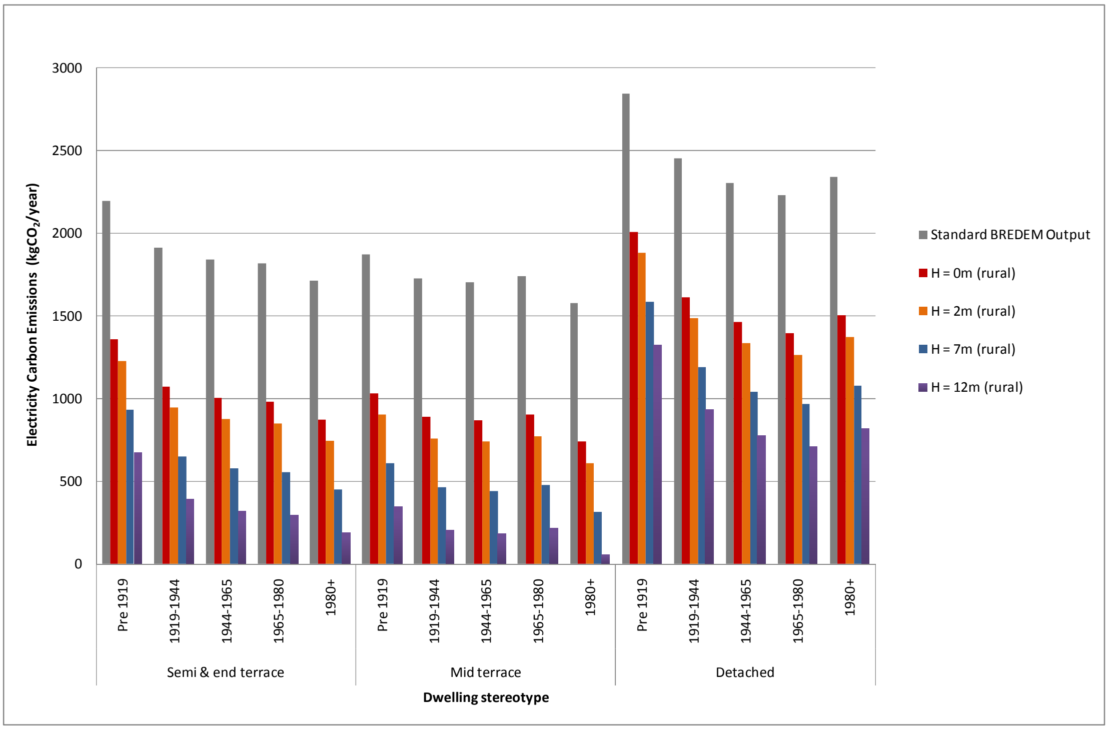

Figure 44 **Wind turbines: modelled impact of rotor height on electricity CO_2 emissions**

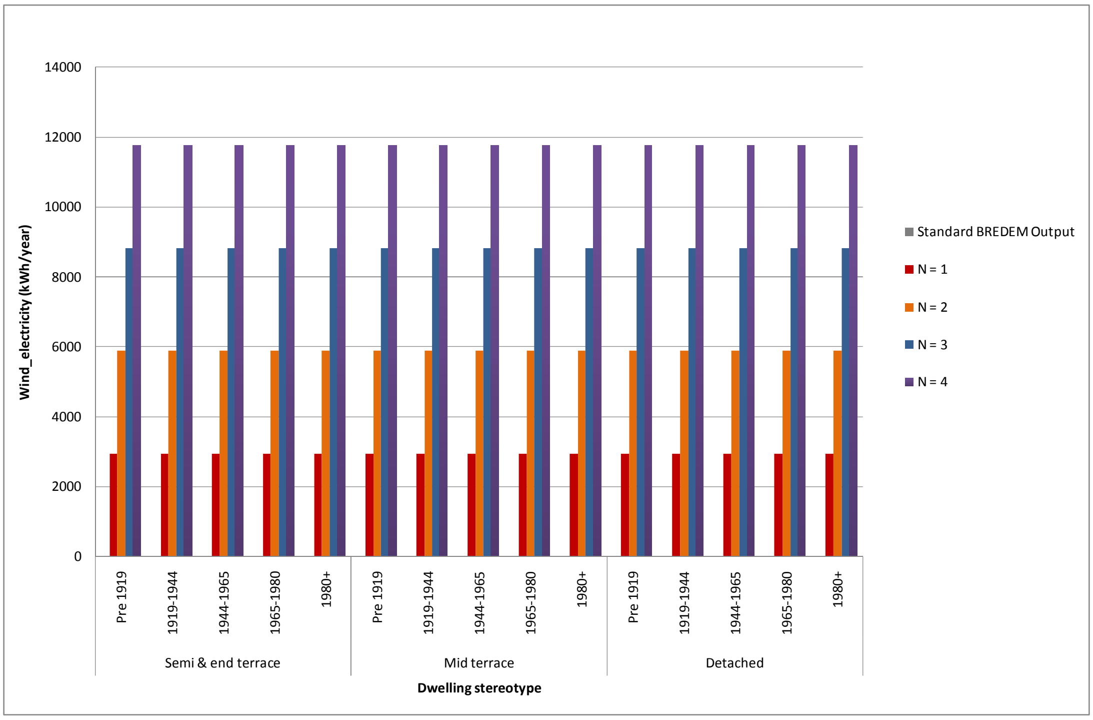

Figure 45 **Wind turbines: modelled impact of number of units on electricity production**

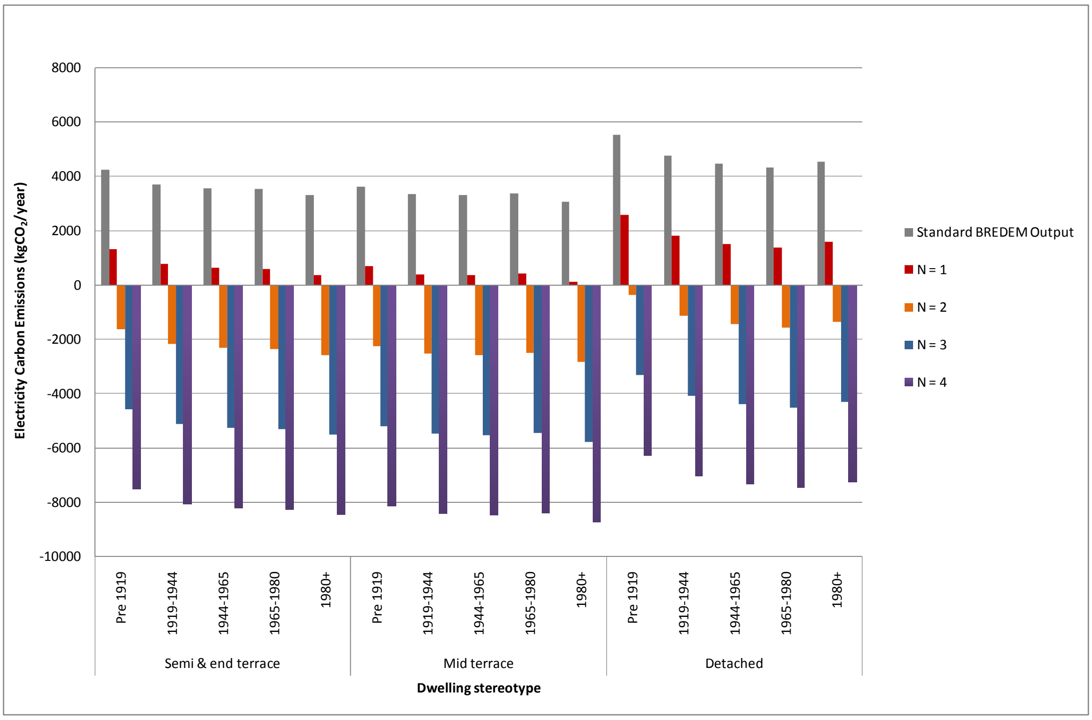

Figure 46 **Wind turbines: modelled impact of number of units on electricity CO_2 emissions**

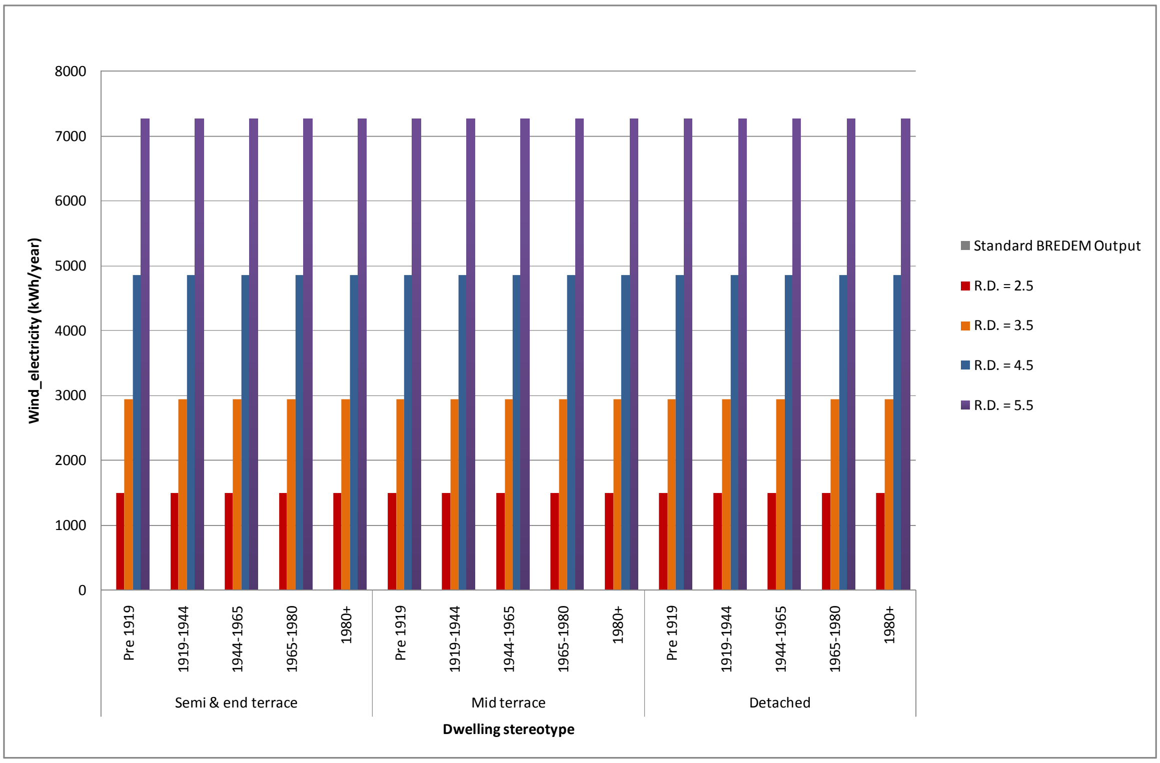

Figure 47 Wind turbines: modelled impact of rotor diameter on electricity production

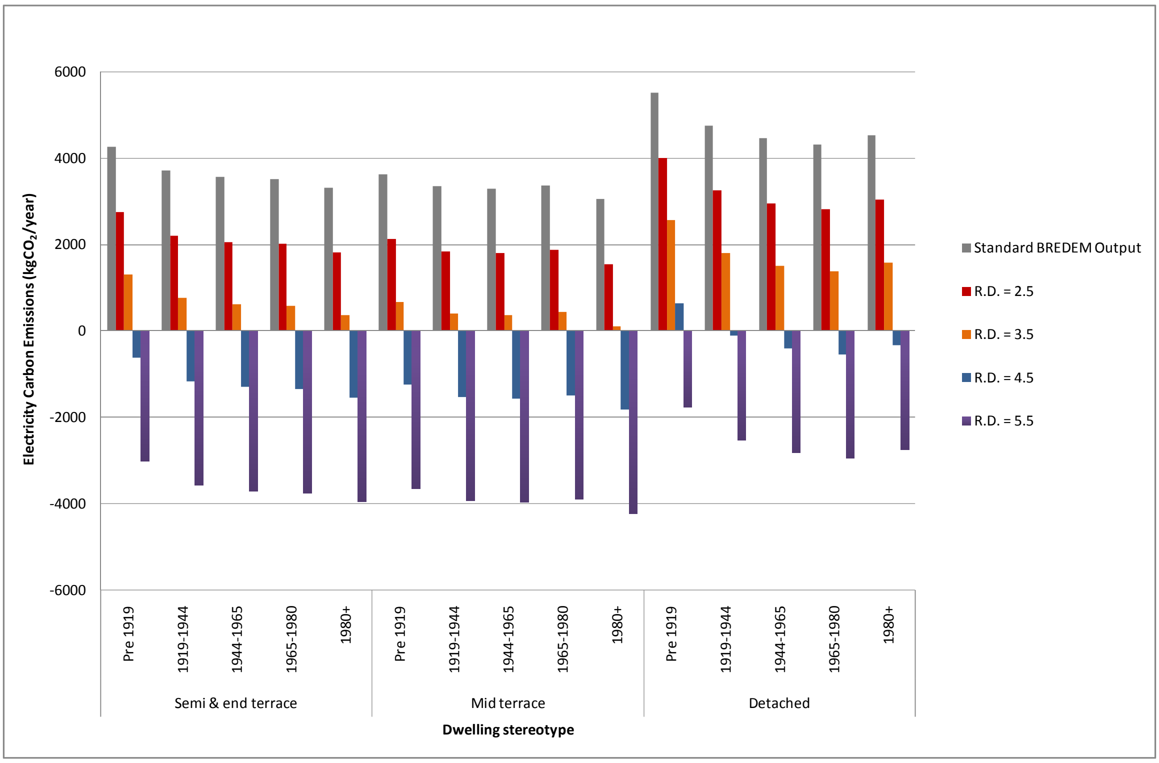

Figure 48 Wind turbines: modelled impact of rotor diameter on electricity CO_2 emissions

