Programme Area: Distributed Energy

Project: Macro DE

Title: GB Benefits Case for Macro DE

Abstract:

This deliverable is number 1 of 3 in Work Package 5. Its objective is to identify and quantify the potential for distributed energy across Great Britain with a range of currently available and mature technologies. The work pulls together the findings from all 4 preceding work packages to provide a holistic analysis of the impact that macro scale distributed energy could make to the GB energy system. The report identifies technical and regulatory environment which is needed to support the increased up-take of distributed energy.

Context:

This project quantified the opportunity for Macro level Distributed Energy (DE) across the UK and accelerate the development of appropriate technology by 2020 for the purposes of significant implementation by 2030. The project studied energy demand such as residential accommodation, local services, hospitals, business parks and equipment, and is developing a software methodology to analyse local combinations of sites and technologies. This enabled the design of optimised distributed energy delivery solutions for these areas. The project identified a number of larger scale technology development and demonstration projects for the ETI to consider developing. The findings from this project is now being distilled into our Smart Systems and Heat programme. The ETI acknowledges that the project was undertaken and reports produced by Caterpillar, EDF, and the University of Manchester.

ETI Macro Distributed Energy Project

Work Package 5, Task 5.1.

Version 2a

The GB Benefits Case
FINAL REPORT

August 2012

Andrew Turton (AECOM). Work Package 5 Leader.
Paul Woods (AECOM). Chief Technologist Officer

Table of Contents

Executive Summary

Introduction

The UK Government's Climate Change Act (2008) sets a legally binding target of 80% reduction in CO_2 emissions from 1990 levels by 2050. Meeting this target will require action across all energy consuming and carbon emitting sectors to reduce energy demand and provide energy more efficiently and from lower carbon sources.

This Macro Distributed Energy Study for the ETI aims to examine the role that DE could have in Great Britain (GB)[1] in providing low carbon and low cost heat to buildings. The work examines schemes of up to 50 MWe CHP capacity representing large scale networks which would cover a significant part of towns and cities. The key aims of this work are to:

- understand the technologies, tools, and skills available for DE deployment in GB, and where gaps exist;
- identify areas which may be suitable for DE schemes;
- assess the performance of schemes using a range of technologies in these areas in terms of cost, and CO_2 savings;
- calculate the GB benefits case with mass deployment of DE.

Methodology

The assessment of the potential for DE across GB follows a staged process. It makes use of the 20 Characteristic Zones (CZs) which have been identified in work package 2 of this macro DE study as representative of areas potentially suitable for macro DE.

A macro DE scheme is optimised for each CZ made up of a District Heating Network (DHN) and energy centre. The optimisation produces the lowest 'levelised heat cost' solution for the CZ. These results are then aggregated to a GB level by multiplying up to all zones within each class represented by a CZ. By comparing the macro DE heat costs with counterfactual costs from air source heat pumps (ASHPs) and gas boilers, an assessment can be made on where macro DE offers a more economic solution. Different GB uptakes can then be assessed based on zones where macro DE is economic, a net economic case (with some economic zones cross subsidising some un-economic zones), and a maximum CO_2 reduction case (where the macro DE costs are not considered).

The modelling in work package 5.1 is based around twelve assessment scenarios. These scenarios are used to define the input assumptions used in the optimisation model, and allow the assessment of sensitivities which may impact the potential for DE across GB.

The central scenario (scenario 7) is termed the "base case" and contains the central set of assumptions around which the other scenarios are constructed. The base case assumes that schemes are commenced in the 2020s, representing a period of mass deployment of DE. The economic assumptions include an 8% discount rate, central capital cost assumptions, central energy prices, and the inclusion of CO_2 pricing. A market penetration of 80% is assumed meaning that 80% of the potential customers in a zone connect to the DE scheme.

Sensitivities examined in the other scenarios include:

- 2010 (scenario 1) and 2030 (scenario 12) deployment of schemes.
- A 3.5% discount rate (scenario 2).
- 100% market penetration (scenario 3)

---

[1] The project has been limited to Great Britain as data from which heat demands could be predicted was not available for Northern Ireland (see WP2 report)

- Plus and minus 20% changes to capital expenditure of the DHN and energy centre prime mover (scenarios 4, 5, 9, 10).
- No carbon price included (scenario 11).
- Low and high energy prices projections (scenarios 6 and 8).

The scenarios are illustrated schematically in figure i:

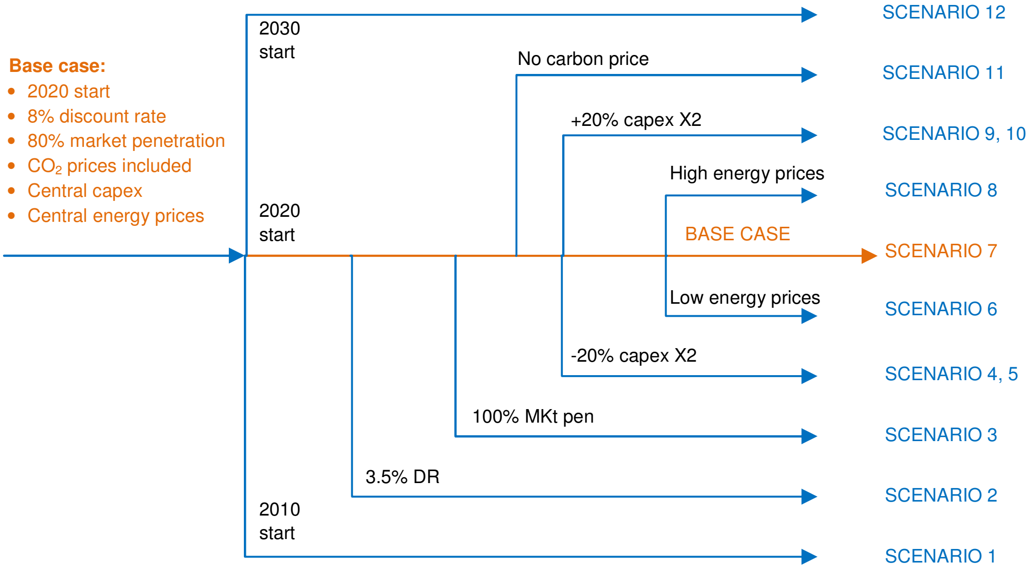


Figure i: Schematic of the scenarios. Sensitivities are indicated around the base case.

Conclusions

(1). There is a very large potential for macro DE using gas fired CHP in the 2010s and 2020s.

This report demonstrates that up to 43% of the GB heat market, consisting of 12.4 million homes and 2.9 million non-domestic connections, could be economic for macro DE schemes using gas engine CHP. This is predicted under the central conditions of an 8% discount rate, 80% market penetration, and central energy price projections. This provides a large economic benefit to customers with a saving of £5.6 billion in heat cost against a gas boiler counterfactual (equivalent to a 29% reduction in cost) and £15.4 billion saving against an ASHP counterfactual (equivalent to a 53% reduction in cost) in the 2010s. Large CO_2 reductions are also achievable of 38% of the current emissions associated with heating buildings. The cost and carbon savings available from macro DE schemes are largest in the 2010 scenario suggesting that GB should be investing and installing macro DE schemes as soon as possible. This will provide the largest annual benefits, but also the largest cumulative benefits over the lifetime of the schemes. This is particularly important in the context of climate change where a reduction in cumulative emissions (i.e. early savings) is more important than annual savings (i.e. late savings).

The macro DE schemes are predicted to save circa 50% in primary energy compared with a gas boiler counterfactual, and 31% compared with an ASHP counterfactual. The flexibility offered by the DHNs provides future opportunities for new technologies and alternative energy and fuel sources, allowing energy and CO_2 savings to be retained in the future compared with the counterfactual building scale options.

In the 2010s and 2020s, virtually all zones are economic for all scenarios compared with both counterfactuals, resulting in heat cost savings of between 30% and 50%. The savings per a domestic customer are circa £62 per year per £1 billion GB saving, and for non-domestic customers £79 per year per £1 billion GB saving. This means that in scenario 1, the average home connected could save approximately £350 per year annualised cost against gas boilers and £950 per year annualised cost against ASHPs.

Using the central case as an example to understand the order of magnitude of the market size, the following figures are obtained:

- The total investment potential in energy centres is circa £35 billion. This includes the plant (and replacement during a schemes lifetime), energy centre building, and associated services.
- The total investment potential in DHNs is circa £93 billion.
- The total potential for installed CHP capacity is circa 47 GW thermal.

These values show that the potential market for macro DE equipment and services is significant enough to support extensive up-scaling of relevant industries in the GB if local manufacture and supply chain is to be developed. Sectors that could particularly benefit are: steel pipe, gas-engines and generators, civil engineering construction, domestic plumbing components and installers.

(2). Despite the technical and economic potential, many barriers exist which future policy aimed at supporting macro DE can help overcome.

By overcoming the barriers associated with macro DE schemes, in particular facilitating strong levels of uptake to access the heat market, and providing a fair electricity price for CHP generated electricity through changes to the electricity market, macro DE can be economic in all the classes identified in both the 2010s and 2020s. The importance of a favourable electricity price is demonstrated in the modelling, with a reduction in revenue of 20% reducing the GB potential for economic macro DE schemes to around half. This has a larger effect than carbon pricing therefore suggesting that policy which only considers carbon pricing may have limited impact on the viability of macro DE if electricity revenues are not also directly supported.

Achieving a high market penetration will be important, and policy could be used to assist with this. The modelling demonstrates that provided a high proportion (typically around 80% but scheme dependent) of the market can be achieved, it is not necessary to access all customers allowing for some flexibility, but these types of penetration levels, especially in the private sector and domestic sectors will require policy support. Schemes will need to be effectively marketed, and customers potentially incentivised, or the use of regulation to encourage connection.

These conditions combined with large scale deployment and diversified schemes, results in optimised schemes where large proportions of the heat can be provided by the CHP units, improving the overall efficiency and primary energy savings.

(3). Macro DE may be a significant contributor to GB electricity supply with wide spread deployment.

Achieving the economic potential of macro DE will result in high levels of electricity generation of up to 62% of the total GB demand. It will be important to understand how feasible this is, although there will be good synergies between heat generation and electricity demand, especially if non-macro DE areas take up heat pumps. The performance of the grid in the modelling is independent of the amount of macro DE generated electricity and these need to be examined together in future work.

(4). DHN costs dominate the capital expenditure and access to low cost finance can help reduce this impact.

The economic and environmental performance of macro DE in the 2020s will be affected by a number of factors. The lowest levelised costs are achieved with access to lower discount rates of 3.5% in scenario 2, demonstrating the importance of controlling the cost of capital finance. This represents significant public sector investment in schemes. The DHN costs typically represent around two thirds of the overall capital expenditure, except in commercial/institutional building orientated zones (where they can be considerably lower). Therefore changes in DHN costs (scenarios 5 and 10) have a greater impact than energy centre costs (scenarios 4 and 9). WP1 also identified that DHNs may cost more in the UK than in Continental Europe and so this disparity needs investigating. Importantly, macro DE remained economic in virtually all zones across all scenarios, demonstrating the robustness of the solution.

(5). The CO_2 savings from gas CHP will reduce in the 2030s, but alternative forms of generation can make use of the flexibility offered by DHNs.

In the 2030s, gas CHP remains the most economic technology for macro DE schemes, but is no longer predicted to save carbon. It is not predicted that large scale heat pumps will be taken up if cost is the prime driver, and additional CO_2 constraints and market interventions are required to ensure that macro DE schemes are developed which save CO_2 compared to the counterfactuals. The combination of large scale heat pumps and gas engine CHP allows CO_2 savings of greater than 50% compared with gas boilers to be achieved in this period, with a commercial GB Benefits Case potential of 6% of the heat market, and an economic GB Benefits Case of 21% of the heat market.

If heat pumps are used as a replacement on existing macro DE schemes, the economics will be improved due to the prior payback of part or all of the DHN, creating a larger economic market and greater CO_2 reduction.

In order to maintain a larger share of the heat market, the 5.1 modelling demonstrates that further technology development and potentially newer technologies will be required to ensure that schemes can remain economic and provide acceptable CO_2 reductions. This will be examined in the 5.3 report and analysis.

Introduction

Background

The UK Government's Climate Change Act (2008) sets a legally binding target of 80% reduction in CO_2 emissions from 1990 levels by 2050. Meeting this target will require action across all energy consuming and carbon emitting sectors to reduce energy demand and provide energy more efficiently and from lower carbon sources.

Distributed energy (DE) schemes offer one method of providing lower carbon energy to buildings. The CO_2 emissions associated with heating are around a third of the total UK greenhouse gas (GHG) emissions with the majority of this used for heating domestic and non-domestic buildings. Therefore the provision of lower carbon heat will be important in achieving the 80% reduction target. It also possible that buildings will need to exceed the 80% target due to difficulties in reducing emissions in other sectors such as aviation and shipping, and therefore taking a strategic approach is vital.

Emissions can be reduced in the buildings sector by reducing the demand through efficiency improvements, and building highly efficient new buildings. However the majority of the building stock which is likely to exist in 2050 has already been built with much of this difficult to make more efficient or classed as "hard to treat". Reducing emissions therefore requires the widespread provision of low carbon heat, potentially through DE schemes.

DE schemes consist of a heat producing technology or combined heat and power (CHP) system providing heat to a district heating network (DHN). This consists of a series of insulated pipes distributing heat from the central source to individual buildings. The advantages of DE are that technologies providing high overall efficiencies (such as CHP) can be used, or other sources of heat such as waste heat from industry can be collected and distributed. However the cost of installing heat networks and energy centres can be high, and the viability of a DE scheme can depend on the economic performance of the DE scheme compared with alternative options employed at an individual building or dwelling scale.

This Macro Distributed Energy Study for the ETI aims to examine the role that DE could have in Great Britain (GB)[2] in providing low carbon and low cost heat to buildings. The work examines schemes of up to 50 MWe CHP capacity representing large scale networks which would cover a significant part of towns and cities. The key aims of this work are to:

- understand the technologies, tools, and skills available for DE deployment in GB, and where gaps exist;
- identify areas which may be suitable for DE schemes;
- assess the performance of schemes using a range of technologies in these areas in terms of cost, and CO_2 savings;
- calculate the GB benefits case with mass deployment of DE.

The work in the Macro DE project is split into distinct 5 work packages which aim to characterise DE in GB, and develop a suite of data and materials to allow the assessment of the potential and benefits from DE across GB. In summary, the separate work packages are:

- WP 1: DE Design Practice Characterisation. The first work package provides an overview of current practices and regimes for DE deployment. It identifies key suppliers and stakeholders in the industry, business and deployment models, and a range of barriers to uptake.

---

[2] The project has been limited to Great Britain as data from which heat demands could be predicted was not available for Northern Ireland (see WP2 report)

- WP 2: Site and Zone Energy Demand Characterisation. This work package examines the energy demand characteristics of GB on a spatial basis, identifying the suitability of different areas for DE deployment. A number of zones are identified which may be suitable for DE (these typically represent towns and cities) which are then analysed and represented by grouping into 20 distinct Classes based on a range of criteria. For each class, a Characteristic Zones (CZ) is selected for subsequent analysis. A set of energy demand profiles are developed which will allow modelling of energy supply technologies in work package 4.
- WP 3: Energy Supply Characterisation. This work package develops energy supply options for the CZs based around DHN infrastructure and generation technologies. DHNs were designed for three CZs which contain representative areas for most of the other CZs covering a range of building types and layouts. The outputs from this were used to develop a set of algorithms describing the cost of networks based on energy demand information and spatial information. The second main component of work package 3 is the development of a database of energy supply technologies covering currently available and mature technologies (work package 3.2) and future or developing technologies (work package 3.3).
- WP 4: Tool Development Methodology and Performance Evaluation by Zones. The focus of work package 4 is to develop an optimisation tool for the evaluation of DE schemes for each CZ. The tool optimises solutions for each CZ based on the performance of supply technologies, lifecycle costs, CZ demand characteristics, and a number of other inputs. The output from the tool is the most appropriate system based on either minimising lifecycle cost or CO_2 emissions.
- WP 5: GB Benefits Case Opportunity Identification & Summary of the Individual Development Options. Work package 5 is the final work stage, and includes the assessment of potential for DE at a GB level, assessment of the opportunity for new or novel technologies, and a summary report of the overall study.

Further details for each of the previous work packages can be found in the relevant technical reports produced for each stage.

Work package 5.1: The GB benefit case.

This report is part of work package 5 and provides results and analysis from work package 5.1 which aims to identify the potential for DE across GB with a range of currently available and mature technologies. The potential for the deployment of DE will depend on what solutions exist and how well they perform economically for each of the representative CZs. Then, by aggregating the CZs to a GB level, the overall impacts for GB can be calculated in terms of the penetration of DE into the heat market, the overall economic impact, and the potential for CO_2 reduction across GB.

When reading this report, it is important to consider the scope of the assessment. The results, analysis and conclusions in this work are based around mass-scale deployment of DE in GB. At present the uptake of DE in GB has been relatively low and there are many barriers, (both economic and non-economic) to increasing deployment (a discussion of these can be found in the WP 1 report and the WP 5.4 summary report). The widespread uptake of DE will mean that many of these non technical or economic barriers will need to be addressed so that DE is effectively treated as any other recognised utility, for example potentially regulating the heat market, developing new business structures, understanding and allocating risk, or financing schemes in a manner which accepts the long term payback from macro DE schemes. The assessment of potential in this report is based around the technical and economic viability of schemes, and the softer barriers will also need to be addressed to achieve the levels of uptake described. In particular the following are implicit in all the analysis:

- Large town and city wide DHNs can be created with a strong customer base. As a base case, it is assumed that 80% of potential customers connect to the scheme – this factor is scheme dependent but represents a majority uptake whilst allowing for some flexibility. This implies some form of regulation which could incentivise or mandate connection, and provide certainty to potential investors and customers, similar to current gas and electricity supplies.
- There is sufficient electricity network capacity to accommodate high levels of decentralised generation. It is likely that the grid will become smarter in future allowing the connection of a greater range and scale of electricity generators.
- The current electricity market distortions which do not favour decentralised electricity generation are removed and CHP operators can receive a higher value for all the electricity they produce. This might be achieved through changes to the licensing regime to allow operators to sell some electricity directly to customers, or for the benefits to the distribution system of local de-centralised generation to be recognised in the price paid for exported power.
- That the CO_2 savings resulting from CHP operation are valued at a cost per tonne of carbon equal to the social non-traded cost of carbon published by DECC.

These assumptions present a somewhat idealised view of macro DE. This is intentional in that it allows assessment of the true potential of DE both in terms of economic and environmental benefit. The level of potential identified under the various modelling scenarios will enable decision makers to determine the importance of macro DE in future energy policy, and hence the level of effort put into overcoming the barriers and enabling wide scale deployment in a timely manner.

Methodology for assessing the GB benefits case

Methodology overview

The assessment of the potential for DE across GB follows a staged process.

- Stage 1. Scheme optimisation for each CZ. By using the energy demand characteristics for each CZ from WP2, and the supply and distribution technology libraries and datasets from WP3, DE schemes are optimised for each of the CZs in WP4. The output from this task is the identification of the lowest "levelised heat cost" (see below) scheme for each CZ with corresponding performance characteristics, economic characteristics and CO_2 emissions.
- Stage 2. Aggregation to a GB level for each class. This takes the results for each representative CZ and scales them up to a GB level based on the total heating load in each class.
- Stage 3. Comparison with counterfactuals. DE schemes will have to compete with alternative baseline technologies providing heat at a building or dwelling scale. Therefore the potential for DE can only be assessed by comparing its performance against these counterfactual systems. The net additional cost or cost saving of DE against a counterfactual and the net CO_2 savings therefore can be used to assess which types of zone are suited to DE.
- Stage 4. Assessing the GB uptake. The uptake of DE is likely to depend on the net cost of providing heat using DE. Three different benefits case scenarios are examined based on different economic view-points which may be taken to represent a range between a commercially driven up take scenario through to a CO_2 reduction priority scenario.

The following sections discuss the methodology and assumptions in more detail, with additional material supplied for reference in the appendices. The final section provides a simple overview of the results presentation format to introduce the reader to the results in the analysis sections.

Characteristic zones

The zones classes used throughout this modelling were developed in WP2 based on extensive analysis of a number of variables which can be used to describe an area. By grouping the zones identified across GB into classes, and then statistically selecting a central or average zone (called the characteristic zone or CZ), the assessment of GB can be simplified to the 20 CZs which are then aggregated.

Figure 1 shows a map of all the zones identified and their classes. The map is presented in the form of a heat map with colouring representing the range of heat density from the lowest density (class 19) to the highest (class 1). It can be seen that in general the zones represent urban areas and are distributed across GB, but with the highest density zones in the city centres.

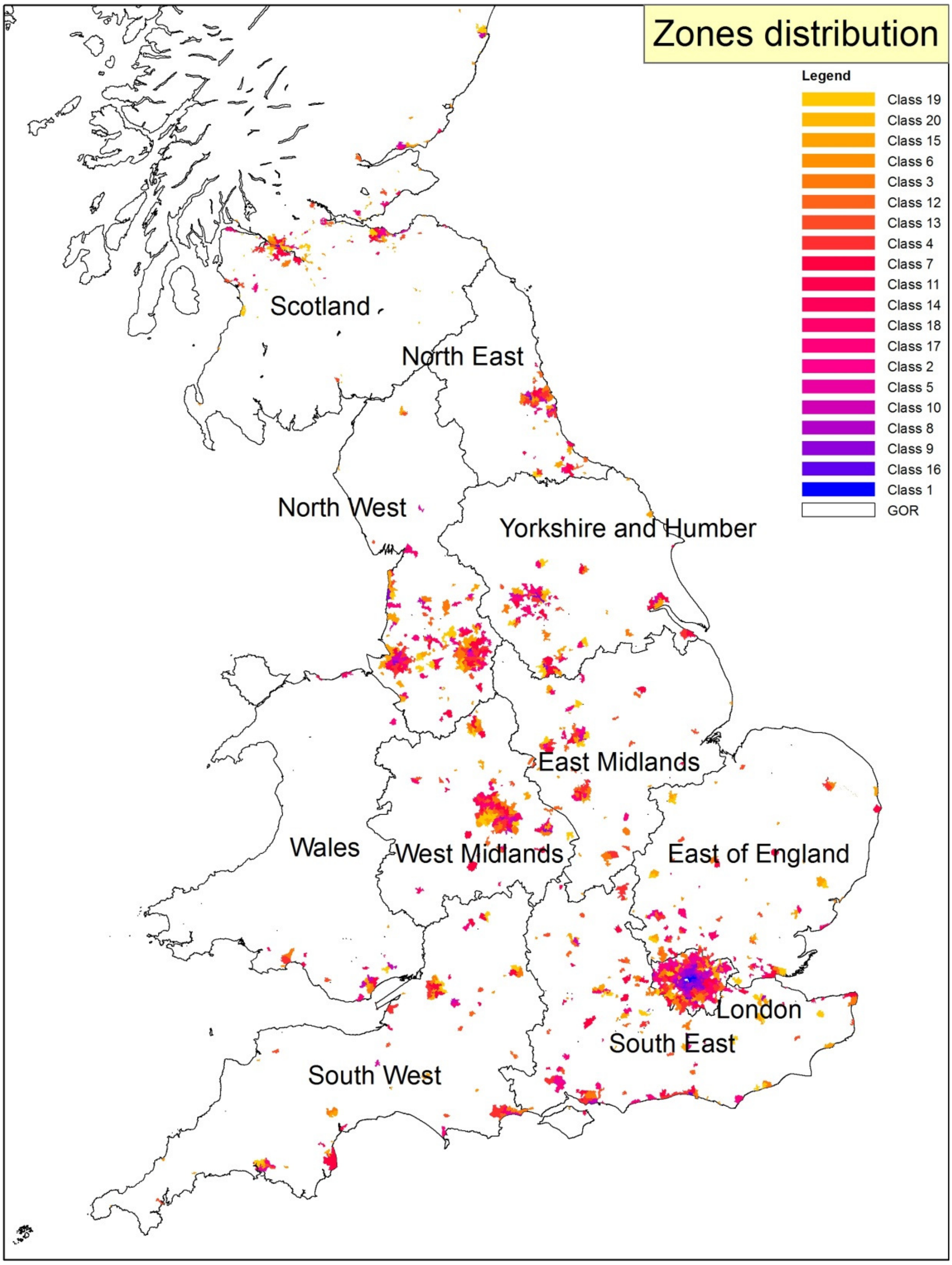
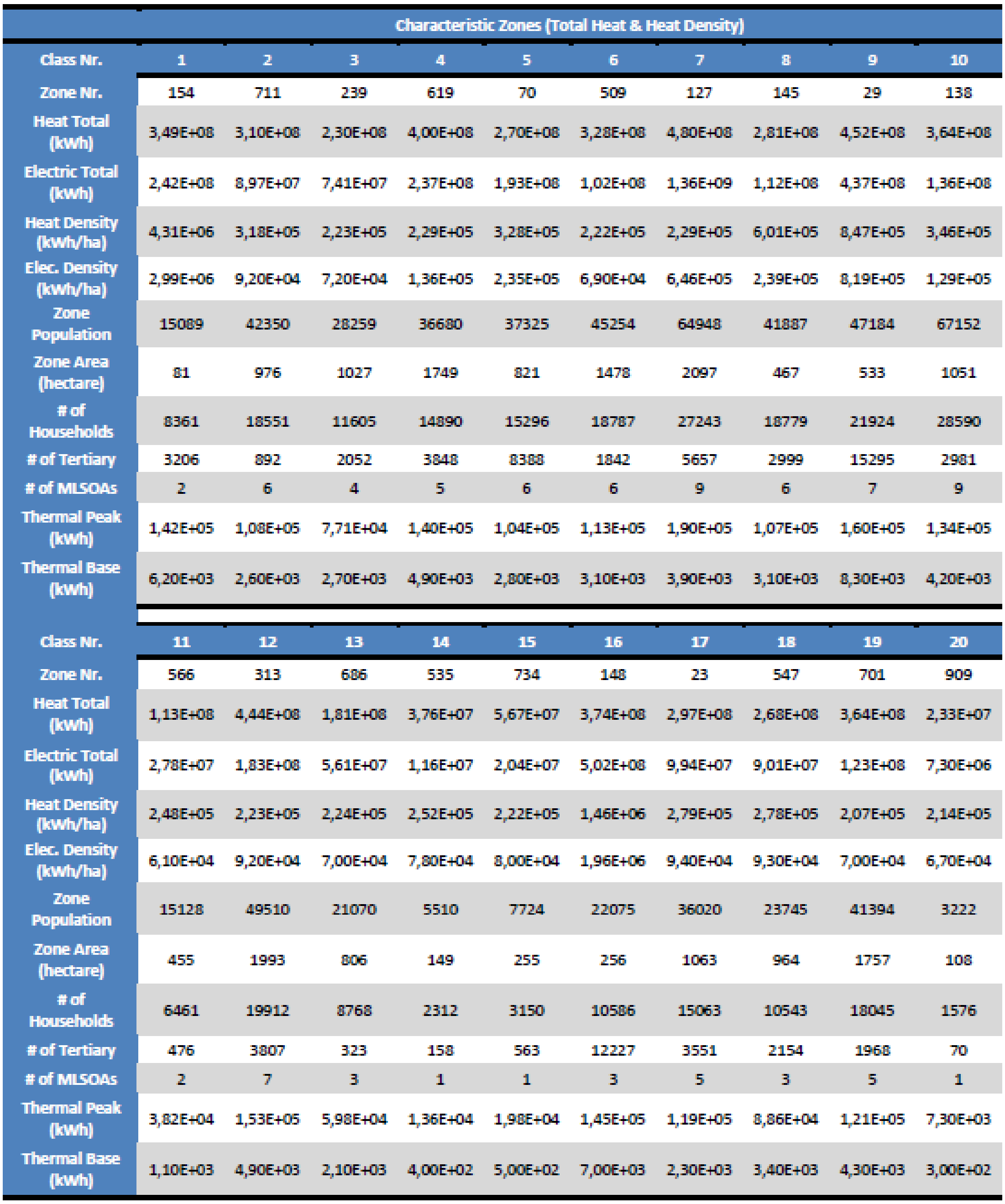