A.4 Biomass

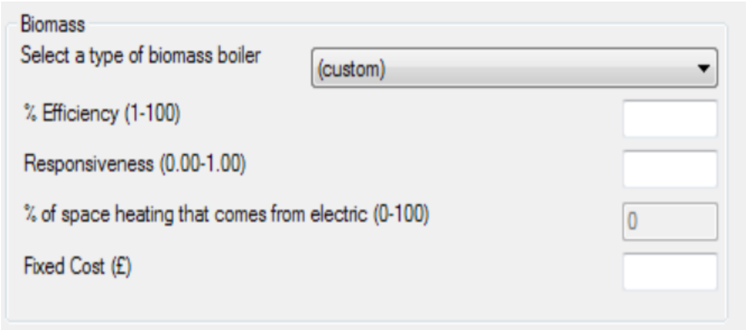

Figure 49 Snapshot of the BRE model interface (biomass section)

The model includes only one preset, a woodchip pellet independent boiler, and also allows the user to vary the efficiency, the responsiveness of the biomass system and the proportion of secondary heating. The same winter and summer efficiency is used in the model. The sensitivity of results to efficiency values was tested by varying the efficiency between 60% and 80%. This range selection was informed by the nominal and overall efficiency values given in the Biomass Factsheet documents produced by Mabilat and Schraube-Eifer (2011) within the context of the ETI µDE project.

A.4.1 Biomass test results

The model output for a biomass wood chip/independent boiler of varying efficiency and 0.75 responsiveness is illustrated in the two graphs below. As expected, the total solid fuel consumed by the system decreases as efficiency increases, as shown in the first graph. In addition, CO_2 emissions are reduced linearly with boiler efficiency (more than 50% in most cases), as can be observed in the second graph.

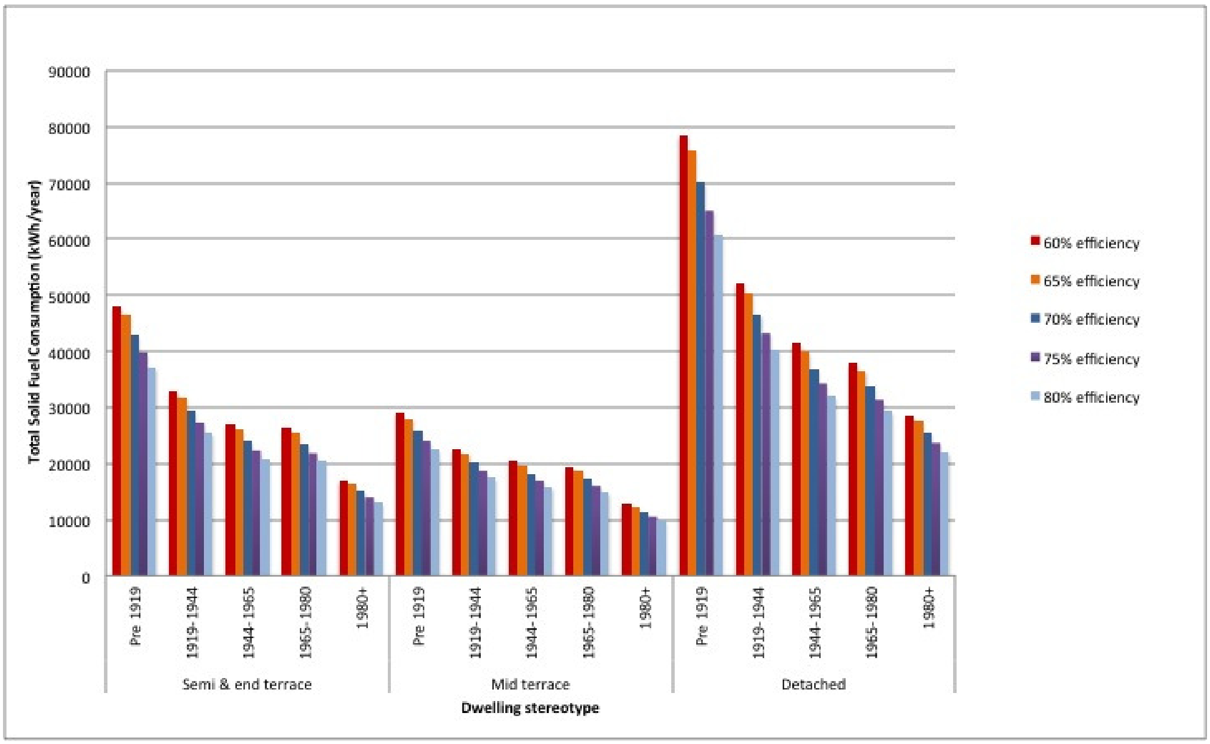

Figure 50 **Biomass: modelled impact of boiler efficiency on total solid fuel consumption**

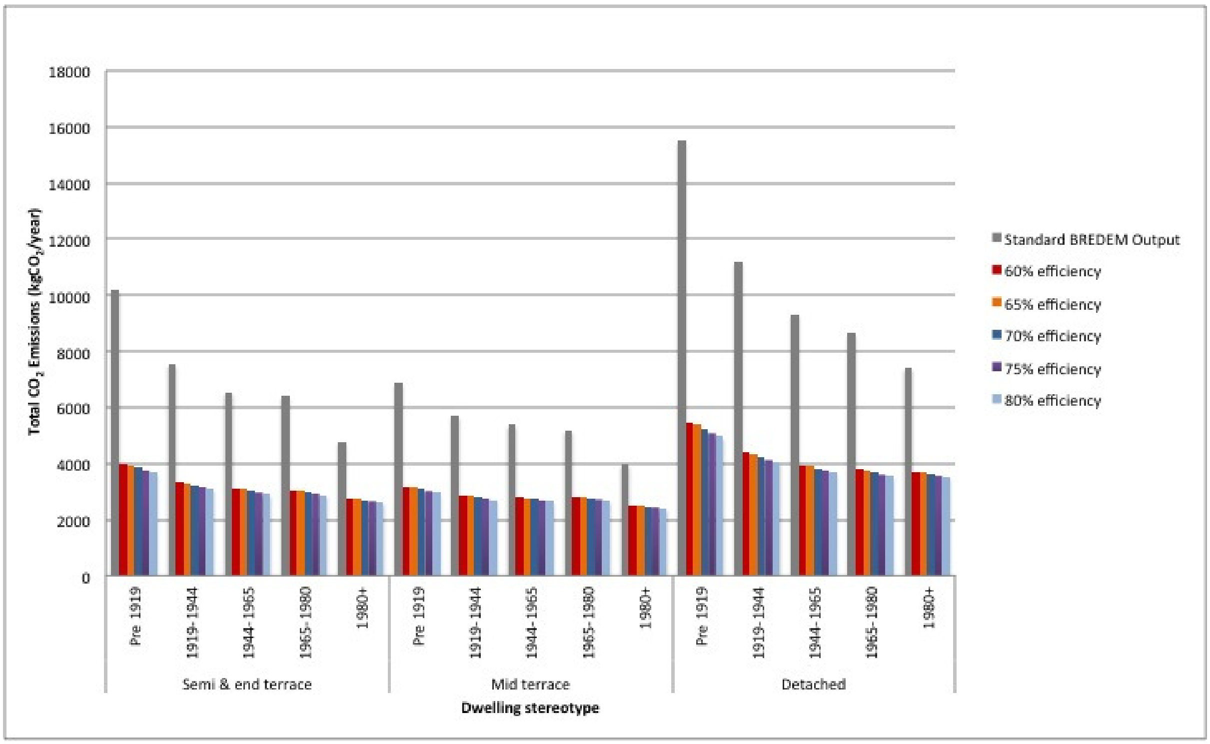

Figure 51 **Biomass: modelled impact of boiler efficiency on CO_2 emissions**

A.5 Micro CHP

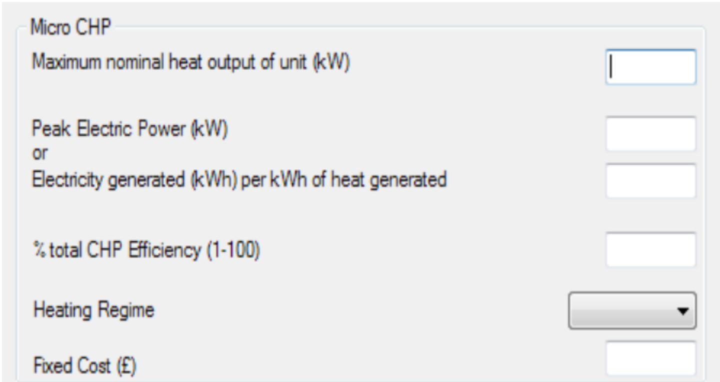

Figure 52 **Snapshot of the model interface (micro CHP section)**

Micro-CHP systems are specified by the following sets of parameters:

- heat output and peak power;
- heat output and ratio of heat to power; and
- peak power and ratio of heat to power.

Two sensitivity analyses were carried out:

a) by varying the heat output for a constant peak power of 1 kW_e; and
b) by varying the peak power for a constant heat output of 5 kW_{th}.

With regard to the latter, a case of 1:1 power to heat ratio was modelled. This analysis mainly focuses on Stirling Engine and Internal Combustion Engine micro-CHP systems. However, higher power-to-heat ratios were examined as systems with such characteristics (e.g. fuel cell micro-CHP) may become available in the market by the 2040s.

Postscript: as this report was finalised, a significant bug was found and fixed in the Alpha v5.1 model, for micro-CHP. The following section provides results for the Alpha v5.1 model; however, the scenario results presented in Section 3 of this report, were made using the debugged Alpha v6.1 model.

A.5.1 Varying peak heat output with a constant electrical peak power of 1 kW_e

Some properties have a higher space-heating demand than others, with pre-1919 detached houses having the highest space-heating demand. In some cases modelled below, the space-heating energy available from the micro-chp is insufficient for the property: in those cases, secondary electrical resistance heating is used to top up the heat from micro-CHP (whereas in the base case, gas provides the secondary heating). Depending on the ratio of electricity:heat produced, this additional electric demand in some cases is higher than the electricity generated by the micro-CHP. In other cases, it is lower. The net result is that in some cases, the consumption of electricity from the grid goes down when micro-CHP is introduced; but in other cases, it goes up.