Figure 1: Map of GB showing all the zones and classes, with classes ordered by heat density (class 1 being the most dense). (Taken from WP 2.5 report).

Table 1 provides a summary of the key characteristic used to identify and define the characteristic zones. Further details on the methodology behind this analysis and the CZs can be found in the WP 2.3 report.

Table 1: Factors and values defining the characteristic zones (taken from WP 2.3 report).



	Characteristic Zones (Total Heat & Heat Density)									
Class Nr.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Zone Nr.	154	711	239	619	70	509	127	145	29	138
Heat Total (kWh)	3,49E+08	3,10E+08	2,30E+08	4,00E+08	2,70E+08	3,28E+08	4,80E+08	2,81E+08	4,52E+08	3,64E+08
Electric Total (kWh)	2,42E+08	8,97E+07	7,41E+07	2,37E+08	1,93E+08	1,02E+08	1,36E+09	1,12E+08	4,37E+08	1,36E+08
Heat Density (kWh/ha)	4,31E+06	3,18E+05	2,23E+05	2,29E+05	3,28E+05	2,22E+05	2,29E+05	6,01E+05	8,47E+05	3,46E+05
Elec. Density (kWh/ha)	2,99E+06	9,20E+04	7,20E+04	1,36E+05	2,35E+05	6,90E+04	6,46E+05	2,39E+05	8,19E+05	1,29E+05
Zone Population	15089	42350	28259	36680	37325	45254	64948	41887	47184	67152
Zone Area (hectare)	81	976	1027	1749	821	1478	2097	467	533	1051
# of Households	8361	18551	11605	14890	15296	18787	27243	18779	21924	28590
# of Tertiary	3206	892	2052	3848	8388	1842	5657	2999	15295	2981
# of MLSOAs	2	6	4	5	6	6	9	6	7	9
Thermal Peak (kWh)	1,42E+05	1,08E+05	7,71E+04	1,40E+05	1,04E+05	1,13E+05	1,90E+05	1,07E+05	1,60E+05	1,34E+05
Thermal Base (kWh)	6,20E+03	2,60E+03	2,70E+03	4,90E+03	2,80E+03	3,10E+03	3,90E+03	3,10E+03	8,30E+03	4,20E+03

Class Nr.	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Zone Nr.	566	313	686	535	734	148	23	547	701	909
Heat Total (kWh)	1,13E+08	4,44E+08	1,81E+08	3,76E+07	5,67E+07	3,74E+08	2,97E+08	2,68E+08	3,64E+08	2,33E+07
Electric Total (kWh)	2,78E+07	1,83E+08	5,61E+07	1,16E+07	2,04E+07	5,02E+08	9,94E+07	9,01E+07	1,23E+08	7,30E+06
Heat Density (kWh/ha)	2,48E+05	2,23E+05	2,24E+05	2,52E+05	2,22E+05	1,46E+06	2,79E+05	2,78E+05	2,07E+05	2,14E+05
Elec. Density (kWh/ha)	6,10E+04	9,20E+04	7,00E+04	7,80E+04	8,00E+04	1,96E+06	9,40E+04	9,30E+04	7,00E+04	6,70E+04
Zone Population	15128	49510	21070	5510	7724	22075	36020	23745	41394	3222
Zone Area (hectare)	455	1993	806	149	255	256	1063	964	1757	108
# of Households	6461	19912	8768	2312	3150	10586	15063	10543	18045	1576
# of Tertiary	476	3807	323	158	563	12227	3551	2154	1968	70
# of MLSOAs	2	7	3	1	1	3	5	3	5	1
Thermal Peak (kWh)	3,82E+04	1,53E+05	5,98E+04	1,36E+04	1,98E+04	1,45E+05	1,19E+05	8,86E+04	1,21E+05	7,30E+03
Thermal Base (kWh)	1,10E+03	4,90E+03	2,10E+03	4,00E+02	5,00E+02	7,00E+03	2,30E+03	3,40E+03	4,30E+03	3,00E+02

Levelised cost methodology

The basis of the economic analysis in this study is the levelised cost of heat where all of the costs and revenues associated with a scheme over a 25 year assessment period are attributed to the heat delivered to customers. The notion of levelised cost allows different schemes with different financial structures to be compared by expressing the total costs on an identical basis, typically in terms of cost per unit of energy output, for example £ per MWh or pence per kWh, and is used extensively in the energy industry[3]. It is recommended that the IEA reference is used for a more detailed background and understanding of levelised costs.

The calculation of levelised cost is based around a discounted cashflow where all future incomings and outgoings are discounted by the desired rate to provide a net present value (NPV) of the cashflow. This NPV is then divided by the sum of the discounted thermal output (kWh) to provide a present day "levelised cost" of heat. This process means that the thermal output from different systems is directly comparable with a present day heat value (i.e. is not discounted and therefore independent of project life), but that the expenditure and revenue profile over time of the schemes is reflected in this value.

This methodology also allows for the lifetime of components to be taken into account. Plant with a lifetime of less than the 25 year assessment period is replaced at a discounted capital replacement cost. The DHN is assumed to last the 25 years without replacement, but also with no residual value at the end of the period. This represents a typical commercial scenario although in reality the DHN will have a remaining life which could be capitalised as a final year revenue, improving the scheme economics.

In this study, the levelised cost is used to allow comparison of the DE options with the counterfactual technologies, and the comparison of DE economic performance across a range of scenarios and sensitivities.

Assessing the GB uptake - benefits case scenarios

This study aims to assess the potential of DE across the UK to establish the likely scale of deployment and impact this could have on the GB economy, energy markets, and CO_2 emissions. To allow the potential to be calculated, a method is required to determine the level of uptake which may arise based on the economic performance in each CZ. Three simple scenarios are used to represent the uptake of DE:

> Case 1. Commercially driven uptake. Only zones where DE provides a lower levelised cost of heat than the counterfactual are considered to have potential. The effect is for a net cost saving across GB.
>
> In a rational commercially driven future, a DE scheme will only be implemented where it can provide cost savings compared with a counterfactual scheme. With the absence of regulation requiring customers to connect to a network, the decision to connect is likely to be influenced by the cost of heat from the DE scheme relative to the existing or alternative heating system options. Therefore the maximum heat tariff is effectively set by the alternative counterfactual options available, and the scheme needs to perform economically to pay back the capital investment, cover operation and maintenance costs, and potentially provide a profit for the operator.
>
> Case 2. GB economy based approach. Zones are assumed to have potential where the net effect across GB is zero additional cost.
>
> At a GB level it may be desirable to increase the level of CO_2 reduction whilst ensuring that the overall costs of supplying heat at a national level do not increase above the alternative counterfactual options. Therefore this would allow schemes in zones which are economically attractive to subsidise zones where DE has an additional cost, providing cost neutrality overall. In practice this may be difficult to achieve unless there is increased regulation and centralised control, but it could be envisaged at a city wide scale where more economic areas subsidise less economic areas with the same operator. This would present more of a public sector driven approach.

---

[3] The "levelised cost" of heat presents the effective cost of heat per unit delivered based on lifecycle costs. This methodology is described in "Projected costs of generating electricity", International Energy Agency. 2010.

Classes are included in the DE potential in order of cost effectiveness until cost parity is achieved. If this falls part way through a class, only a proportion of the zones in the class are included.

Case 3. Maximum CO_2 reduction. All zones are assumed to have potential where a technically viable DE scheme which reduces CO_2 exists.

The inclusion of all CO_2 reducing zones will probably result in an increase in the overall cost of heat at a GB level and therefore the viability of this will need to be assessed on a cost per tonne of CO_2 basis and compared with other potential national CO_2 reducing approaches. This case would result in higher heating costs for some customers and so regulation and / or subsidy will be required to ensure uptake. The impact on fuel poverty would also need to be considered if costs are passed on to consumers.

Under each of the cases, the results from the modelling at CZ level are aggregated to all zones in a class, and hence GB, to calculate the GB costs and CO_2 reduction. This aggregation is conducted on the basis of scaling up the CZ results to a class by the ratio of thermal demand in a CZ to its class. This allows for the variability in size of thermal demand of zones in a class but does make the implicit assumption that all zones in a class will perform similarly to the representative CZ.

Counterfactual technologies

The counterfactual technologies represent the baseline heat supply systems against which the DE schemes need to compete economically and environmentally. There are a wide range of heating systems currently in use in GB based around different fuel types, different heat sources and different heating system types. However the majority of heating in GB is from the combustion of natural gas in boilers, connected to water based heating systems (predominantly radiators). The use of gas is even more dominant in urban areas where DH will have greatest potential, and therefore the use of a gas boiler is the most appropriate counterfactual for assessing DH schemes at the present day. It is important to note that the intention of this report is to use counterfactual technologies as a baseline against which macro DE schemes can be compared in terms of cost and carbon performance. The macro DE project is not intended to suggest optimal levels of macro DE vs micro DE/counterfactual technologies, and this will be investigated in the ETI's ESME modelling which contains a mix of energy sectors and supply systems.