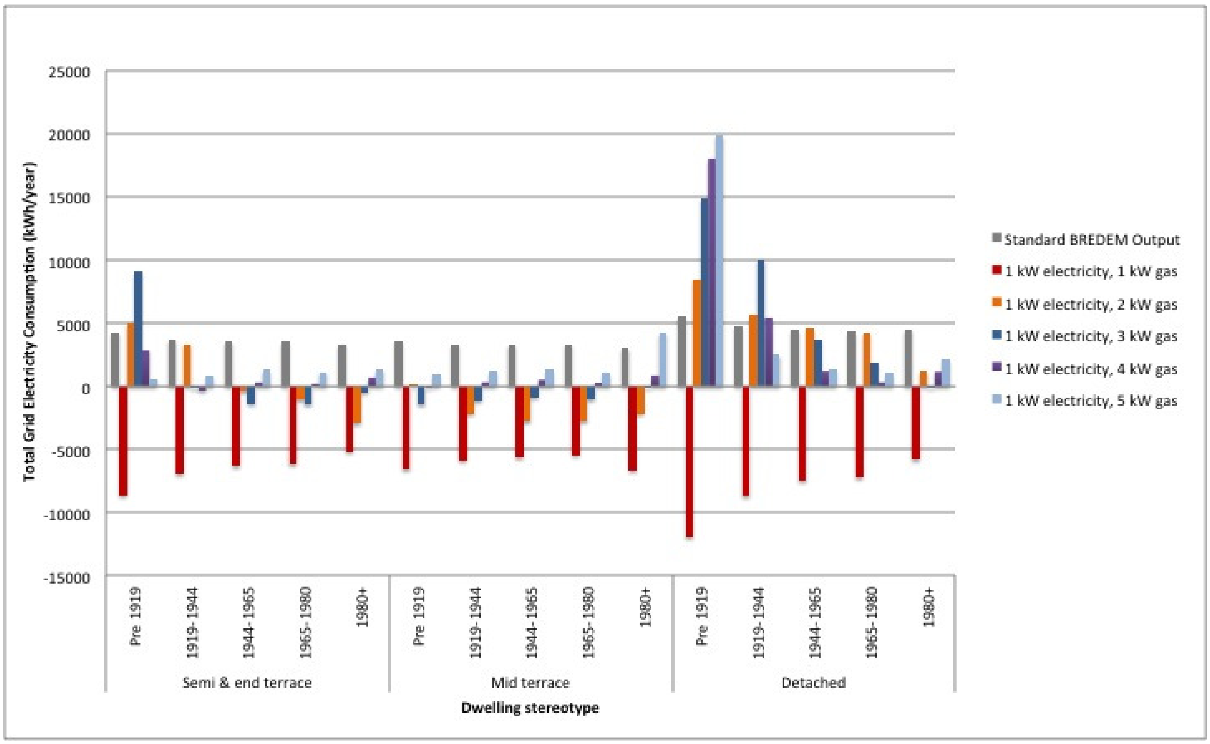

Figure 53 Micro-CHP: modelled impact of varying heat output on grid electricity consumption for a constant peak power of 1 kW

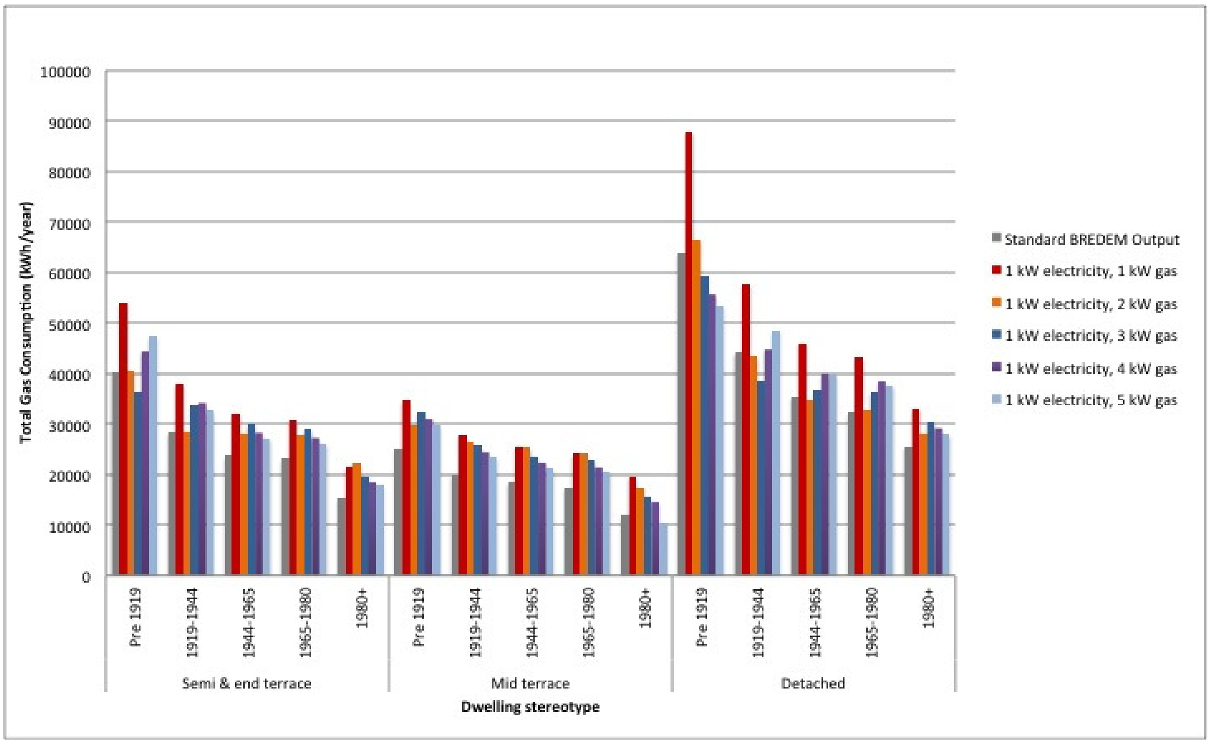

Figure 54 Micro-CHP: modelled impact of varying heat output on gas consumption for a constant peak power of 1 kW

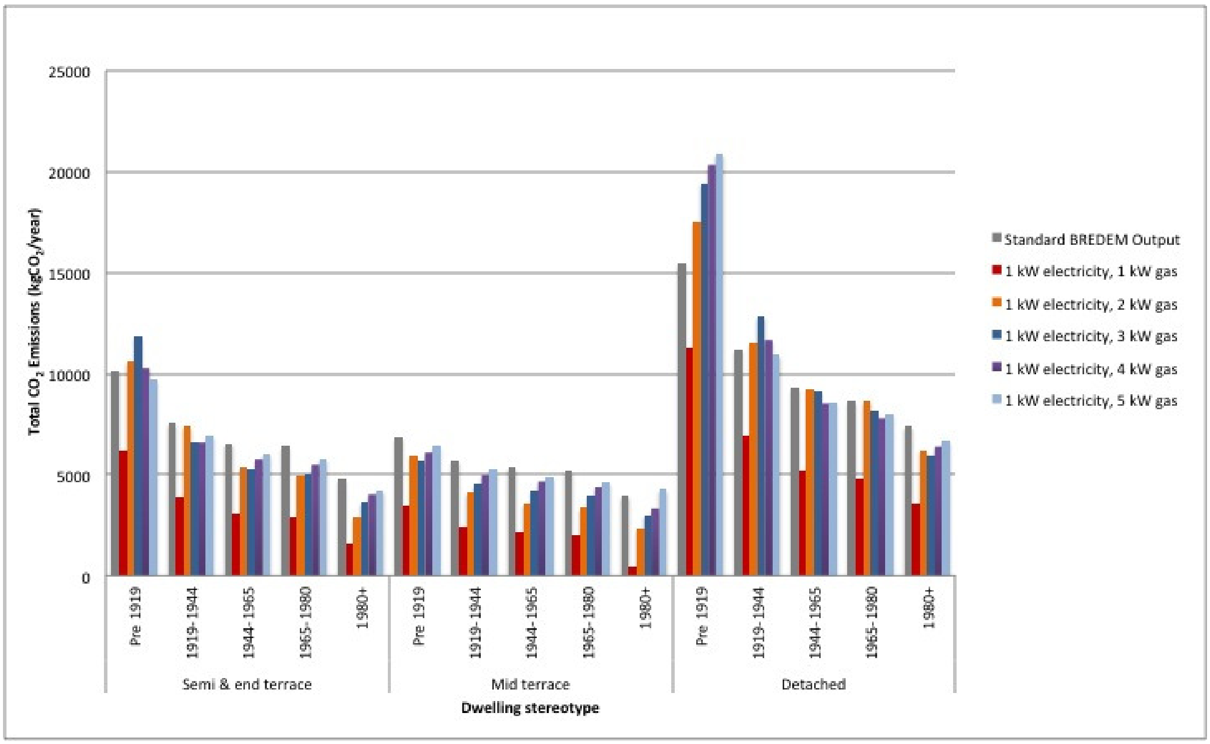

Figure 55 Micro-CHP: modelled impact of varying heat output on CO_2 emissions for a constant peak power of 1 kW

A.5.2 Varying peak electrical power, with a constant peak heat output of 5 kW_{th}

As demonstrated in the graphs below, total energy consumption and CO_2 emissions decrease linearly with electricity output for a constant heat power of 5 kW. The majority of dwellings appear to produce surplus electricity, thus becoming net exporters of electricity. Similarly, as power to heat output ratios approach 1:1, higher energy and carbon savings are achieved.

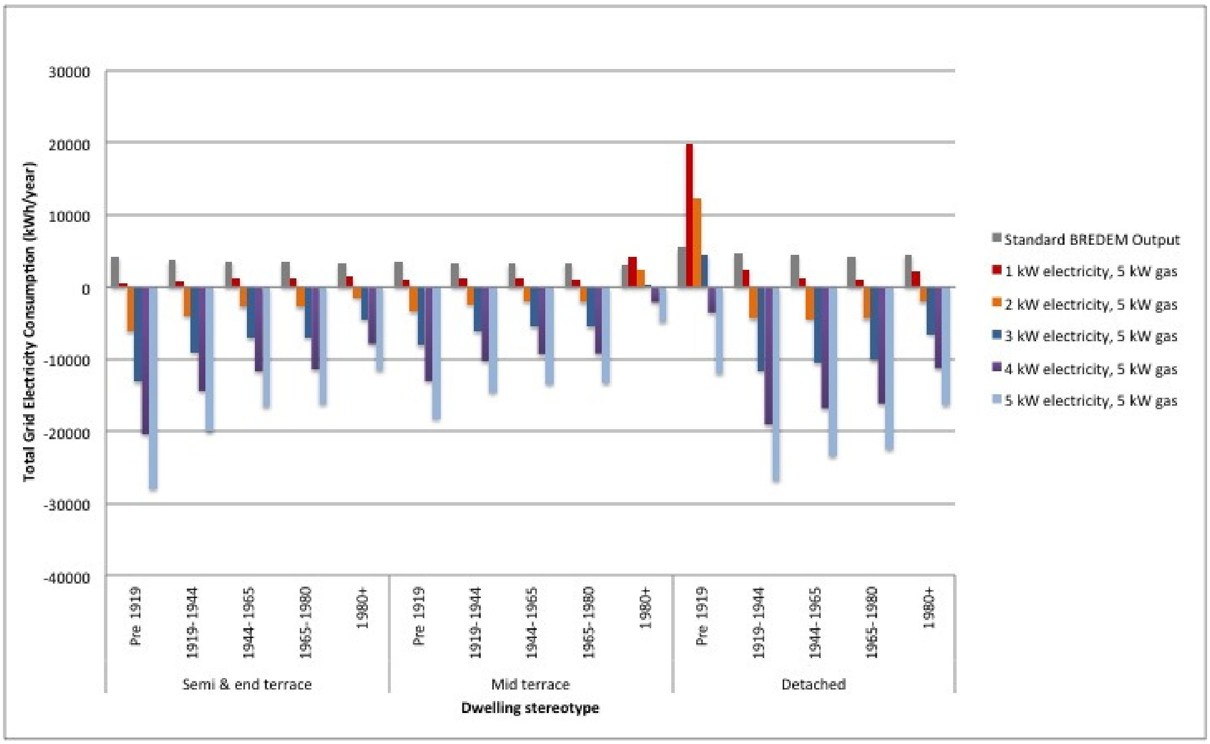

Figure 56 Micro-CHP: modelled impact of varying heat output on grid electricity consumption for a constant peak power of 5 kW

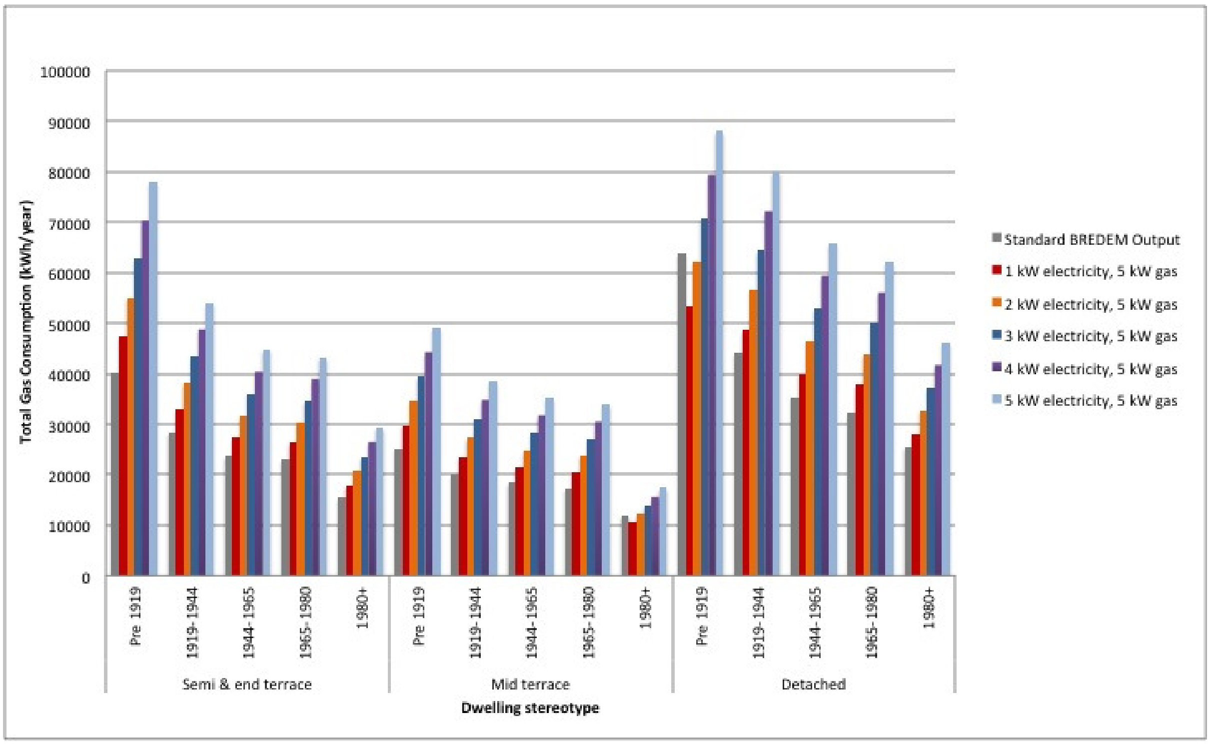

Figure 57 Micro-CHP: modelled impact of varying heat output on gas consumption for a constant peak power of 5 kW