Heat pumps offer an alternative approach for the generation of heat at a building scale. In rural areas or for larger buildings, ground source heat pumps (GSHPs) either using surface arrays or boreholes may be most appropriate. In urban areas and for smaller buildings, in particular dwellings, air source heat pumps (ASHPs) are more appropriate, taking thermal energy from the ambient temperature air and not requiring large ground collectors. At present, heat pumps may provide negligible or even negative CO_2 reduction and cost reduction compared to gas boilers due to the currently achievable Coefficient of Performance (CoP) values obtained, combined with the relatively high CO_2 intensity of the electricity grid. However with a combination of technology development and future reductions in the CO_2 intensity of the electricity grid, heat pumps may provide greater cost savings and CO_2 savings in the future. ASHPs are therefore considered an important counterfactual against which DE schemes will need to compete with in the future and are included in this study.

The calculation of the levelised cost of heat and CO_2 emissions from the counterfactual technologies uses the same input datasets and the same calculation procedures as for the DE schemes, ensuring the results are consistent and comparable. Full input assumptions for the counterfactual technologies are provided in Appendix 4. Calculations are made for both the domestic and non-domestic sectors based on the number of customers of each in each CZ.

The assumption that gas boilers and wet heating systems represent the current baseline is somewhat of a simplification. For example there will be sites within cities which use electric heating, and industrial and warehouse sites which use direct fired space heating. However over the uptake phase of DE at a mass scale in GB, many of these existing systems will be replaced and therefore the opportunity exists (assuming that a long term strategy is in place) for these systems to be made compatible with DE schemes. Electric heating is usually more expensive than gas heating, and therefore the exclusion of electric heating in the counterfactual means the cost comparison between DE and the counterfactual will be conservative and savings with macro DE may in reality be larger and more favourable.

At a DE scheme level, large-scale heat pumps could be used to provide heat to a DHN allowing the potential for more efficient and cost effective heat pumps than may be available at a single building/dwelling level. Large centralised heat pumps connected to a DHN could allow the capture of low grade heat from waste heat sources (for example industrial processes). They could also be used alongside gas fired CHP units and be operated in conjunction with the CHP to help balance the electricity grid, with heat pumps used at times of high grid electricity generation (for example from wind) and low demand, or the CHP to be operated when there is insufficient electricity generation (at times of low renewable output and maximum demand). In this approach, the heat network becomes part of a smart grid, connecting the electricity and thermal energy vectors.

At the wider GB scale, heat pumps could be used to provide lower carbon heat for rural buildings where DE schemes are not economically viable. The increased electricity demand from the heat pumps can be partially provided by electricity output from urban CHP DE schemes. There will be a strong synergy between the two, with the CHP typically operating to provide heat to urban areas at the same time as the electricity demand for the heat pumps peaks.

This study aims to explore some aspects of these concepts using the following analysis:

- Examining the use of heat pumps for supplying heat to a DH network. In 5.1, the use of low grade heat source heat pumps are examined (for example taking thermal energy from the air, ground, or water courses). In 5.3, higher temperature source heat pumps are examined which may connect to industrial processes or other sources of waste heat.
- Assessing the electricity output from CHP units corresponding to DE potential in GB. The widespread use of heat pumps in rural areas will significantly increase the peak demand on the electricity grid. CHP could help support this additional demand.

A full analysis of how CHP, large-scale heat pumps, thermal storage and increasing use of individual scale heat pumps could operate together as described is however outside the scope of this study.

Assessment scenarios

The modelling in work package 5.1 is based around twelve assessment scenarios. These scenarios are used to define the input assumptions used in the optimisation model, and allow the assessment of sensitivities which may impact the potential for DE across GB. It is impossible to simulate all possible future conditions, and therefore the sensitivities selected are intended to represent the key variables. These scenarios have been developed in collaboration with the ETI (and some of the values are selected to be consistent with other ETI studies), and agreed with the ETI prior to the modelling.

The central scenario (scenario 7) is termed the “base case” and contains the central set of assumptions around which the other scenarios are constructed. The base case assumes that schemes are commenced in the 2020s, representing a period of mass deployment of DE. The economic assumptions include an 8% discount rate, central capital cost assumptions, central energy prices, and the inclusion of CO_2 pricing. A market penetration of 80% is assumed meaning that 80% of the potential customers in a zone connect to the DE scheme.

Sensitivities examined in the other scenarios include:

- 2010 (scenario 1) and 2030 (scenario 12) deployment of schemes. These represent early and late adopters. 2010 provides an important reference as it should present the current DE status. Deployment of DE in 2030 will need to consider alternative technologies alongside the de-carbonisation of the electricity grid.
- A 3.5% discount rate (scenario 2). This allows the economics to be viewed in a public sector financed scenario. The 8% used in the base case is consistent with other ETI studies and represents a commercially led scheme, but with significant risk reduction through public sector support / involvement.
- 100% market penetration (scenario 3). This will assess the impact of all potential customers connecting to the DHN, increasing the heat density.
- Changes to capital expenditure (scenarios 4, 5, 9, 10). These scenarios examine the impact on DE potential with a variation of +/- 20% on energy centre capital cost (scenarios 4 and 9 respectively), and +/- 20% on DHN capital cost (scenarios 5 and 10 respectively). This will enable the study to identify how important the capital costs are in the viability of schemes and the relative importance of future policies aiming to reduce the capital cost of equipment.
- No carbon price included (scenario 11). The inclusion of a carbon price in the base case should incentivise CO_2 reducing DE schemes. This scenario will identify the importance of carbon pricing in improving the potential for DE.
- Low and high energy prices (scenarios 6 and 8). These prices are derived from DECC/HMT predictions

The scenarios are illustrated schematically in Figure 2.

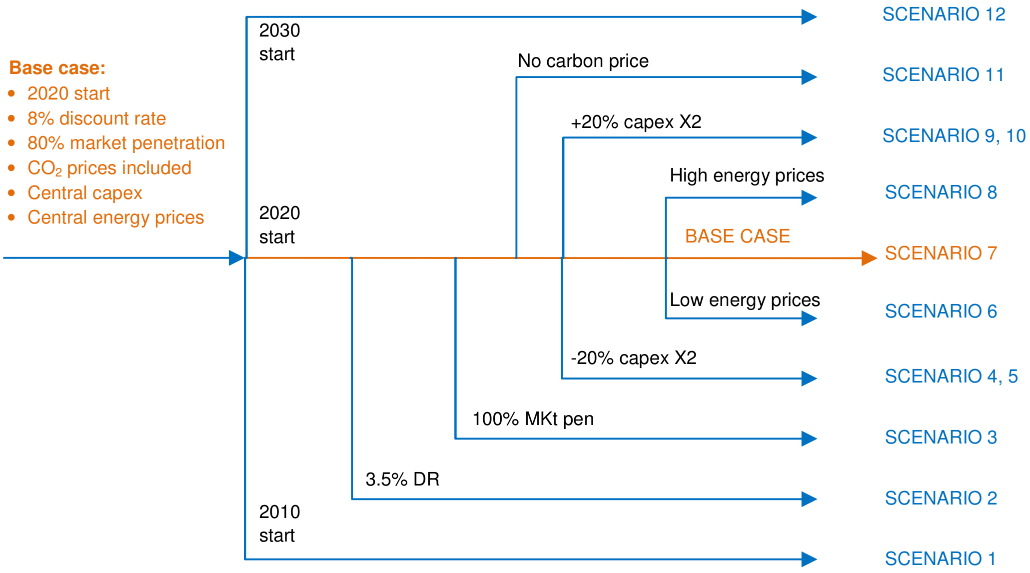


Figure 2: Schematic of the scenarios. Sensitivities are indicated around the base case.

Full details of the scenarios and inputs are provided in Appendix 3.

Presentation of results

The main results outputs which are used as the foundation of the further analysis are:

- Levelised cost of heat expressed as £ per MWh or pence per kWh.
- The CO_2 intensity of heat expressed as mass of kg CO_2 per kWh of thermal energy delivered (or tonnes per MWh).

These allow both the economic impact and environmental impact of DE in each of the CZs to be analysed, and aggregated to GB levels.

Results are generated for each of the CZs (20) for each scenario (12). Outputs from each CZ include the values for the DE schemes and the two counterfactuals, and the differences between each. The results are also assessed for each of the three benefits case options, and can also be expressed as averages across all CZs or all scenarios for a single CZ. This large number of outputs therefore requires careful presentation to allow key trends to be observed.

The indicative chart in Figure 3 provides an example of how the data can be presented and the types of data which can be shown.

The X-axis presents the cost of heat for the scheme in terms of p / kWh and the Y-axis presents the CO_2 intensity of the heat in terms of tonnes CO_2 / MWh (or kg per kWh). The data points therefore allow the performance of a scheme to be evaluated on both an economic and environmental basis compared with another scheme. The data format means that both the absolute and relative performance values can be observed.

Data can be shown for a number of CZs or scenarios, indicated by the blue diamonds in the chart. In a chart representing a single scenario, the results are of separate CZs (as in the example in Figure 3), whilst in a chart showing multiple scenarios, the results are of a single CZ, or averaged across all the CZs.

The solid red and solid green data points show the average counterfactual technology performance for each of the benefits case scenarios. Corresponding non-solid data points show the average DE performance for schemes across the three benefits case scenarios. There is a scatter in the average data points for each benefits case due to the change in CZs included for the particular benefits case. In general, benefits case 1 (economic zones only) will have the lowest cost, and benefits case 3 (all zones) will have the highest costs. Average DE results are shown for the benefits cases against both gas boilers and ASHPs because different CZs will perform differently against each.

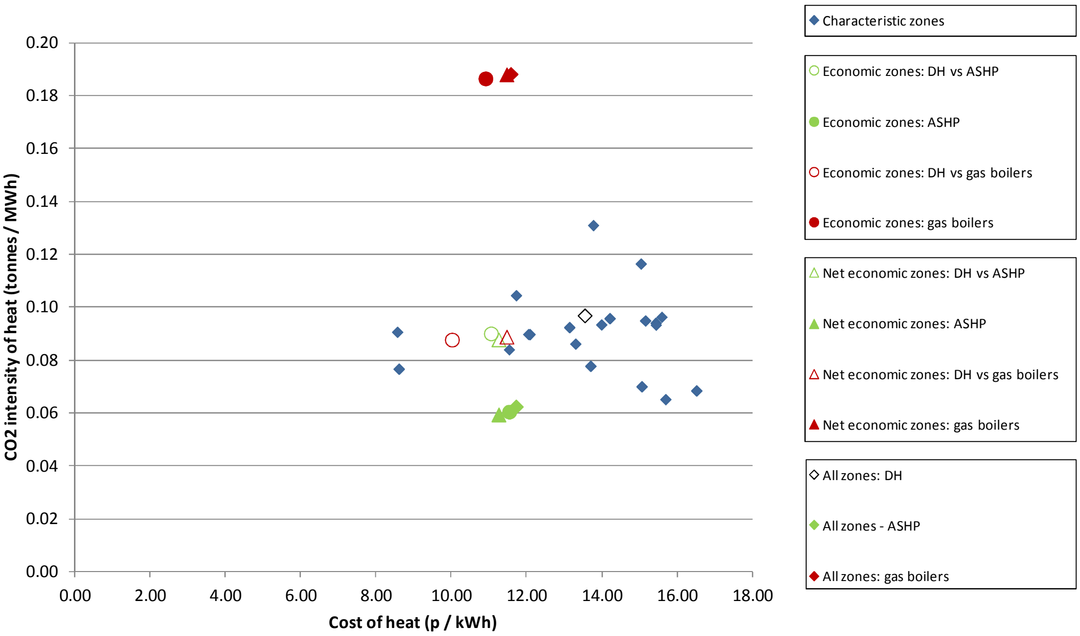


Figure 3: Example chart format showing results from a range of CZs or scenarios. In this example, the levelised cost of heat from macro DE schemes is economic for some zones, and not for others causing the three GB benefits case averages to be different. Macro DE provides lower carbon heat than gas boilers, but higher carbon than the ASHP counterfactual (Note – example results only, shown for the purposes of explaining the chart format).

In the main body of this report, the charts presented will indicate only averages across CZs or scenarios, unless the results are of particular interest (for example, scenario 1 – 2010, and scenario 7 – the base case). A full set of results for each scenario are presented in Appendix 2.

A variation of the chart in Figure 3 is also used to illustrate the relationship between average DE results from all CZs and their respective counterfactuals across different scenarios. An example of this chart is illustrated in Figure 4. The average DE results for each scenario are indicated by the blue diamonds, whilst the red and green "tails" connect the DE results to the ASHP (red tails) and gas boiler (green tails) counterfactuals respectively. The tails show the linkages between the corresponding data points, but their gradients also visually highlight the relative sensitivities to levelised cost and CO_2 emissions. For example, if the gradient remains the same for two different scenarios, it demonstrates that both the levelised and CO_2 intensity are equally affected. But if the gradient becomes shallower, there is a greater change in CO_2 intensity over the levelised cost. For simplicity, the charts in the analysis sections only show the tails for the scenarios being discussed and the central case.

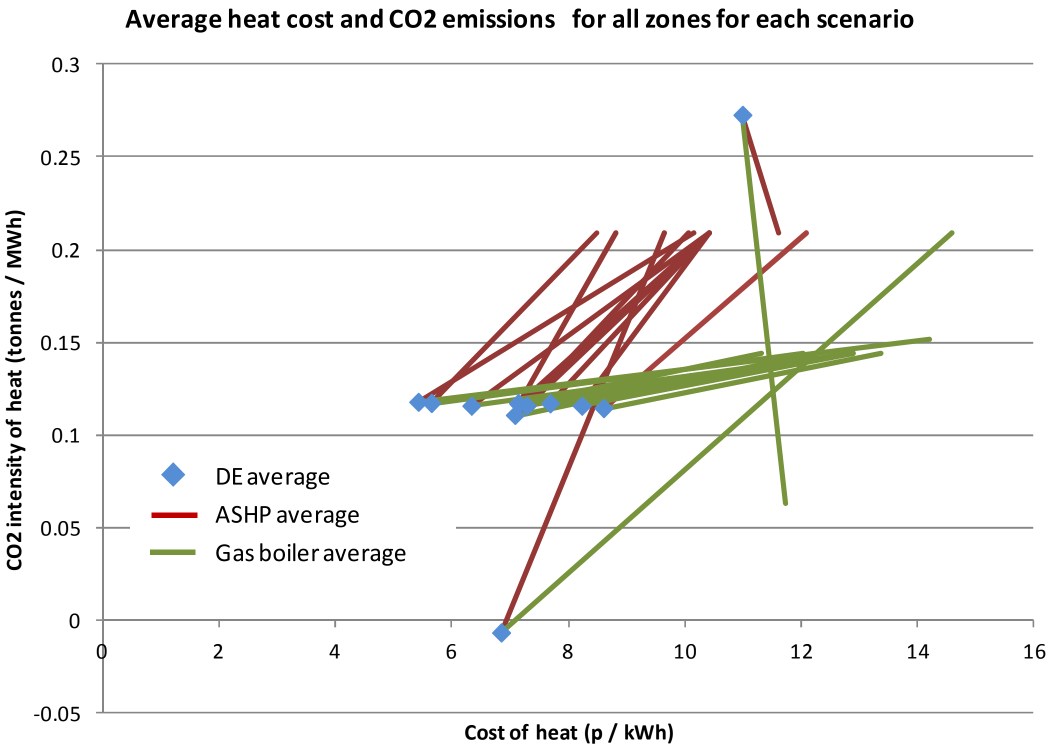


Figure 4: Example chart format showing relationship between average scenario results and the corresponding counterfactuals. Outliers are produced in the 2010 and 2030 cases due to changing electricity grid CO_2 intensity. (Note – example results only, shown for the purposes of explaining the chart format).

Figure 3 and Figure 4 chart formats allow schemes to be assessed on a performance basis but do not demonstrate the GB benefits case. This report also makes use of marginal abatement curves (MAC) to visually demonstrate the national overall CO_2 reduction potential and the costs associated with this (see example in Figure 5). MAC curves can be useful when assessing policies by not only demonstrating the CO_2 saving potential and costs, but also the order in which certain measures (in this case, which class type should have DE) should be implemented. Data which has a negative levelised cost is already economic, and therefore taking these measures could result in cost effective CO_2 savings. If CO_2 reductions are required from measures which are not deemed economic, then the MAC curve identifies which sectors should be targeted first to give the least additional cost.

The MAC curve can be used to illustrate the three benefits case scenarios. The ‘economic zones only’ scenario is represented by classes which appear as economic below the X-axis. The ‘net economic zones’ scenario is achieved when (working from left to right), classes are included such that the total area above the X-axis is equal to the total area below the X-axis. The ‘all zones’ scenario obviously includes all the classes.

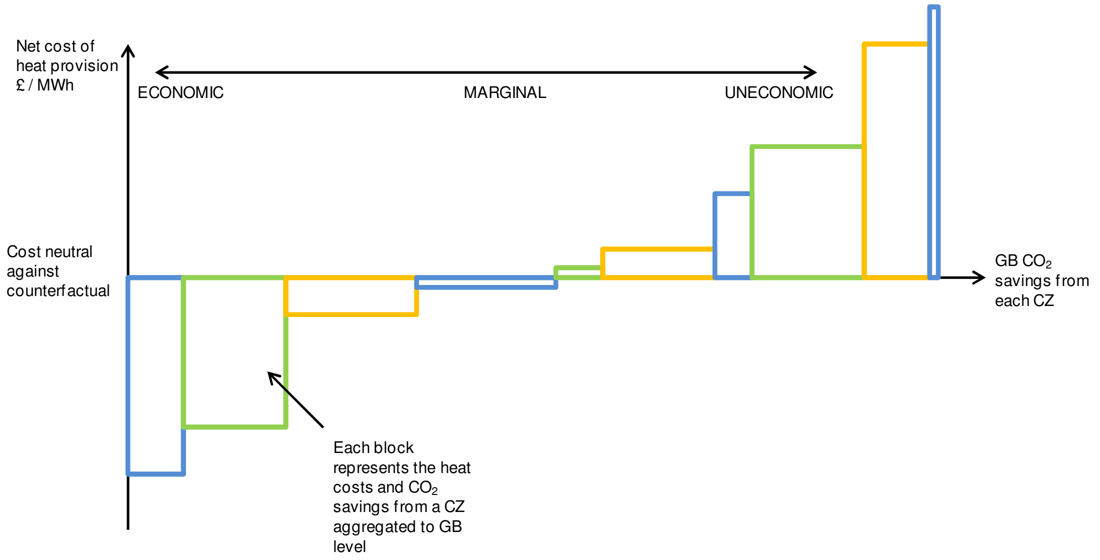


Figure 5: Indicative chart format showing a MAC curve illustrating the GB CO_2 savings potential from each class and the corresponding levelised cost.

Throughout the report, other forms of data presentation are used where necessary. These are either based on the above formats, or require no additional explanation.

The current potential for DE – Scenario 1 results

Introduction

This section presents the results from modelling macro DE schemes in the 2010 scenario, and therefore a reflection on the current costs and benefits of DE in GB. Whilst it is expected that mass scale deployment of DE would occur in the 2020s, providing time for the identification and development of schemes, understanding the 2010 case is an important test for the modelling to ensure that the results are similar to current experience, and to help identify where the early deployment of DE could take place.

Description of the optimised schemes

The optimisation modelling for scenario 1 identifies natural gas fired CHP engines as the most suitable technology for use in macro DE schemes. A combination of CHP engines and gas back-up boilers was selected for every CZ, with up to 18 engines per zone.

The modular nature of the CHP capacity, driven by a maximum engine size of 7 MWe, enables the CHP capacity to closely follow the thermal load profile. In this situation, some CHP engines provide base load thermal demands by operating for long periods each year, whilst other engines are used intermittently for meeting the peak thermal demands. The modular design and load following allows almost all the thermal energy to be provided by the CHP systems. Most zones have a CHP proportion of 99% or above, with only one zone at 98%, due to the smaller size of the CZ (CZ 20) reducing the potential for modularity.

Achieving this high proportion of heat from the CHP units means that the CHP capacity is relatively high in comparison with the CZ peak capacity. Across all CZs (apart from CZ 20), the thermal capacity of the CHP engines is between 60% and 80% of the peak load. However it must be remembered that some of this capacity will only be used intermittently.

A key driver for the deployment of DHNs is the ability to make use of CHP and access the overall efficiency benefits which CHP provides. The energy centre optimisation in scenario 1 results in schemes which provide an overall reduction in primary energy demand of 49% compared with the gas boiler counterfactual, and 31% compared with the ASHP counterfactual [4].

The nature of the schemes identified in scenario 1 differs from the current UK schemes which are generally much smaller and only comprise one or two CHP engines. Typical schemes currently in place or being planned may have a proportion of heat from the CHP engines of around 70% - 80%, and CHP capacity of around 25% to 50% of the peak demand. This is due to the need to maximise CHP engine size to increase efficiency and reduce capital costs resulting in a small number of engines which cannot follow the load as well, and therefore act as a base load supply. In addition, the higher electricity price assumed means that it is more worthwhile to invest in CHP capacity than in the current market. Also maintenance downtime is minimised as multiple units are being used and maintenance can be carried out when the engine is not needed to operate. Finally there is no space constraint imposed for thermal storage and at this scale thermal storage is very cost-effective. As a result daily peaks can be met by stored CHP heat rather than boilers.

The load modelling used in this study simplifies the annual energy demand profile into 39 demand periods (an example of a load profile for CZ 1 is shown in Figure 6 – note that this does not relate directly to Scenario 1 and is shown for indication only). This will remove large sharp peaks in the thermal demand, allowing the CHP systems to meet more of the peak

---

[4] This calculation is an average assuming that all classes have macro DE. An average efficiency of 50% is used to represent modern large scale gas CCGT electricity generation on the grid.

load. However given the general large size of the zones assessed resulting in diversity, and the access to adequate thermal storage, this smoothed profile is a reasonable assumption.

This the schemes optimised for scenario 1 illustrate the benefits from large scale deployment of DE, with DHNs which are significantly larger than current planned or operating schemes allowing greater use and optimisation of CHP.

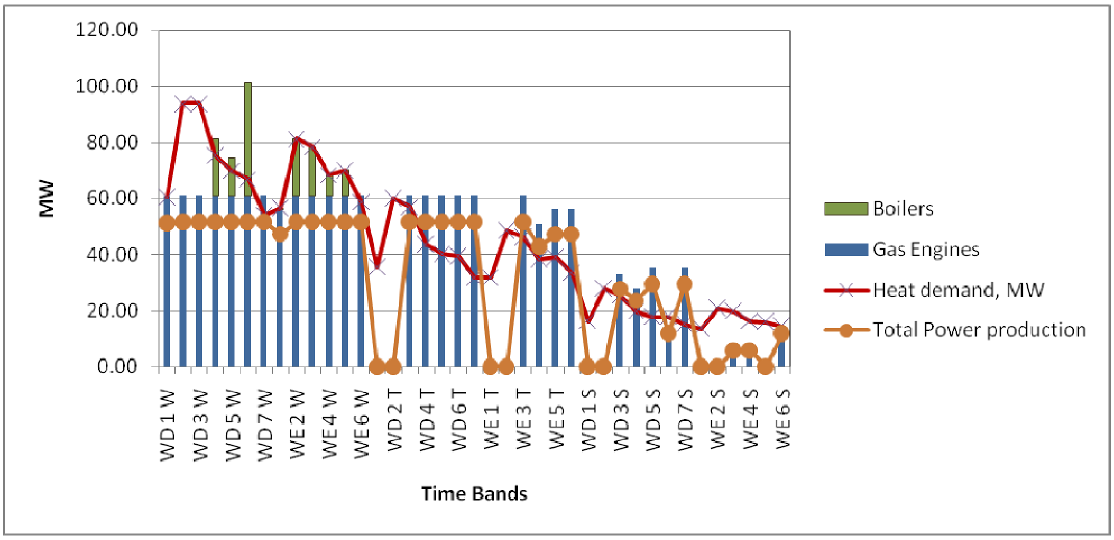


Figure 6 Example of a load profile taken from WP 4, showing the sizing and outputs from plant designed to meet the 39 profile bands (WD – Weekday, WE – Weekend, W – Winter, T – Transition, S – Summer). Note that this is not specific to scenario 1 assumptions and is shown for indication only of how the banding operates.

Deployment costs

The majority of capital costs of a DE scheme are typically due to the DHN installation and it is therefore important to understand the capital cost breakdown of schemes to assess the likely impact of different scenarios and policies. The data presented in Figure 7 and Figure 8 shows the annualised capital cost of installing the DHN and energy centre for each CZ, both in absolute terms (Figure 7) and normalised to the annual thermal demand of the respective CZ (Figure 8).