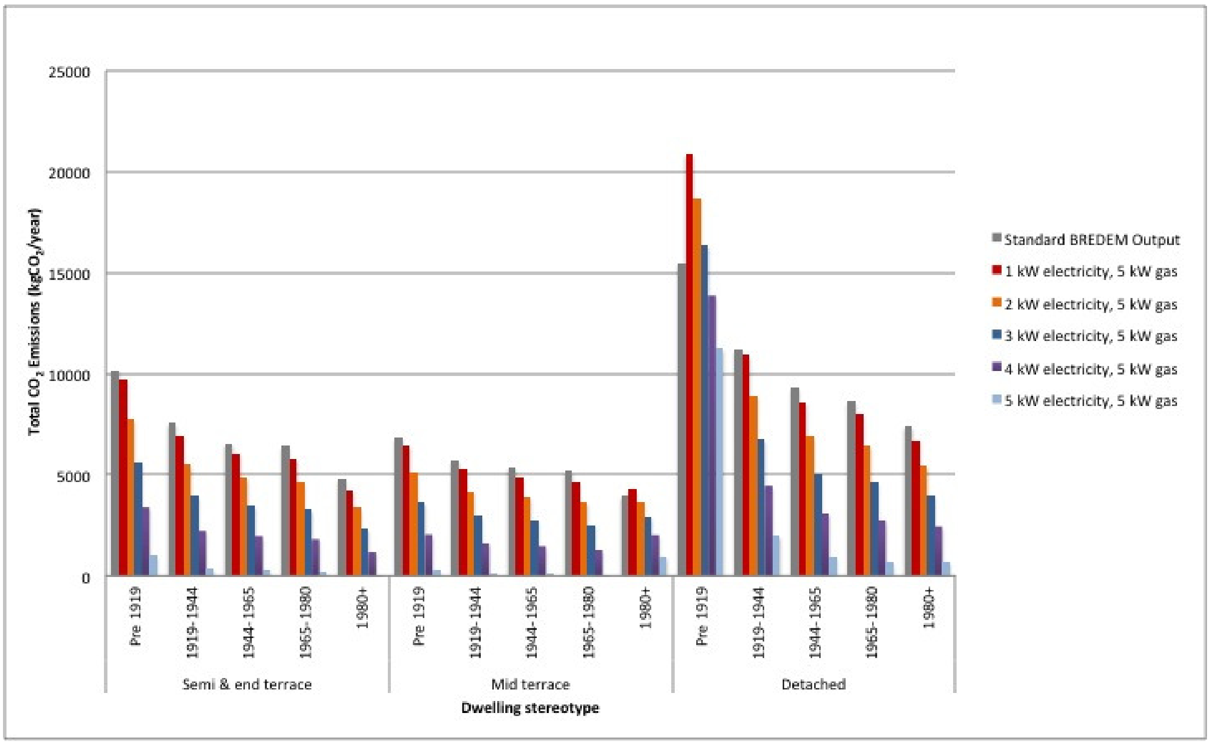

Figure 58 Micro-CHP: modelled impact of varying heat output on CO_2 emissions for a constant peak power of 5 kW

A.6 Heat Pumps

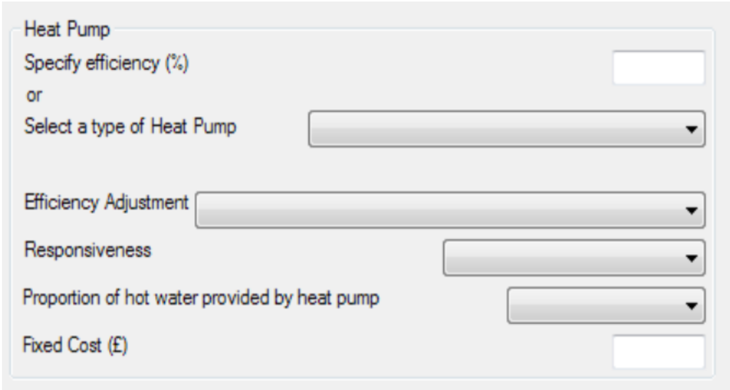

Figure 59 Snapshot of the model interface (HP section)

The two cases chosen were air source heat pump (air to water) and ground source heat pump (ground to water). For each type of heat pump, the following cases were considered: different proportion for the secondary heating and different COP. The COP was set between 2.5 and 3.8 (equivalent to electrical efficiencies of 250% to 380%). As demonstrated in the graphs below for ASHP, total energy consumption and CO_2 emissions decrease linearly with the different efficiency considered.

A6.1 ASHP – Proportion of DHW provided: 100%

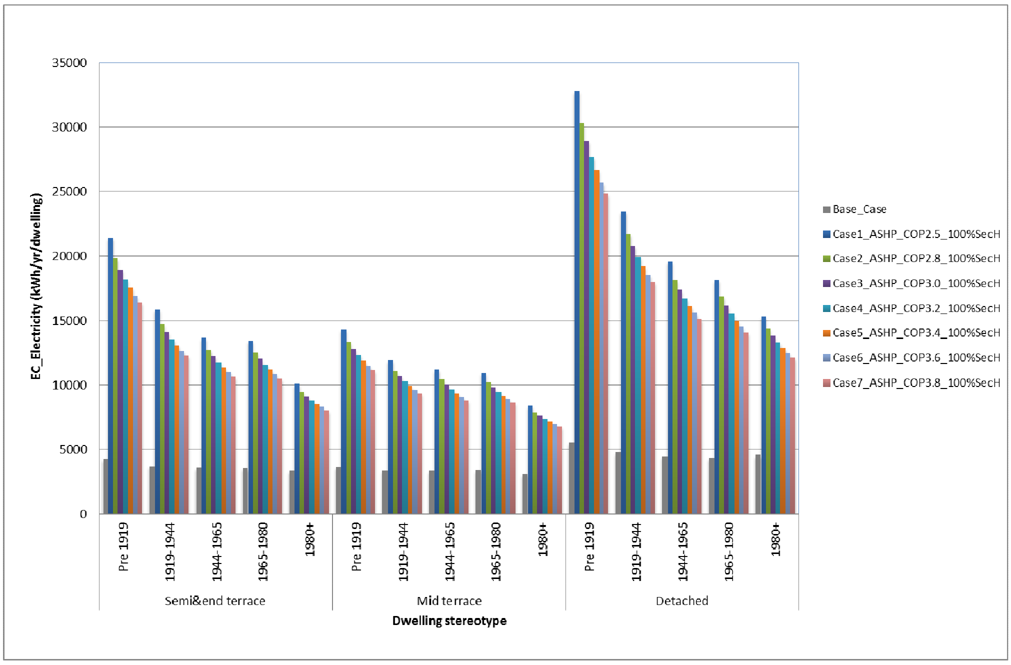

Figure 60
ASHP: modelled impact of varying COP (DHW 100%) on Electricity Energy Consumption

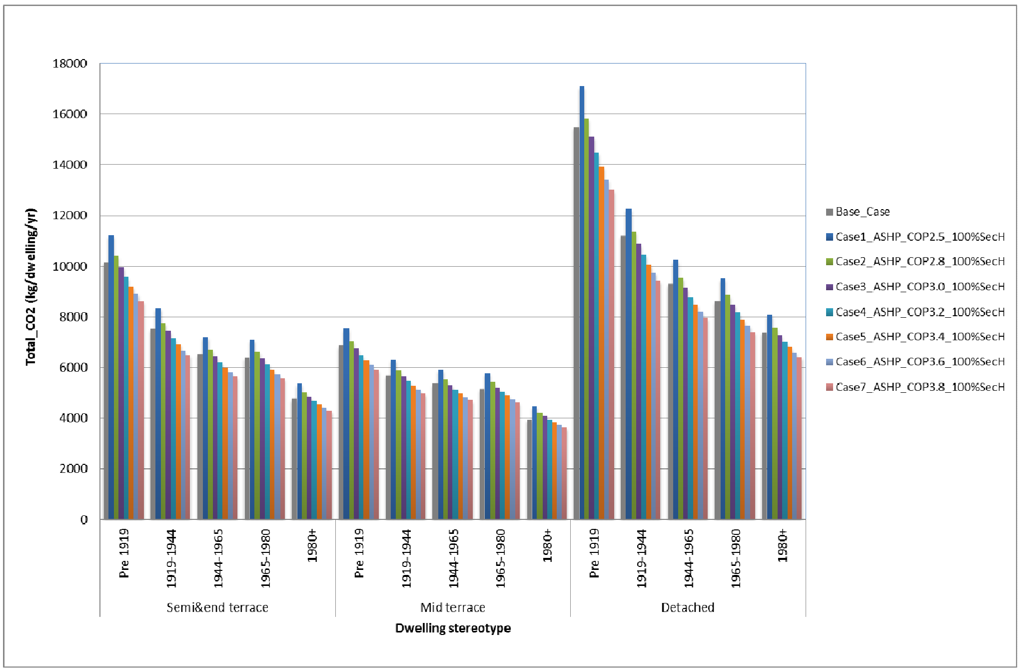

Figure 61 ASHP: modelled impact of varying COP (DHW 100%) on Total CO_2 emissions