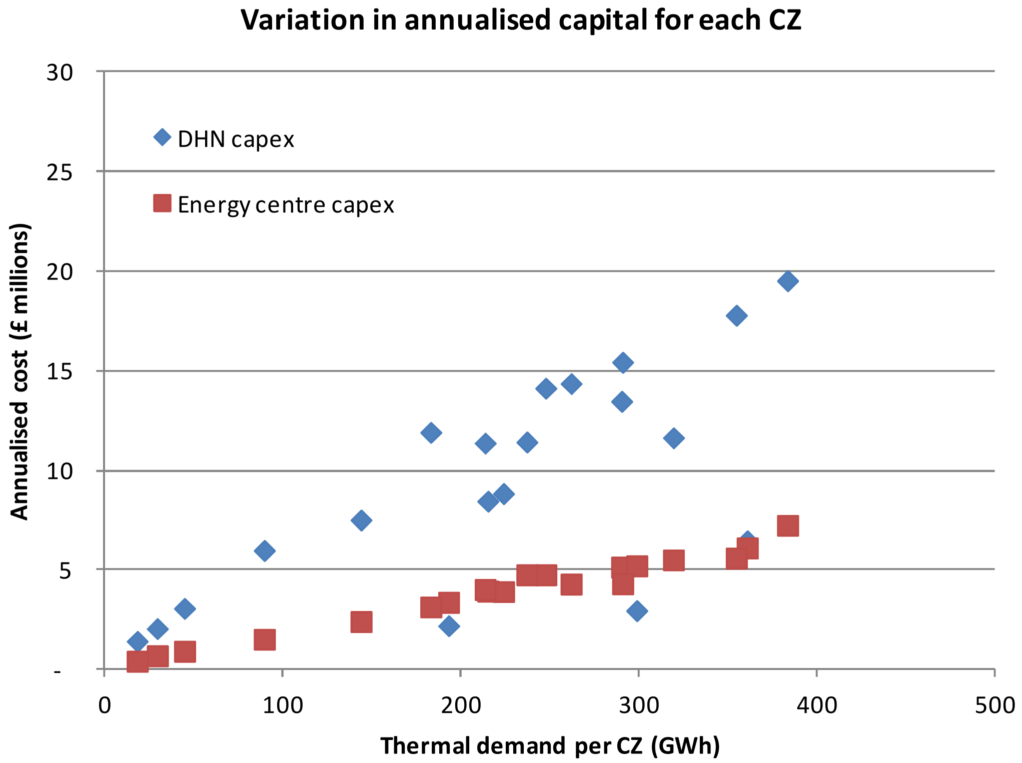


Figure 7: Chart showing the capital cost of DHN and Energy centres for each of the CZs.

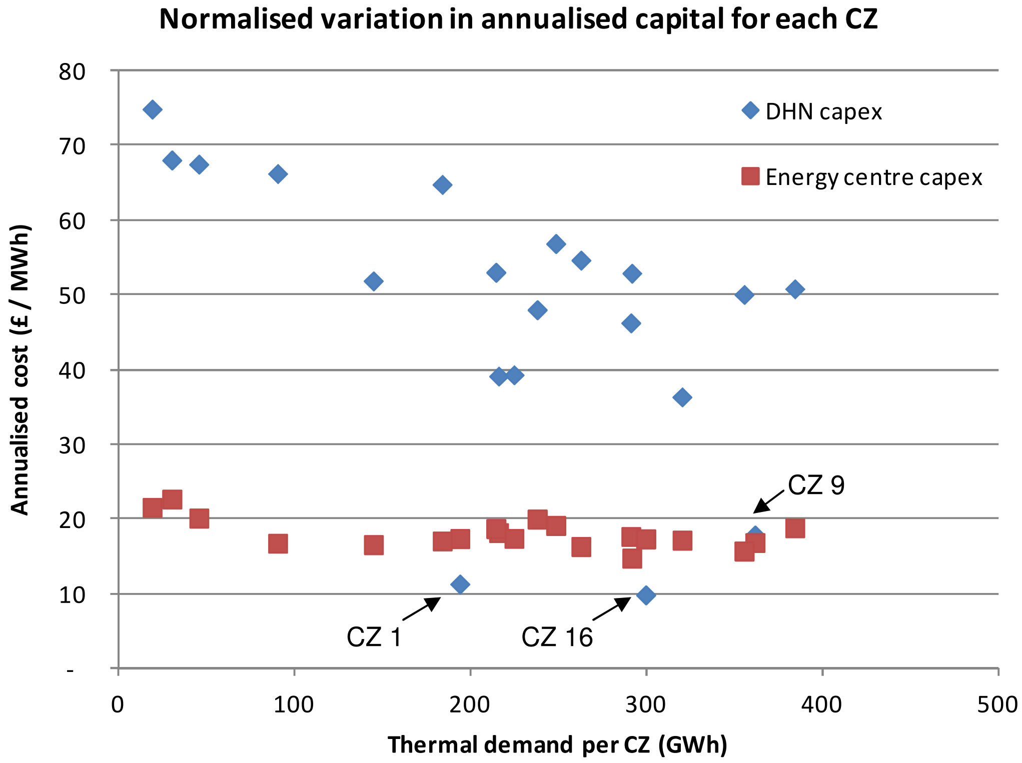


Figure 8: Chart showing the capital cost of DHN and Energy centres for each of the CZs normalised by annual thermal demand of each CZ.

The absolute cost values demonstrate the strong dependence between energy centre capital cost and the thermal demand of the CZ. This is to be expected due to the modular nature of schemes and suggests that it should be possible to benchmark energy centre costs based on thermal demands for large optimised DE schemes. This is supported by the normalised annualised costs which show a consistent result of between £15 / MWh and £20 / MWh for all but the smallest CZs. The higher costs for the smallest CZs (of between 6 MW and 16 MW) is due to the reduced optimisation and modularisation.

The annualised costs show that the DHN costs are approximately two thirds of the overall capital expenditure for most of the schemes. The absolute values show a strong relation between maximum DHN cost and size of scheme, although three CZs in particular have a significantly lower cost: CZs 1, 9, and 16. The majority of CZs have a domestic load which is similar to or much higher than the commercial load, and therefore the domestic connections strongly influence the overall DHN costs. However the commercial loads in CZs 1, 9, and 16 are all high, and in the case of CZs 1 and 16 higher than the domestic loads. This results in higher heat density, a smaller number of buildings to be connected and therefore a much lower capital cost of the DHN compared to the typical level where domestic customers dominate. The normalised results highlight these trends with a strong relationship between DHN capital cost and annual thermal demand for the majority of CZs, but significantly lower costs per GWh for the areas with a high proportion of commercial buildings (highlighted in Figure 8).

The DHN costs demonstrate that the network costs will dominate the capital expenditure in the majority of zones. In these zones, the costs can be benchmarked based on the annual thermal demand, albeit with a range of circa +/- 20% (based on £40 / MWh to £60 / MWh for a 200 GWh zone). However in areas with large commercial thermal loads, the costs can be reduced but are more likely to be determined by site specific factors such as size of individual buildings and network layout.

Performance of schemes

The performance of each CZ is shown in Figure 9, illustrating both the levelised cost of the DE schemes and CO_2 intensity of the heat delivered, compared to the counterfactual technologies. (It should be noted that the chart includes average results relating to the three different GB benefits case scenarios and these are discussed in the next section).

Counterfactual performance

The gas boiler counterfactual has an average (across all CZs) levelised cost of circa

9.6 p/kWh and a CO_2 intensity of 0.21 kg CO_2/kWh. The alternative counterfactual of ASHPs has an identical average CO_2 intensity and therefore at present offers no environmental benefit over gas boilers, but has a higher levelised cost of circa 15 p/kWh.

Levelised cost of heat from macro DE

The macro DE results from each CZ have a range of levelised costs from around 3 p/kWh to 10 p/kWh with an average around 7 p/kWh. These are all lower than either their respective gas boiler or ASHP counterfactuals. A significant conclusion is therefore that if sufficiently large DE schemes can be developed, all of the CZs, and therefore classes identified, could be economic for macro DE deployment, representing nearly half of the total heat demand of buildings in GB.

The wide range of levelised costs can be related to the following factors:

- **The cost of the heat network.** The three CZs with the lowest cost of heat are CZs 1, 9 and 16 as identified in Figure 8 and have low DHN costs in relation to the annual thermal demand as a result of their high proportion of commercial and institutional buildings.

- **Energy centre costs.** The analysis in Figure 8 demonstrates that for the smallest schemes (typically less than 100 GWh or circa 30 MWth peak), the normalised cost of the energy centre increases. The average levelised cost of heat from DE schemes across the CZs is 7p / kWh with most schemes between 6 p/kWh and 8 p/kWh. However from Figure 10, it is clear that there is a relation between heat price and size of scheme with the four smallest CZs having the highest levelised cost of heat (all above 8p / kWh).

These two factors are linked to the scale and type of scheme as discussed earlier in this section, in particular the mix between domestic and non-domestic customers.

The values presented show that Macro DE schemes could be economic for all of the classes considered, under the scenario presented. It must be remembered though that the schemes identified to represent mass deployment for this study are large in comparison to current DE schemes, and achieving these economies would require a step change in scheme size.

CO_2 emissions from macro DE

The results also demonstrate that macro DE schemes deployed in the 2010s using modular gas fired CHP engines to deliver the majority of heat on the DHN, will deliver near zero carbon heat in most of the CZs. The high carbon savings are generated through the displacement of the current relatively high carbon grid electricity. The CO_2 savings are perhaps larger than exhibited in existing schemes, or other analyses. This is a reflection of the high proportion of heat provided by the CHP systems due to their modularity combined with the large scale of the schemes, and the corresponding increase in electricity generation and export offsetting high-carbon grid electricity.

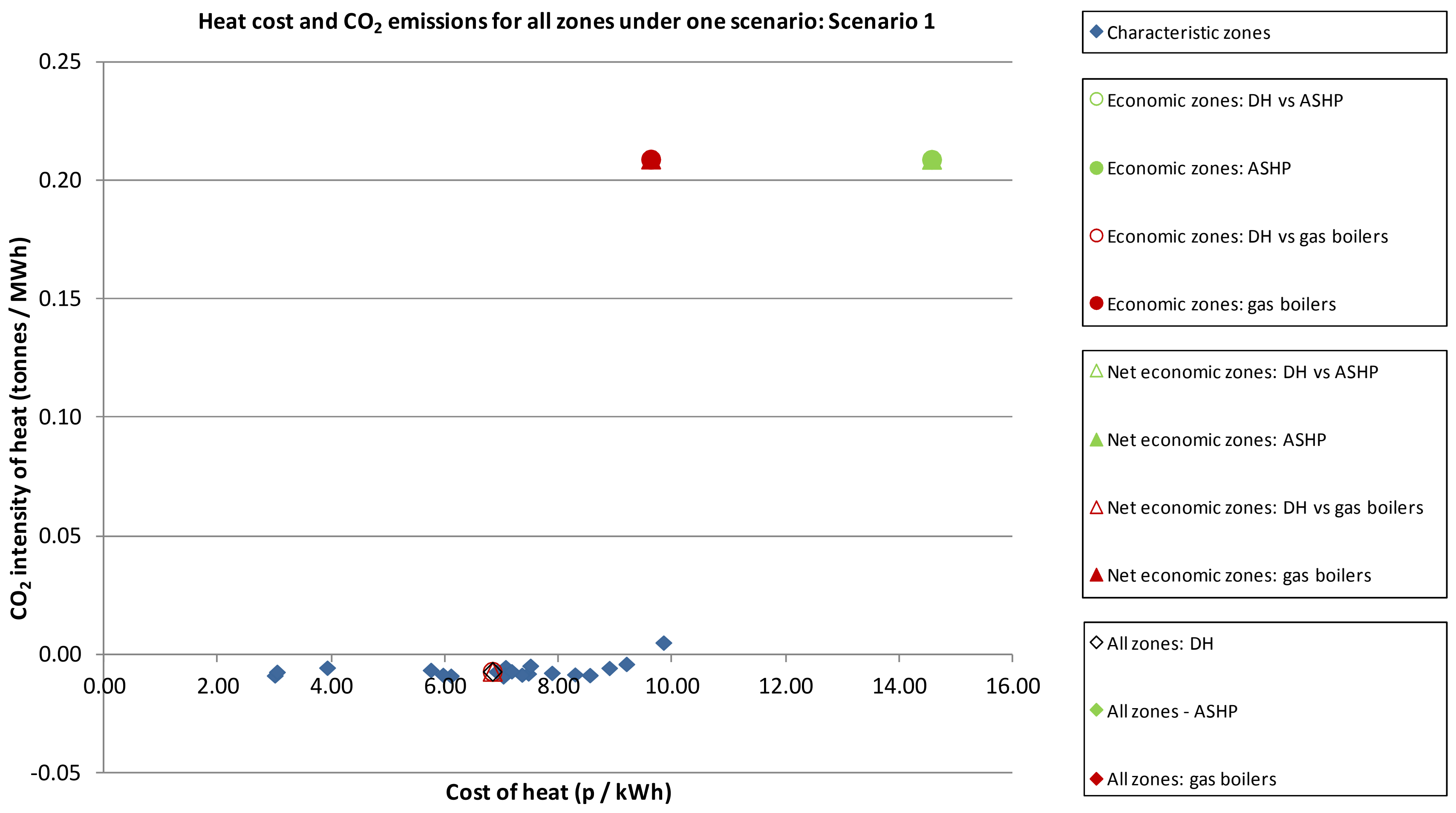


Figure 9: The carbon and cost performance of all CZs in scenario 1.

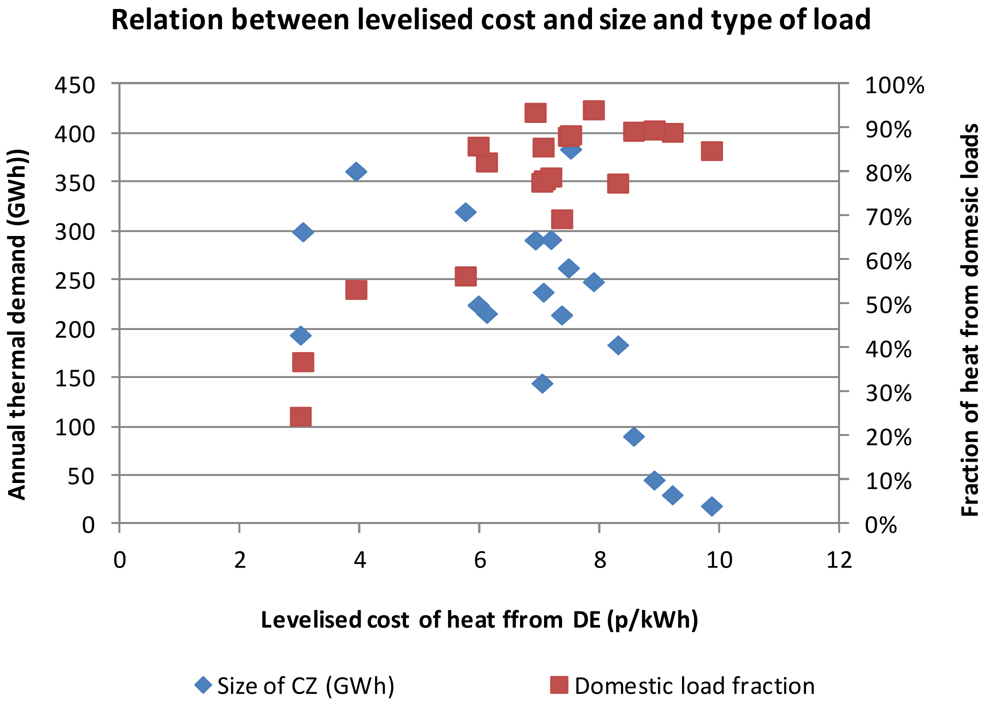


Figure 10: Chart showing the relation between levelised cost of heat and the size (by annual thermal demand) of each CZ, and the fraction of thermal load in each CZ from domestic uses. This demonstrates that in general, the levelised cost is higher for schemes with a larger fraction of domestic loads, and is also higher for smaller schemes. The lowest cost schemes in CZs 1, 9, and 16 (represented by the 3 squares on the left hand side) are dominated by non-domestic loads and are also relatively large. The higher heat density and reduced DHN requirements provide the lower costs in non-domestic areas.

The GB benefits case

The optimisation results demonstrate that macro DE in scenario 1 has an economic solution for every CZ using natural gas fired CHP. This means that under each of the benefit's case scenarios, all CZs are deemed to be suitable for DE, and therefore by implication, all of the zones identified in this study are deemed to have potential. For this reason, the data points which represent the averages for each of the counterfactuals and the DE schemes under each benefits case in Figure 9 are identical.

A summary of the GB benefits case for scenario 1 is provided in Table 2 and shows that in all benefits case scenarios, macro DE has the economic potential to provide heat to 43% of the GB building heat demand, with an annual saving of £5.6 billion in heating bills against a gas boiler counterfactual, equivalent to a 29% reduction in heating costs for the connected customers. This represents DE being connected to almost half of the housing stock in GB cost effectively [5].

The CO_2 reduction across all zones is the same for both counterfactuals and calculated at

---

[5] Statistics from the Department of Communities and Local Government suggest that there were 26.5 million dwellings in GB in 2010.

43 Mtonnes per year. This is equivalent to a 38% reduction in CO_2 emissions arising from heating buildings in GB[6].

Table 2: Summary of the GB benefits case for scenario 1.

	DE heat provision	DE heat provision	Commercial connections	Domestic connections	CO_2 reduction	CO_2 reduction	GB cost reduction
	TWh	% of GB heat	millions	millions	Mtonnes	%	£ billion
Counterfactual - gas boilers							
Case 1. Commercially driven uptake	199	43%	2.9	12.4	43.0	38%	5.6
Case 2. GB economy driven uptake	199	43%	2.9	12.4	43.0	38%	5.6
Case 3. Maximum CO2 reduction	199	43%	2.9	12.4	43.0	38%	5.6
Counterfactual - ASHP							
Case 1. Commercially driven uptake	199	43%	2.9	12.4	43.0	38%	15.4
Case 2. GB economy driven uptake	199	43%	2.9	12.4	43.0	38%	15.4
Case 3. Maximum CO2 reduction	199	43%	2.9	12.4	43.0	38%	15.4

The marginal abatement curves in Figure 11 and Figure 12 show the carbon and cost performance of each class (CZs aggregated to GB level). They both show characteristics typical of many abatement or supply curves, with a high cost sensitivity in the lower and upper cost regions, and a lower cost sensitivity for the majority of central zones. This means that if an economic threshold (such as the level deemed to be economically viable) falls within the zones at either extreme, small changes to the threshold will have little impact on the overall potential. However if the threshold falls within the central region, then small changes in the threshold could result in large changes to the potential.

For the gas boiler counterfactual (Figure 11), the eight mid classes (CZ 4 to CZ 12 on the MAC curve) have a net cost saving of circa 2.5 p/kWh – 3 p/kWh with macro DE, and provide a CO_2 reduction of 28 Mtonnes, or 65% of the total reduction potential. Classes represented by CZs 9 to 5 on the curve provide more cost effective DE solutions with a saving of up to 5 p/kWh and therefore these schemes are obvious targets for early deployment of DE. They provide a total CO_2 reduction of 7.8 Mtonnes or 18% of the total reduction potential. These more cost effective classes each generally have a lower CO_2 reduction potential than the classes in the centre of the curve due to the reduced number of zones across GB and the

---

[6] The total emissions associated with heating buildings in the UK is 123 Mtonnes per year (DECC statistics). Heat emissions are not available at a GB level, and therefore the UK figure has been reduced in line with the overall emissions fraction for GB compared to the UK giving a GB figure of 113 Mtonnes per year.

size of each individual zone. In general these classes are likely to be dense urban areas and are therefore limited.

The MAC curve with an ASHP counterfactual demonstrates the increased economic advantage of DE compared with heat pumps. All classes are predicted to have a heat cost of around 6 p/kWh or more lower than the ASHP counterfactual, with up to 11 p/kWh improvement for the class represented by CZ 10. Unlike the results shown for the gas boiler counterfactual, there is no strong trend at the less cost-effective end (to the right of the chart) suggesting that, against an ASHP counterfactual, other zones not included in the current analysis at lower heat densities may also be suitable for DE deployment. Table 2 shows that DE could provide annual cost savings of around £15 billion compared with ASHPs, equivalent to a 53% reduction in cost for the connected zones.

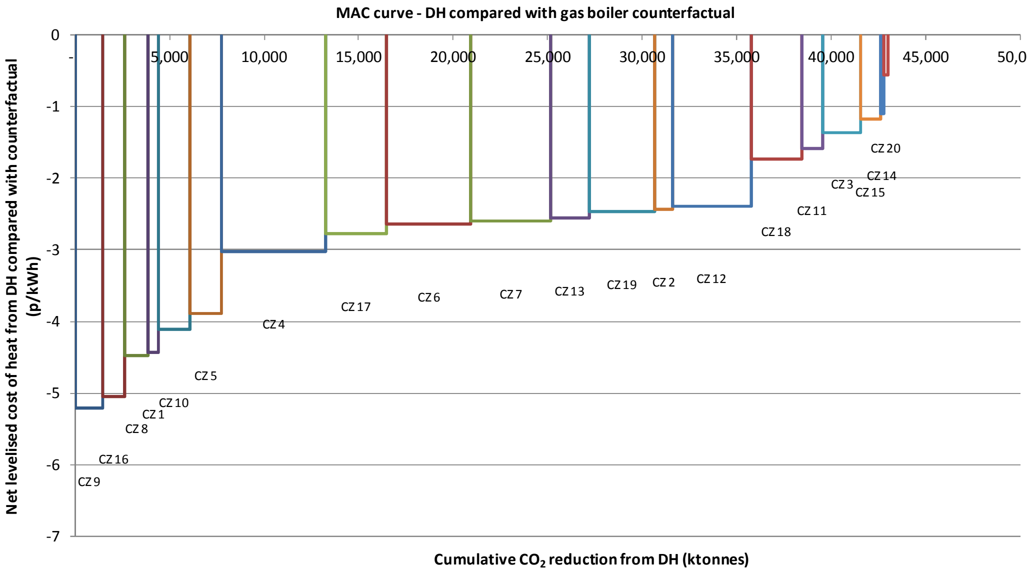


Figure 11: Marginal abatement curve showing the performance of each CZ against a gas boiler counterfactual.

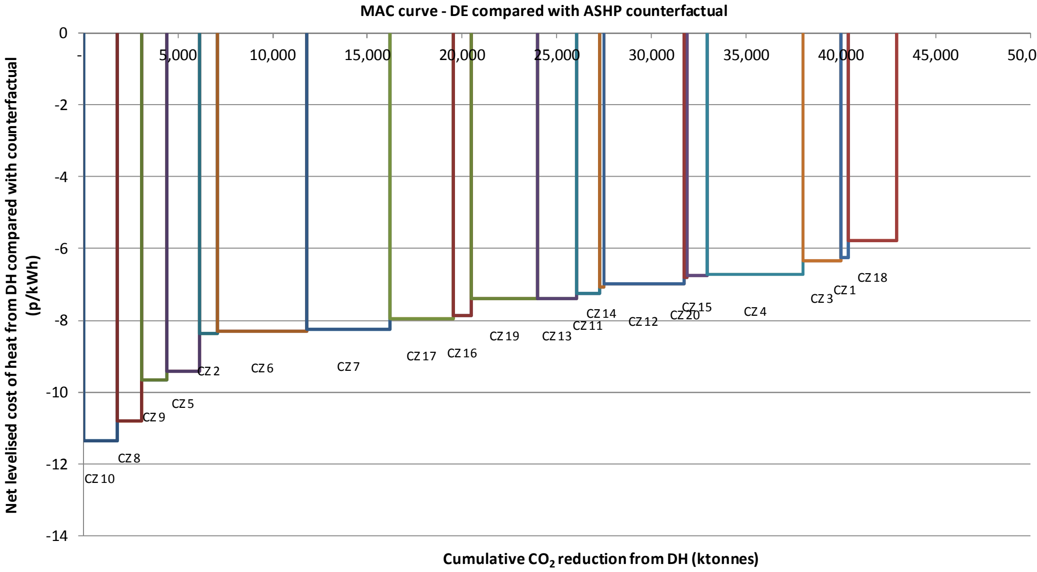


Figure 12: Marginal abatement curve showing the performance of each CZ against an ASHP counterfactual.

Assessment of electricity generation

The discussion so far has examined the production of heat and the impact this has on the GB heat market. However, all of the schemes in scenario 1 make use of gas fired CHP and so it is also important to consider the electricity generation.