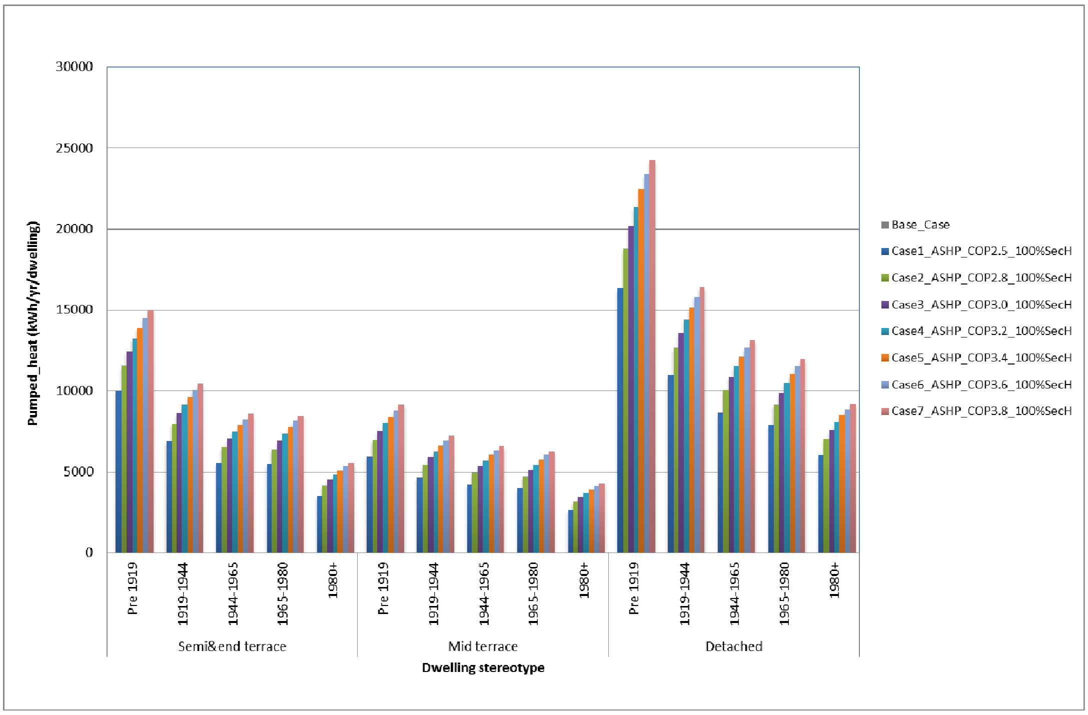

Figure 62 ASHP: modelled impact of varying COP (DHW 100%) on pumped heat

A6.2 ASHP – Proportion of DHW provided: 50%

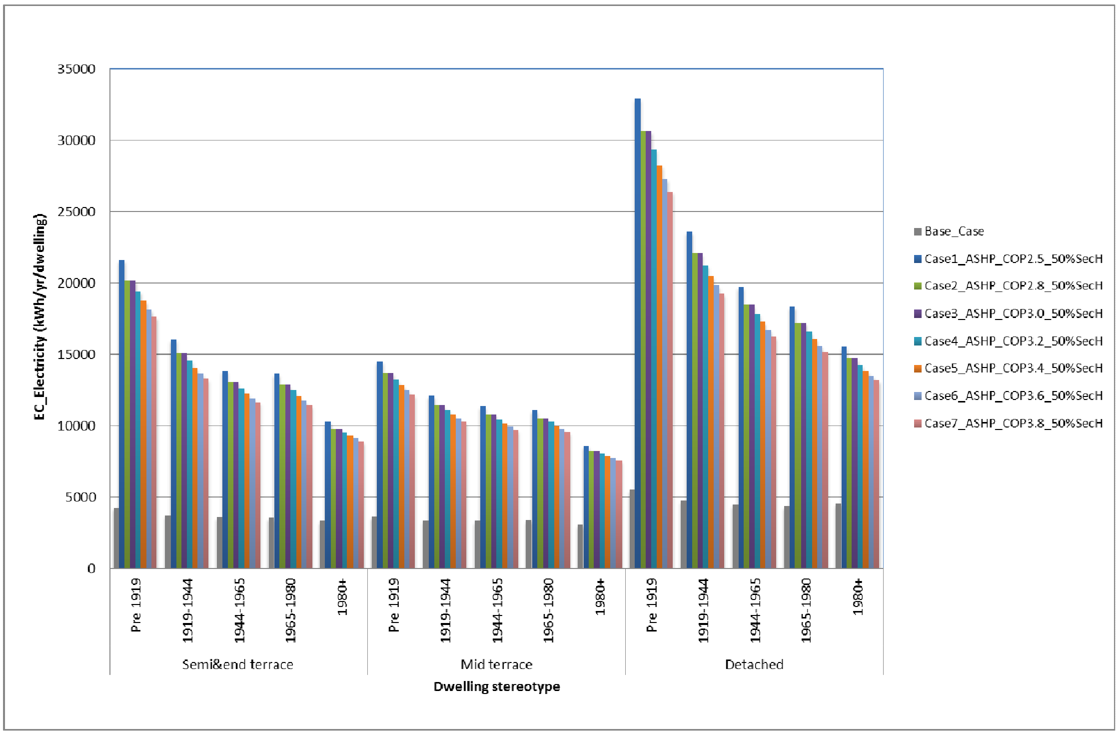

Figure 63 ASHP: modelled impact of varying COP (DHW 50%) on Electricity Energy Consumption

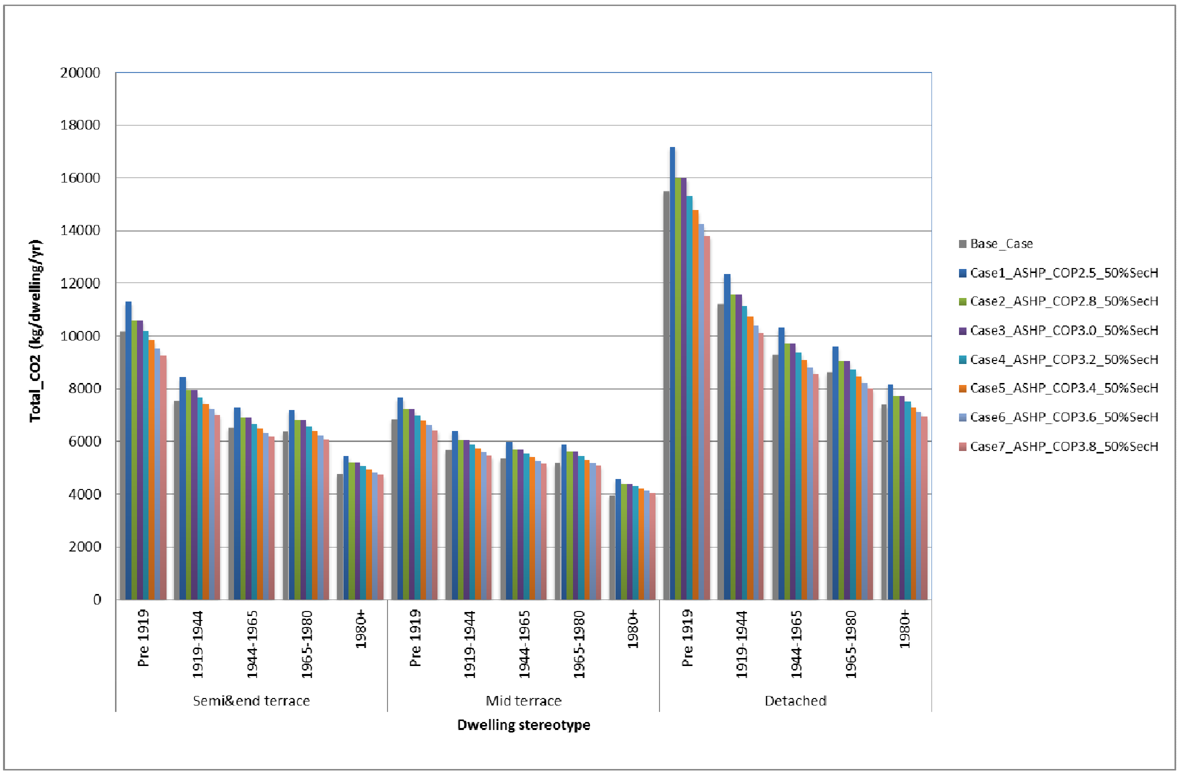

Figure 64 ASHP: modelled impact of varying COP (DHW 100%) on Total CO_2 emissions

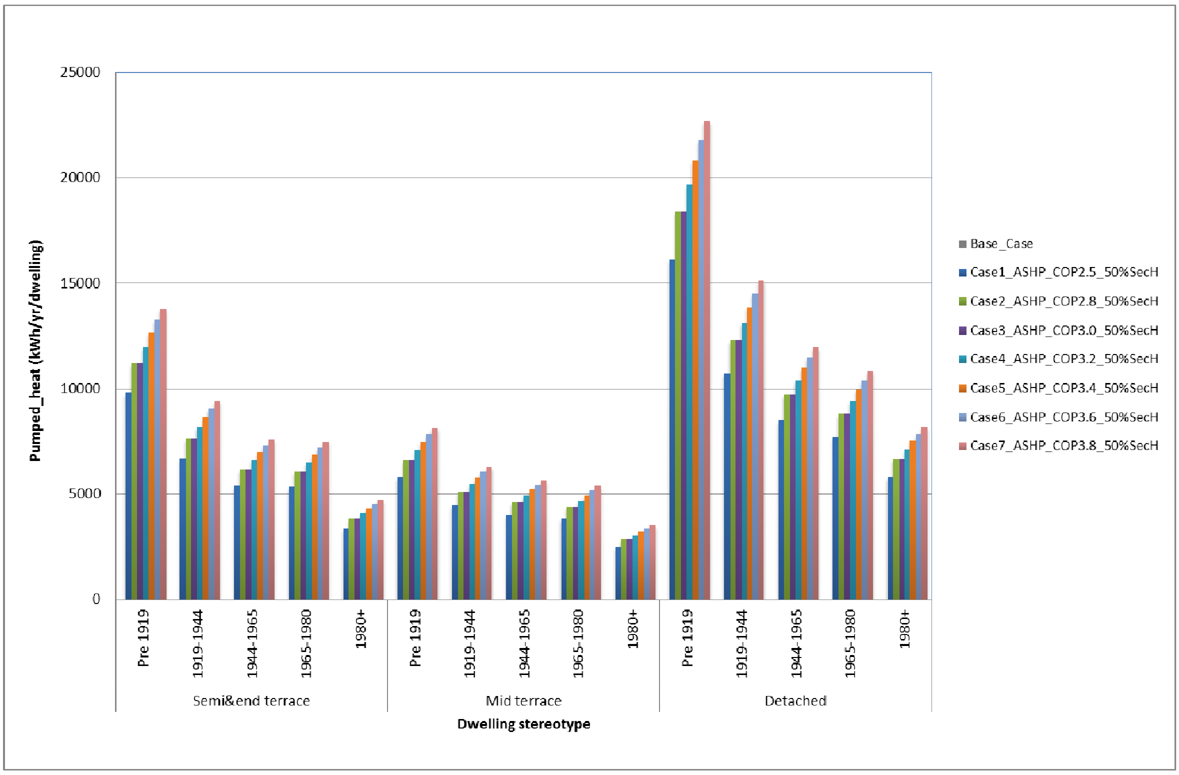

Figure 65 ASHP: modelled impact of varying COP (DHW 50%) on pumped heat

A6.2 ASHP – Proportion of DHW provided: 0%

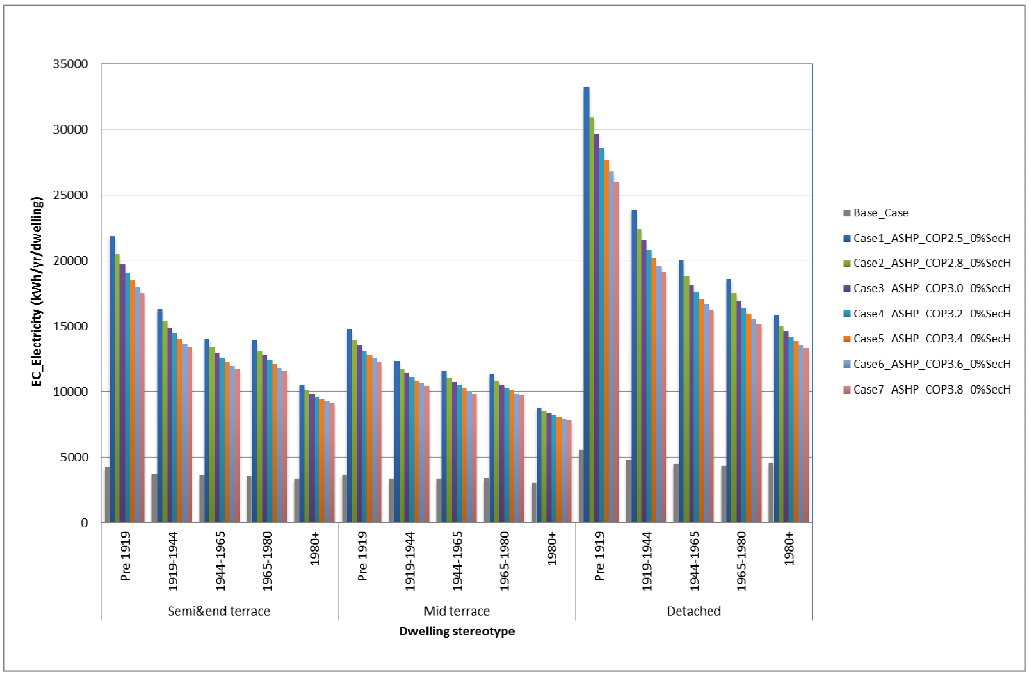

Figure 66 ASHP: modelled impact of varying COP (DHW 0%) on Electricity Energy Consumption

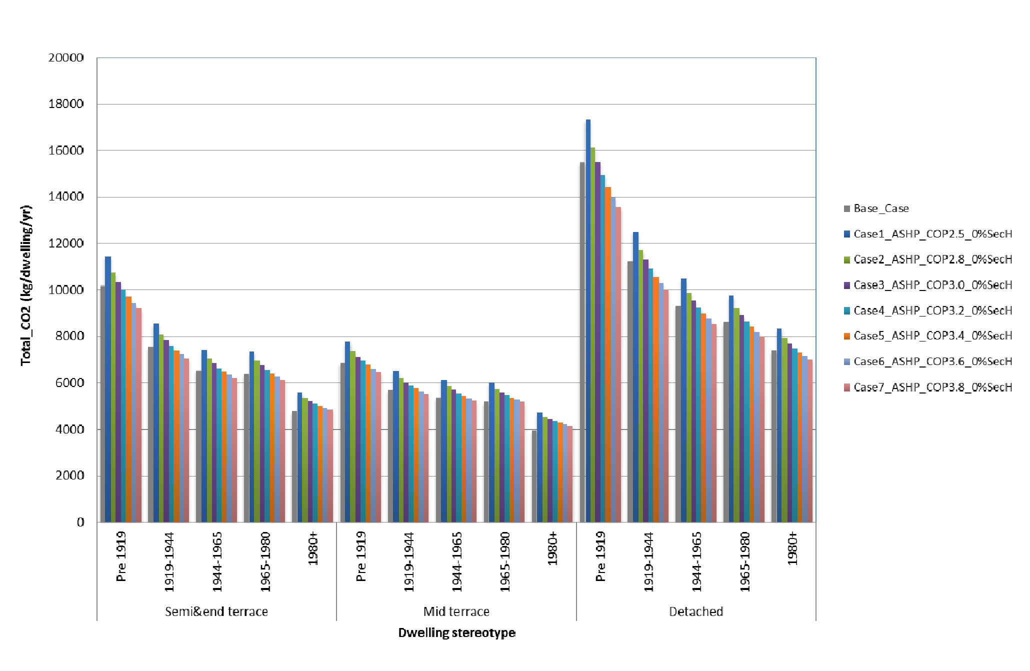

Figure 67 ASHP: modelled impact of varying COP (DHW 0%) on Total CO_2 emissions

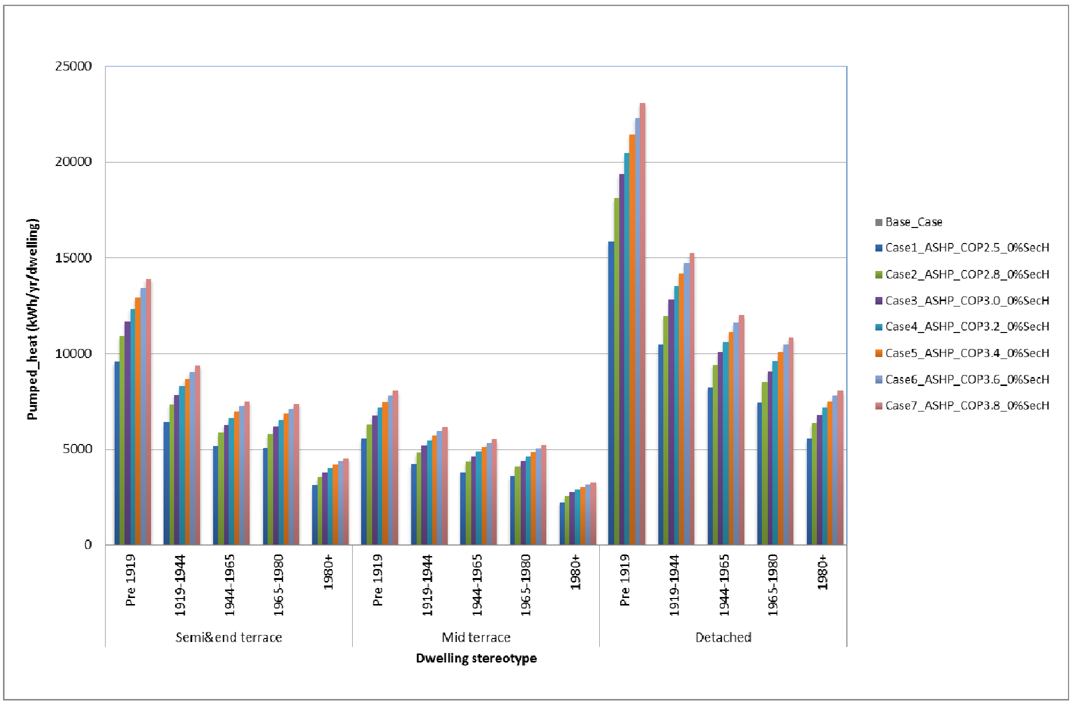

Figure 68 ASHP: modelled impact of varying COP (DHW 0%) on pumped heat

A6.3 GSHP – Proportion of DHW provided: 100%

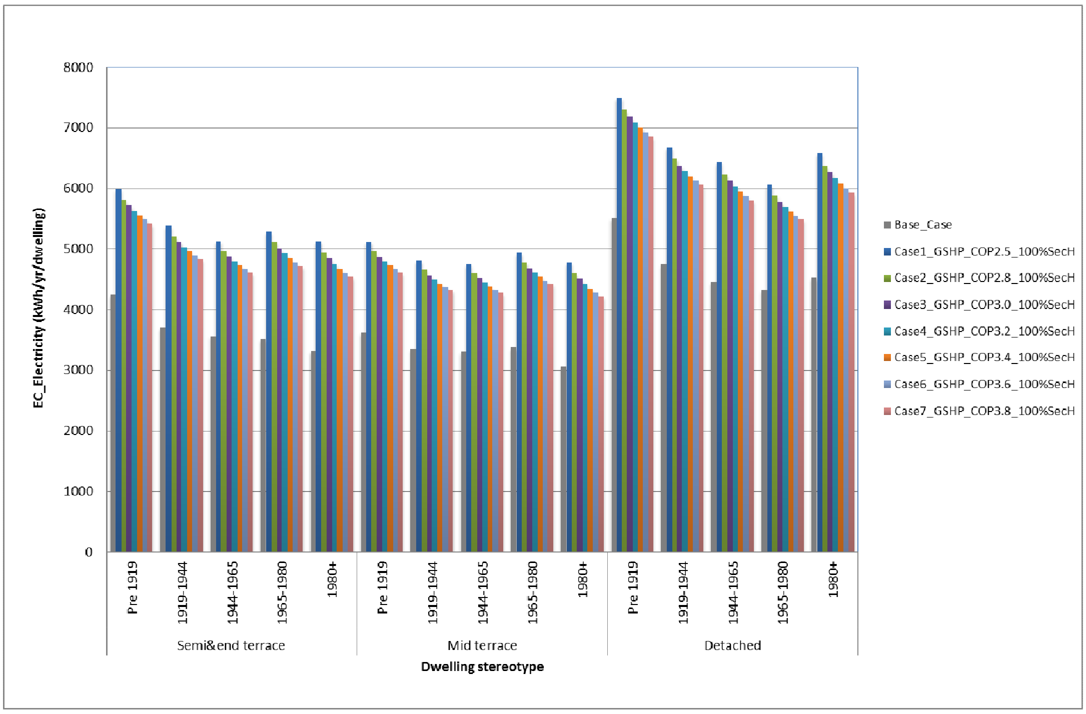

Figure 69 GSHP: modelled impact of varying COP (DHW 100%) on Electricity Energy Consumption

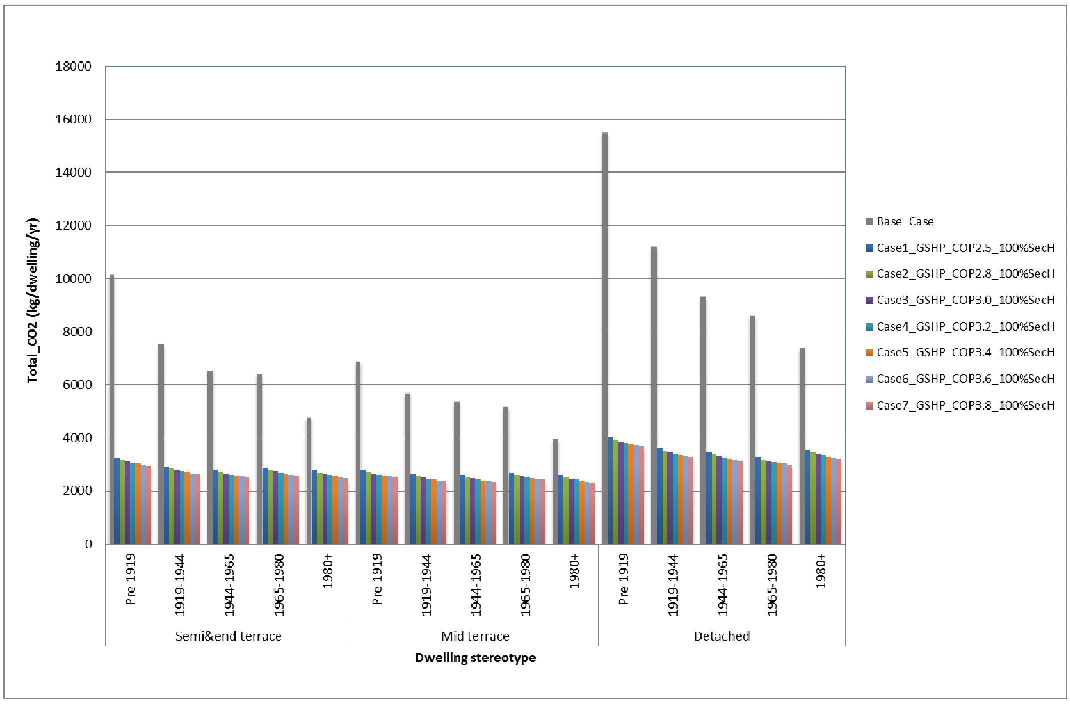

Figure 70 GSHP: modelled impact of varying COP (DHW 100%) on Total CO_2 emissions

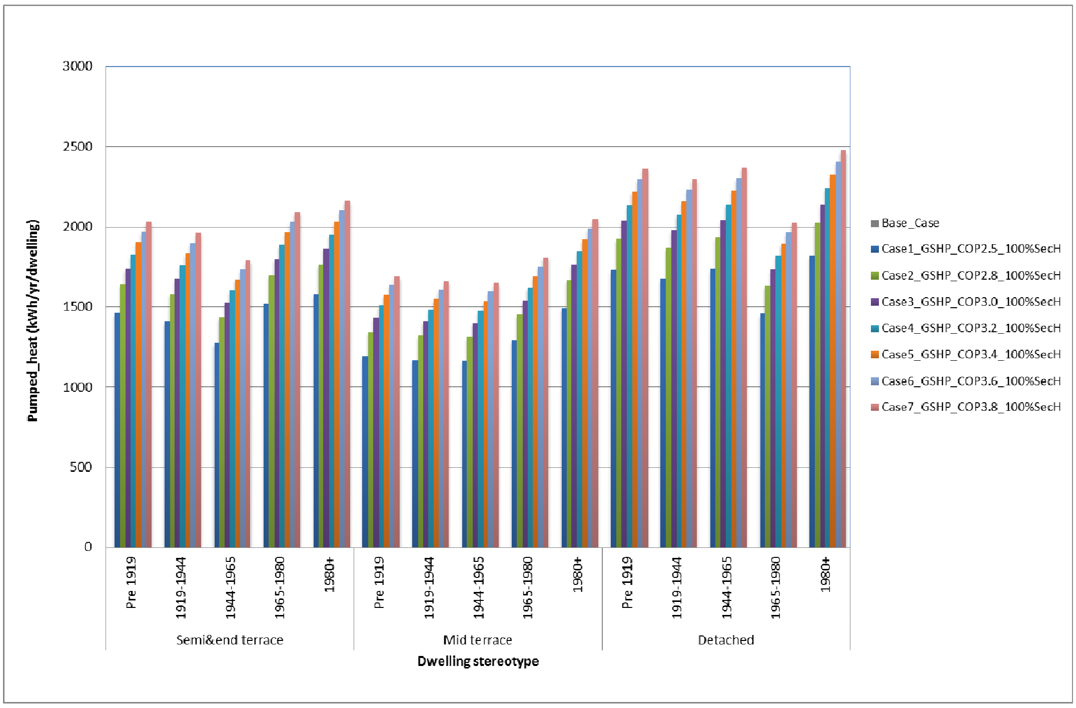

Figure 71 **GSHP: modelled impact of varying COP (DHW 100%) on pumped heat**

A6.4 GSHP – Proportion of DHW provided : 50% Secondary Heating

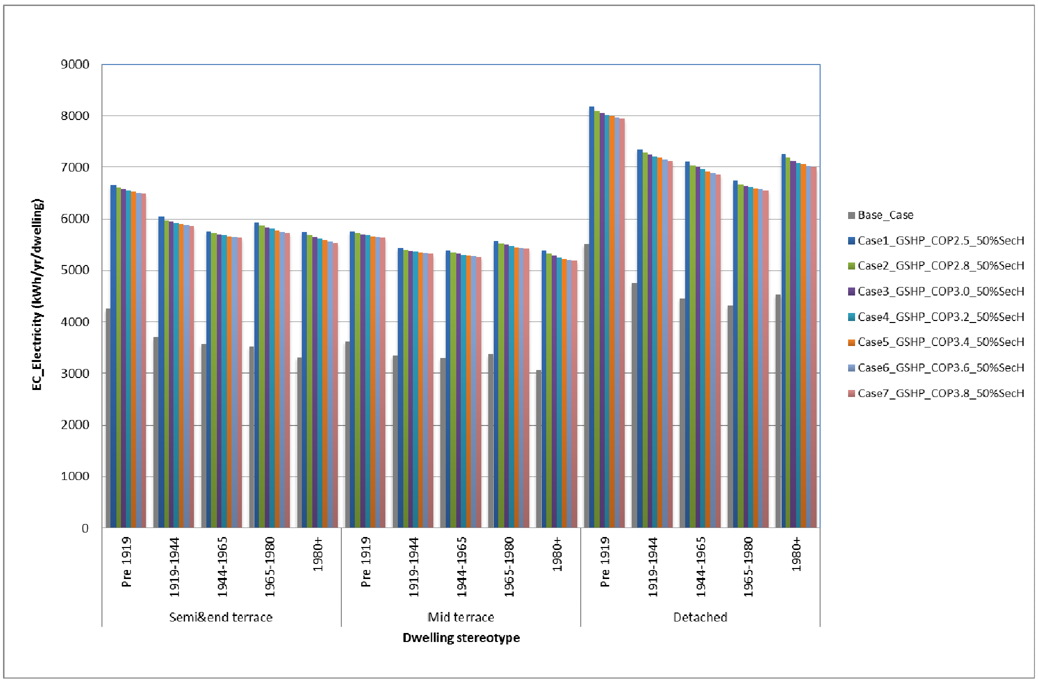

Figure 72 **GSHP: modelled impact of varying COP (DHW 50%) on Electricity Energy Consumption**

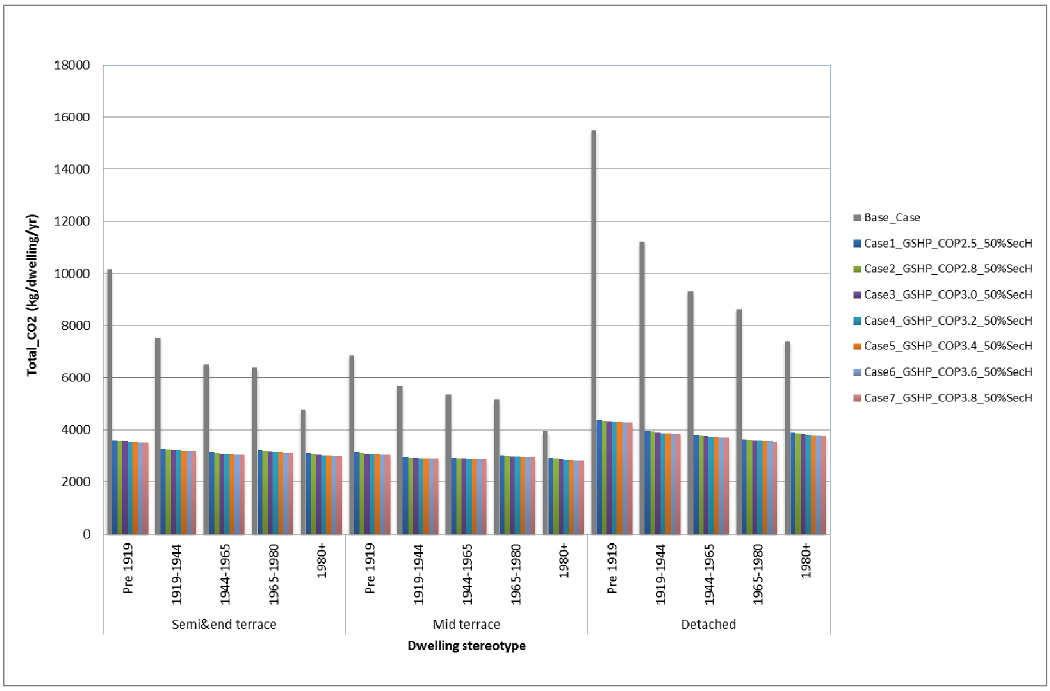

Figure 73 GSHP: modelled impact of varying COP (DHW 50%) on Total CO_2 emissions

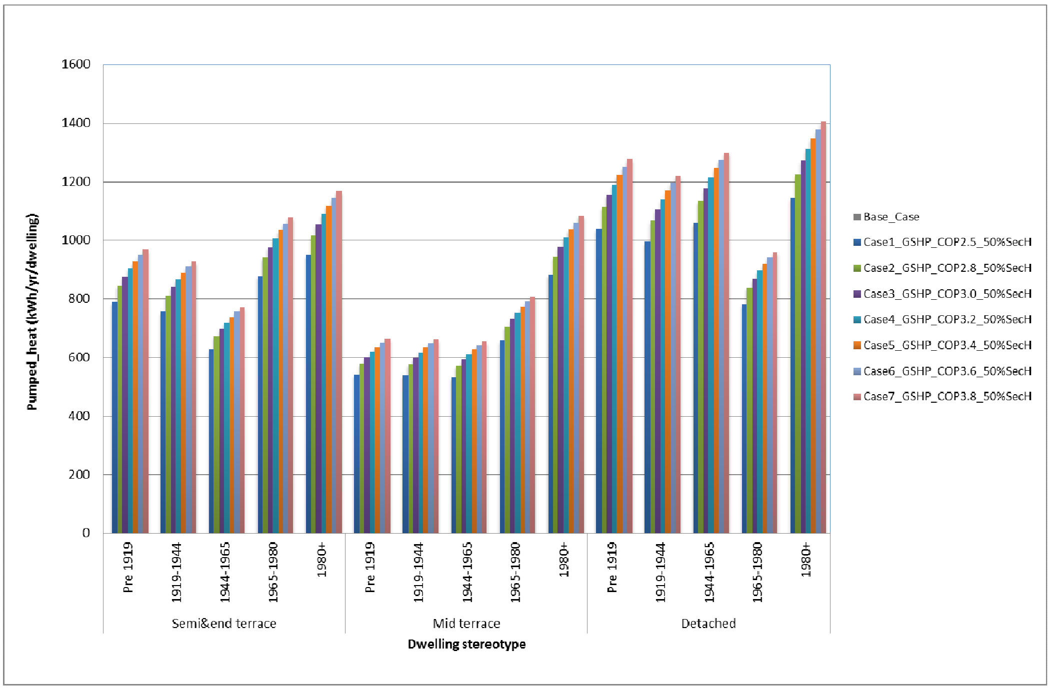

Figure 74 GSHP: modelled impact of varying COP (DHW 50%) on pumped heat

A6.5 GSHP – Proportion of DHW provided: 0%

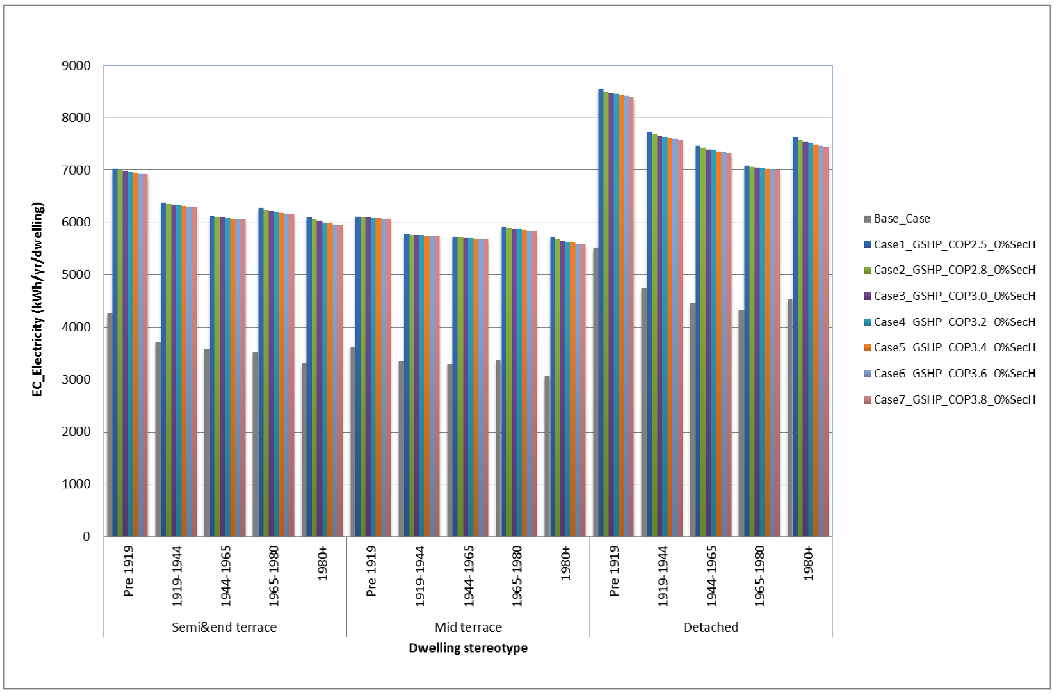

Figure 75 **GSHP: modelled impact of varying COP (DHW 0%) on Electricity Energy Consumption**

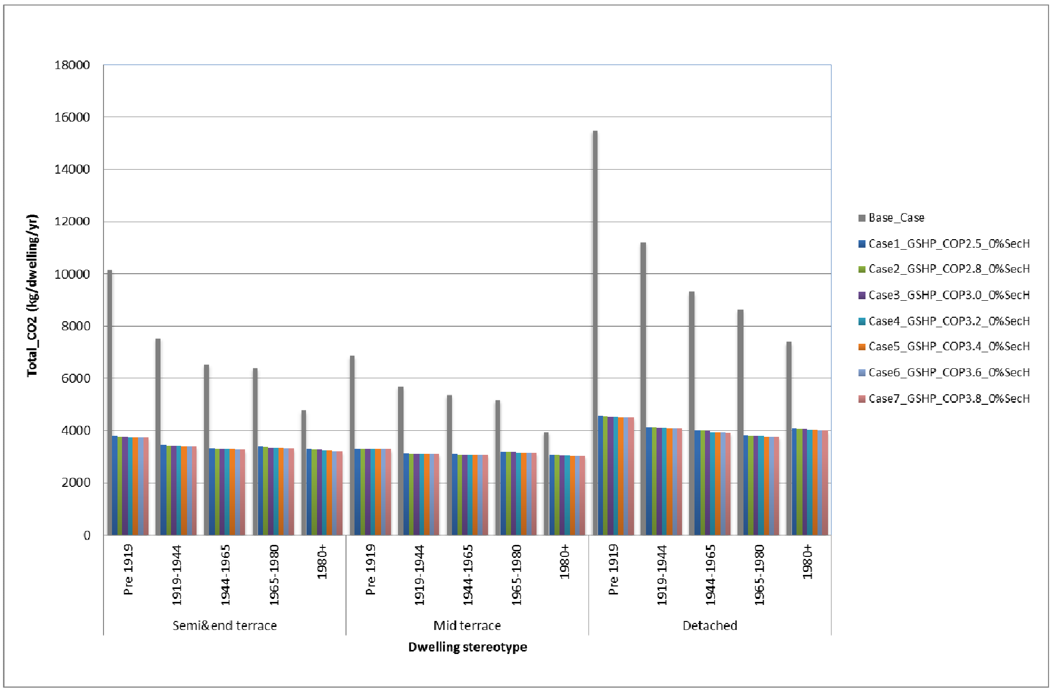

Figure 76 **GSHP: modelled impact of varying COP (DHW 0%) on Total CO_2 emissions**

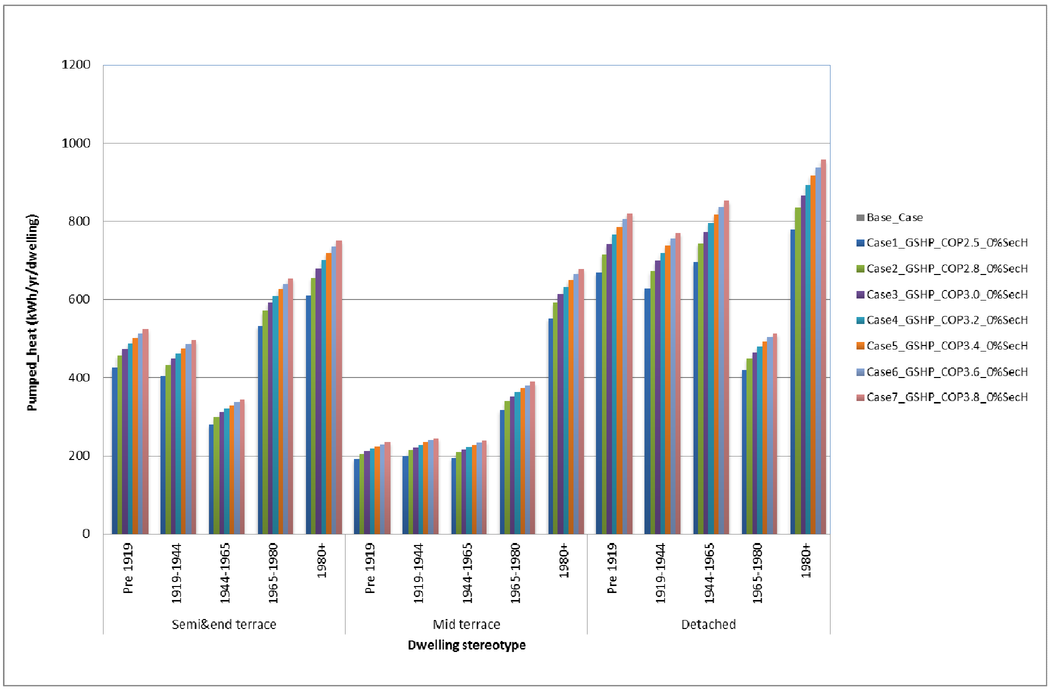

Figure 77 GSHP: modelled impact of varying COP (DHW 0%) on pumped heat

Appendix B Versions of the model

There have been six versions of the model to date. This report deals with the latest version: µDE Alpha V6.1:Stock.

The model has had several corrections made to the algorithms, from previous versions.

B.1 Result-significant differences

µDE Alpha V2 ran with 20 cases: 15 synthetic houses and 5 flats. µDE Alpha V6.1:Stock runs with those 20 cases, or with 12,443 real houses from EHCS.

µDE Alpha V2 allows heat supplied by solar thermal to exceed demand in summer months, thus offsetting demand in other months. This is impossible in real life, without a district-wide thermal store. µDE Alpha V6.1:Stock caps total solar-thermal heat provided in a single month at the level of that month's hot-water demand.

µDE Alpha V2 assumes a carbon intensity of electricity of zero by default. µDE Alpha V6.1:Stock assumes 517gCO_2/kWh.

µDE Alpha V2 crashed for certain dwellings with micro-CHP, due to a code bug. Fixed in µDE Alpha V6.1:Stock.

µDE Alpha V2 crashed if solar thermal met 100% of a month's hot water demand. Fixed in µDE Alpha V6.1:Stock.

B.2 Other differences

µDE Alpha V2 takes 14 hours with EHCS; µDE Alpha V6.1:Stock has some runtime optimisations which do not affect the calculation in any way, that means that a model run takes 1 minute.

µDE Alpha V2 would not allow a case number above 16 bits (i.e. case numbers <= 32767). µDE Alpha V6.1:Stock allows 32-bit integers (up to 10^9)

µDE Alpha V2 will not accept inputs via a text control file, only via user interaction µDE Alpha V6.1:Stock will accept a command-line argument passing the name of a control file, enabling unattended batch running.

µDE Alpha V2 does not log what the parameters were in a particular scenario. µDE Alpha V6.1:Stock records all of the input parameters for a particular run, in a form that the model can re-use later to reproduce the run.

Appendix C Model inputs

The table below shows the inputs that are required for each technology to run the µDE model

TECHNOLOGIES	Inputs that are required
Solar Thermal	Type of collector Collector area Tilt of collector Collector orientation Fixed cost Unit cost
PV	Tilt of collector Collector orientation Peak power Collector area (for cost only) Fixed cost Unit cost
Biomass	Type of fuel Capital cost Fixed cost Unit cost Peak thermal power Efficiency
micro-CHP	Capital cost Fixed cost Unit cost Peak power Ratio of electric power output: heat power output
ASHP	Capital cost Fixed cost Unit cost
GSHP	Capital cost Fixed cost Unit cost Size of plot Peak electric power
Wind Turbines	Capital cost Fixed cost Unit cost Rotor Diameter Hub Height

Appendix D Detailed scenario outputs

Note that owing to time constraints during the production of this report, some of these model runs were made with version 5.1 of the model, and others with version 6.1. The tables below show the percentage changes as forecast by the model. The absolute figures have been rebased to ensure that all scenarios are measured relative to a common base. Hence, new runs with version 6.1 or later will produce different absolute figures.

2010 Scenario

units are TWh/y except where stated otherwise		CO2		Fuel cost		solar thermal heat	pv elec	mchp elec	mchp heat	biomass heat	micro wind elec	pumped heat	Power		Grid elec		Gas		Oil		Solid	
Scenario	% takeup	MTCO2/y	Change	£bn/y	Change									Change		Change		Change		Change		Change
Base		156		29									563		129		387		39		9	
ASHP	100%	151	(-3%)	33	(+17%)	-	-	-	-	-	-	142	443	(-21%)	288	(+124%)	12	(-97%)	-	(-100%)	-	(-100%)
biomass	16%	136	(-13%)	31	(+9%)	-	-	-	-	118	-	-	590	(+5%)	119	(-8%)	336	(-13%)	13	(-67%)	122	(+1277%)
GSHP	37%	136	(-13%)	27	(-6%)	-	-	-	-	-	-	98	507	(-10%)	168	(+31%)	226	(-42%)	10	(-73%)	4	(-53%)
micro-CHP	56%	139	(-11%)	24	(-16%)	-	-	55	274	-	-	-	645	(+15%)	69	(-47%)	519	(+34%)	1	(-96%)	1	(-89%)
PV	13%	152	(-3%)	28	(-3%)	-	8	-	-	-	-	0	563	(-)	121	(-6%)	387	(-)	39	(-)	9	(-)
solar thermal	100%	144	(-8%)	26	(-9%)	24	-	-	-	-	-	0	563	(-0%)	106	(-18%)	385	(-0%)	39	(-)	9	(-)
wind	11%	154	(-1%)	28	(-2%)	-	-	-	-	-	4	0	563	(-)	124	(-3%)	387	(-)	39	(-)	9	(-)

Above are technical constraints. Below are technical & financial constraints

units are TWh/y except where stated otherwise		CO2		Fuel cost		solar thermal heat	pv elec	mchp elec	mchp heat	biomass heat	micro wind elec	pumped heat	Power		Grid elec		Gas		Oil		Solid	
Scenario	% takeup	MTCO2/y	Change	£bn/y	Change									Change		Change		Change		Change		Change
Base		156		29									563		129		387		39		9	
ASHP	4%	154	(-2%)	28	(-2%)	-	-	-	-	-	-	6	562	(-0%)	125	(-3%)	385	(-0%)	38	(-1%)	9	(-0%)
biomass	0%	156	(-0%)	29	(-0%)	-	-	-	-	1	-	-	563	(+0%)	128	(-0%)	387	(-0%)	39	(-)	9	(+7%)
GSHP	1%	154	(-1%)	28	(-1%)	-	-	-	-	-	-	5	562	(-0%)	126	(-2%)	386	(-0%)	35	(-8%)	9	(-)
micro-CHP	30%	141	(-10%)	25	(-13%)	-	-	27	136	-	-	-	596	(+6%)	86	(-33%)	463	(+20%)	17	(-57%)	3	(-66%)
PV	0%	156	(-)	29	(-)	-	-	-	-	-	-	-	563	(-)	129	(-)	387	(-)	39	(-)	9	(-)
solar thermal	0%	156	(-)	29	(-)	-	-	-	-	-	-	-	563	(-)	129	(-)	387	(-)	39	(-)	9	(-)
wind	0%	156	(-)	29	(-)	-	-	-	-	-	-	-	563	(-)	129	(-)	387	(-)	39	(-)	9	(-)

Green Deal scenario

units are TWh/y except where stated otherwise		CO2		Fuel cost		solar thermal heat	pv elec	mchp elec	mchp heat	biomass heat	micro wind elec	pumped heat	Power		Grid elec		Gas		Oil		Solid	
Scenario	% takeup	MTCO2/y	Change	£bn/y	Change									Change		Change		Change		Change		Change
Green Deal	100%	135		25									471		120		313		31		7	
ASHP	100%	132	(-2%)	29	(+17%)	-	-	-	-	-	-	115	377	(-20%)	250	(+108%)	12	(-96%)	-	(-100%)	-	(-100%)
Biomass	16%	119	(-12%)	27	(+8%)	-	-	-	-	94	-	-	492	(+5%)	113	(-6%)	273	(-13%)	10	(-67%)	97	(+1251%)
GSHP	37%	118	(-12%)	24	(-5%)	-	-	-	-	-	-	79	427	(-9%)	152	(+27%)	184	(-41%)	8	(-73%)	3	(-53%)
MicroCHP	56%	116	(-14%)	20	(-19%)	-	-	46	230	-	-	-	537	(+14%)	60	(-50%)	429	(+37%)	1	(-96%)	1	(-88%)
Solar thermal	100%	124	(-8%)	22	(-10%)	22	-	-	-	-	-	0	471	(-0%)	99	(-17%)	311	(-0%)	31	(-)	7	(-)

Above are technical constraints. Below are technical & financial constraints

units are TWh/y except where stated otherwise		CO2		Fuel cost		solar thermal heat	pv elec	mchp elec	mchp heat	biomass heat	micro wind elec	pumped heat	Power		Grid elec		Gas		Oil		Solid	
Scenario	% takeup	MTCO2/y	Change	£bn/y	Change									Change		Change		Change		Change		Change
Green Deal	100%	135		25									471		120		313		31		7	
ASHP	3%	133	(-1%)	25	(-2%)	-	-	-	-	-	-	4	471	(+0%)	117	(-3%)	312	(-0%)	31	(-)	7	(-)
Biomass	0%	135	(-)	25	(-)	-	-	-	-	-	-	-	471	(-)	120	(-)	313	(-)	31	(-)	7	(-)
GSHP	1%	134	(-1%)	25	(-1%)	-	-	-	-	-	-	2	471	(-0%)	119	(-1%)	313	(-0%)	30	(-2%)	7	(-)
MicroCHP	19%	125	(-7%)	23	(-9%)	-	-	16	82	-	-	-	490	(+4%)	94	(-22%)	367	(+17%)	9	(-70%)	4	(-48%)
Solar thermal	0%	135	(-)	25	(-)	-	-	-	-	-	-	-	471	(-)	120	(-)	313	(-)	31	(-)	7	(-)

Note that as PV and micro-wind do not interact with the thermal properties of dwellings, their output does not change if thermal efficiency measures are implemented, and hence they have not been modelled in this scenario

2040 scenario

units are TWh/y except where stated otherwise		CO2		Fuel cost		solar thermal heat	pv elec	mchp elec	mchp heat	biomass heat	micro wind elec	pumped heat	Power		Grid elec		Gas		Oil		Solid	
Scenario	% takeup	MTCO2/y	Change	£bn/y	Change									Change		Change		Change		Change		Change
base2040	100%	78		27		-	-	-	-	-	-	0	471		120		313		31		7	
ashp2040	100%	15	(-81%)	32	(+17%)	-	-	-	-	-	-	115	377	(-20%)	250	(+108%)	12	(-96%)	-	(-100%)	-	(-100%)
bio2040	16%	66	(-16%)	29	(+6%)	-	-	-	-	85	-	-	484	(+3%)	113	(-6%)	273	(-13%)	10	(-67%)	88	(+1128%)
gshp2040	37%	47	(-40%)	26	(-5%)	-	-	-	-	-	-	79	427	(-9%)	152	(+27%)	184	(-41%)	8	(-73%)	3	(-53%)
temchp2040	56%	97	(+23%)	18	(-35%)	-	-	95	237	-	-	-	591	(+26%)	11	(-91%)	484	(+55%)	1	(-96%)	1	(-88%)
pv2040	13%	78	(-1%)	26	(-4%)	-	8	-	-	-	-	0	471	(-)	112	(-7%)	313	(-)	31	(-)	7	(-)
sth2040	100%	77	(-2%)	25	(-10%)	23	-	-	-	-	-	0	471	(-0%)	98	(-18%)	311	(-0%)	31	(-)	7	(-)
wind2040	11%	78	(-0%)	27	(-3%)	-	-	-	-	-	6	0	471	(-)	114	(-5%)	313	(-)	31	(-)	7	(-)

Above are technical constraints. Below are technical & financial constraints

(units are TWh/y except where stated)		CO2		Fuel cost		solar thermal heat	pv elec	mchp elec	mchp heat	biomass heat	micro wind elec	pumped heat	Power		Grid elec		Gas		Oil		Solid	
Scenario	% takeup	MTCO2 /y	Change	(£bn/y)	Change									Change		Change		Change		Change		Change
2040 base	100%	78		27		-	-	-	-	-	-	0	471		120		313		31		7	
ASHP	4%	78	(-0%)	27	(-2%)	-	-	-	-	-	-	5	471	(+0%)	117	(-3%)	312	(-0%)	31	(-)	7	(-)
biomass	0%	78	(-0%)	27	(-0%)	-	-	-	-	1	-	-	471	(+0%)	120	(-0%)	313	(-0%)	31	(-)	8	(+13%)
GSHP	1%	77	(-2%)	27	(-1%)	-	-	-	-	-	-	5	469	(-0%)	119	(-1%)	312	(-0%)	27	(-13%)	7	(-)
micro-CHP	55%	97	(+23%)	18	(-35%)	-	-	91	228	-	-	-	586	(+25%)	11	(-91%)	480	(+53%)	3	(-89%)	1	(-85%)
PV	0%	78	(-)	27	(-)	-	-	-	-	-	-	-	471	(-)	120	(-)	313	(-)	31	(-)	7	(-)
solar thermal	0%	78	(-)	27	(-)	-	-	-	-	-	-	-	471	(-)	120	(-)	313	(-)	31	(-)	7	(-)
wind	0%	78	(-)	27	(-)	-	-	-	-	-	-	-	471	(-)	120	(-)	313	(-)	31	(-)	7	(-)