At a local level, the development of CHP schemes needs to consider the viability of connection and the ability of the local distribution network to accept large amounts of decentralised generation. This study implicitly assumes that the local level connection barriers can be overcome, enabling CHP systems to be connected to the electricity grid and export all of the electricity generated for sale. The availability of a suitable connection with capacity will be site and location dependent. However whilst there may be an impact on local distribution networks, the local generation of electricity will reduce the demands on the wider transmission network by removing the need for the transmission of electricity from supply to demand over long distances. The pattern could become increasingly supply from urban energy centres to surrounding rural areas for electric heating / heat pumps. Over the period of assessment (2010s to 2030s) it is likely that the projected changes in UK electricity generation and supply with significant uptake in renewable generation and other forms of electricity demand (such as transportation) will result in alterations to the electricity grid design and operation. Increased macro DE will be one of the many changes which need to be considered.

The use of direct sales or private wire networks is not considered as part of this work. Whilst these can offer opportunities in specific small scale schemes, large scale DE deployment must rely on the local distribution networks and changes to the electricity market to facilitate distributed generation and provide fair electricity revenue. The scale of electricity generation from macro DE is such that finding large local customers is unlikely in most zones, and a wider customer base will be required, necessitating the use of the wider distribution network.

At a macro scale, the widespread generation of electricity from distributed sources needs to be considered at a GB supply / demand level. If the uptake of macro DE results in significant levels of electricity generation, then the match between electricity supply and demand may impact negatively on the operation of DE schemes. However, the generation of electricity from macro DE schemes will generally coincide with the heating demand pattern, and so could be used to help balance an increased electricity demand from low carbon electric heating systems (such as heat pumps) which could be increasingly used in areas where macro DE and DHNs are not viable.

In scenario 1, the total electricity demand for all buildings connected to the DE schemes is 136 TWh per year, and the total electricity demand for the UK is 298 TWh per year[7]. Under the benefits cases, the annual generation from the DE schemes assuming they are taken up in all economic areas is 185 TWh per year, or 62% of the total annual electricity demand. This is less than the current generation of electricity from fossil fuel power stations.

The output from DE could therefore be a significant proportion of the total GB electricity demand and the results need to be considered both in the context of heat supply, but also strategic electricity provision. This needs to be examined further.

Sensitivity analysis

The results presented show that macro DE can be economic for all zones. However the economics of a CHP scheme can be heavily dependent on the revenue associated with electricity. In this study, this revenue can be split into the electricity sale price, and the carbon value of the electricity.

The following sensitivities are based on CZ 7 which was selected on the basis of being mid way along the MAC curve, and therefore in a region where changes to the economics could

---

[7] The GB demand of 298 GWh per year is based on 2010 statistics from DECC covering all consumers including industry.

have a large impact on the GB potential. Under the base scenario 1 assumptions, the levelised cost of heat from macro DE for CZ 7 is 6.1 p/kWh which is 2.6 p/kWh lower than the gas boiler counterfactual.

Sensitivity to electricity sale price

Current electricity revenue is based on achieving a sale price equal to the variable element of an industrial retail price as given by DECC/HMT[8]. If the electricity revenue is reduced by 20% to a level which represents a typical commercially available contract, the levelised cost of heat for CZ7 increases to 8.5 p/kWh, resulting in only a 0.2 p/kWh benefit over gas boilers. With this change, CZ7 becomes marginal economically viable and it will be likely (from Figure 11) that most zones above CZ7 will be uneconomic, reducing the GB potential by around half. Small changes in electricity revenue around the 20% reduction could have a large impact on whether marginal zones are economic or not.

Despite this change, it is still likely that a 20% reduction in electricity revenue will not alter the potential for Benefits Case 2 (GB Economy) significantly. With around half of the zones becoming uneconomic, from Figure 11 it can be seen that the economic savings to the left of CZ 7 will still approximately balance the increased costs to the right of CZ 7 (assuming that there can be some cross subsidy to fund the schemes) to allow the maximum CO_2 reduction.

Sensitivity to carbon pricing

The future of carbon pricing is uncertain, and whilst it is likely there will be some form of carbon pricing to incentivise low carbon generation, the exact form and cost of this isnot known, and likely to change over time.

If carbon pricing is removed from the optimisation, then both the levelised cost of heat from the macro DE scheme and from the counterfactuals reduces. Against the gas boiler counterfactual, the macro DE scheme is now only 1.3 p/kWh lower in cost, compared to 2.6p/kWh. Therefore the impact on carbon pricing on the economic performance is not as large as a 20% reduction in the electricity revenue value.

Sensitivity to both electricity revenue and carbon pricing

If both the electricity revenue is reduced and carbon pricing removed, the cost of heat from the macro DE scheme becomes 0.5 p/kWh more expensive than the gas boiler counterfactual, although is still over 5 p/kWh cheaper than the ASHP counterfactual.

From Figure 11, if the levelised cost for all classes is adjusted such that CZ 7 lies 0.5 p/kWh above the axis (i.e. is uneconomic), then the GB economic potential is reduced and only the most economic zones remain cost effective. This simulation is illustrated in Figure 13. This sensitivity is closest to the current position using commercial electricity contracts and no carbon related incentive mechanism for gas-fired CHP.

---

[8] Valuation of energy use and greenhouse gas emissions for appraisal and evaluation, Interdepartmental Analysts Group, DECC/HMT, October 2011

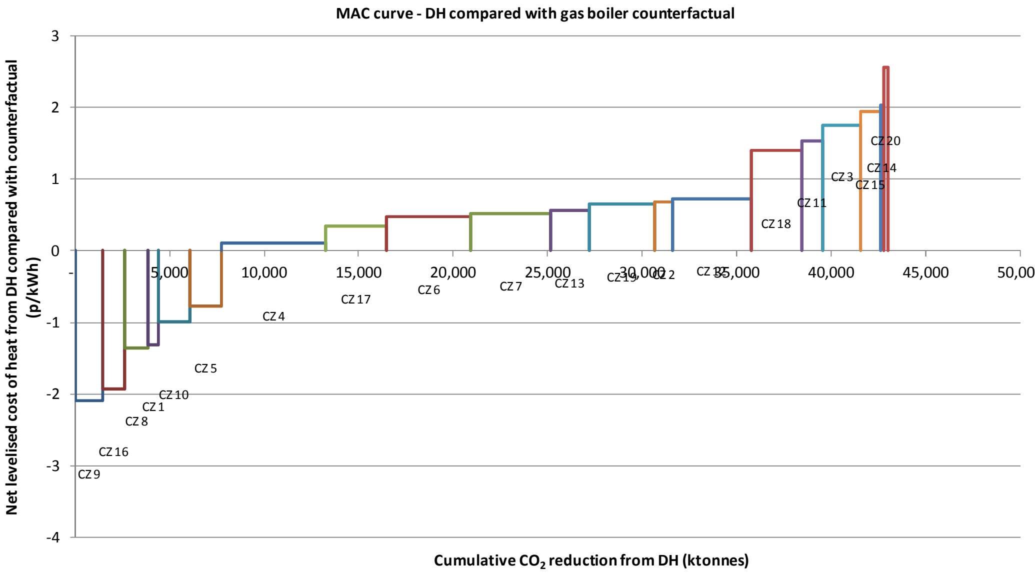


Figure 13: MAC curve for scenario 1 adjusted to represent the impact of reduced electricity revenue and no carbon pricing.

Summary of scenario 1

The results from scenario 1 provide an assessment of the current potential for macro DE in GB with the widespread deployment of DE schemes. The modelling implicitly assumes that many of the non-technical barriers to DE can be overcome enabling the development of large scale schemes with a high uptake of customers (the modelling assumes 80% of customers connect in an area for the central case).

Under these circumstances, all of the classes identified as being potentially suitable for DHNs, represented by the 20 CZs (see Figure 1), have potential for the development of an economic macro DE scheme, which is cost effective against both gas boilers and air source heat pumps. This covers almost half of the dwellings in GB and 43% of the heat market. The optimised schemes consist of modular natural gas CHP engines which provide almost all the heat demand (by closely following the thermal load profile) and result in near zero carbon heat assuming current grid electricity emission factors.

At a GB level, these economic schemes offer the potential for 38% reduction in CO_2 from heating, and annual savings of between £5.6 billion (compared with gas boilers) and £15.4 billion (compared with ASHPs). However the electricity generated by the schemes represents a significant proportion of the GB electricity demand and consideration is required of how this can be accommodated in the electricity system.

The schemes are sensitive to the value obtained for the electricity generated, and to a lesser extent the inclusion of carbon pricing. With simple sensitivity testing on CZ 7, the reduction in revenue from electricity combined with removal of carbon price incentive renders the zone uneconomic. If the same effect is considered across all zones, the economic potential for macro DE would be reduced with a CO_2 reduction from 43 Mtonnes to around 7.8 Mtonnes. This demonstrates the importance of having an electricity market which is suited to mass scale decentralised generation.

Large scale deployment of macro DE – Central Case

Introduction

This section provides an overview of the results from the Central case represented by scenario 7. The central case examines the potential of macro DE in the 2020s when large scale deployment is most likely, using a set of assumptions which are deemed mid range. These include an 80% market penetration, mid energy values, central capital costs, the valuation of carbon, and an 8% discount rate. Also by the 2020s, the electricity emission factor is reduced to reflect new high efficiency CCGT power stations so that the CO_2 benefit from gas-fired CHP is reduced. These results form the basis for further scenario modelling which examines the sensitivity of each input.

Description of the optimised schemes

The schemes optimised in scenario 7 for deployment in the 2020s are identical to the 2010 scenario, with all CZs making use of multiple natural gas fired CHP engines in a modular nature. For all the CZs, the CHP units provide virtually all the heating, with all zones above 96% proportion of CHP heat. The overall energy centre efficiency is correspondingly high at between 82% and 84%.

Performance of the schemes

The performance of each CZ under the central case is shown in Figure 14, illustrating both the levelised cost of the DE schemes and CO_2 intensity of the heat delivered, compared to the counterfactual technologies. (It should be noted that the chart includes average results relating to the three different GB Benefits Cases and these are discussed in the next section).

Counterfactual performance

The average gas boiler counterfactual has a cost of around 10.4 p/kWh, an increase on the 2010 scenario due to an increase in energy prices over the period. The CO_2 intensity remains identical to scenario 1 as it is assumed that there are no changes in gas boiler efficiency or the CO_2 emission factor for natural gas.

The results show that ASHPs are expected to become more competitive, both in terms of cost and carbon over the period 2010 – 2020. Whilst the cost of heat is still higher than gas boilers, it has reduced from the 2010 scenario, despite higher electricity costs, due to improvements in heat pump performance. The combination of efficiency improvements and a reduction in the electricity grid emission factor has also led to a reduction in the heat CO_2 intensity to 0.14 kg/kWh CO_2, providing a 25% improvement over gas boilers.

Levelised cost of heat from macro DE

The results in Figure 14 show that the levelised cost of heat from macro DE schemes remains similar to the 2010 scenario, with a range from 3 p/kWh to 10 p/kWh. For all CZs, the levelised heat cost from macro DE is lower than the respective boiler and ASHP counterfactuals, as demonstrated in the MAC curves in Figure 15 and Figure 16.

The negligible change in levelised heat cost from macro DE, combined with the increase in levelised heat cost from the gas boiler counterfactual, means that macro DE schemes are predicted to be more cost effective in the 2020s than 2010s by around 0.5 p/kWh. The cost advantage over the ASHP is now smaller than in 2010, but there remains a large saving for all CZs with macro DE still being between 4 p/kWh and 8 p/kWh lower in levelised cost.

These results demonstrate that during the 2020s, when mass deployment of macro DE may occur, it provides the lowest cost heat solution for all the identified zones.

CO_2 emissions from macro DE

The change in average electricity grid emission factor between the 2010s and the 2020s from 0.485 kg/kWh CO_2 to 0.351 kg/kWh CO_2 reduces the CO_2 savings from CHP through reduced grid CO_2 displacement. By allocating the CHP CO_2 emissions to the heat produced, this means that the heat emissions factor increases.

The data presented for each CZ in Figure 14 shows that the heat emissions factor has increased from circa 0 kg/kWh CO_2 in the 2010s to around 0.1 kg/kWh CO_2 to 0.14 kg/kWh CO_2 in the 2020s. This increase means that the CO_2 saving potential from macro DE based around natural gas CHP is much smaller than in the 2010s, but still provides a saving compared with both the gas boiler and ASHP counterfactuals.

One trend observable in the CO_2 intensity values for each CZ is an increase in heat CO_2 emission factor with increasing macro DE levelised heat cost. This is likely to be partially a function of the scheme size, with larger schemes having larger more efficient CHP engines. It will also depend on the heat density and the subsequent thermal losses of the scheme which is linked to the type of buildings connected.

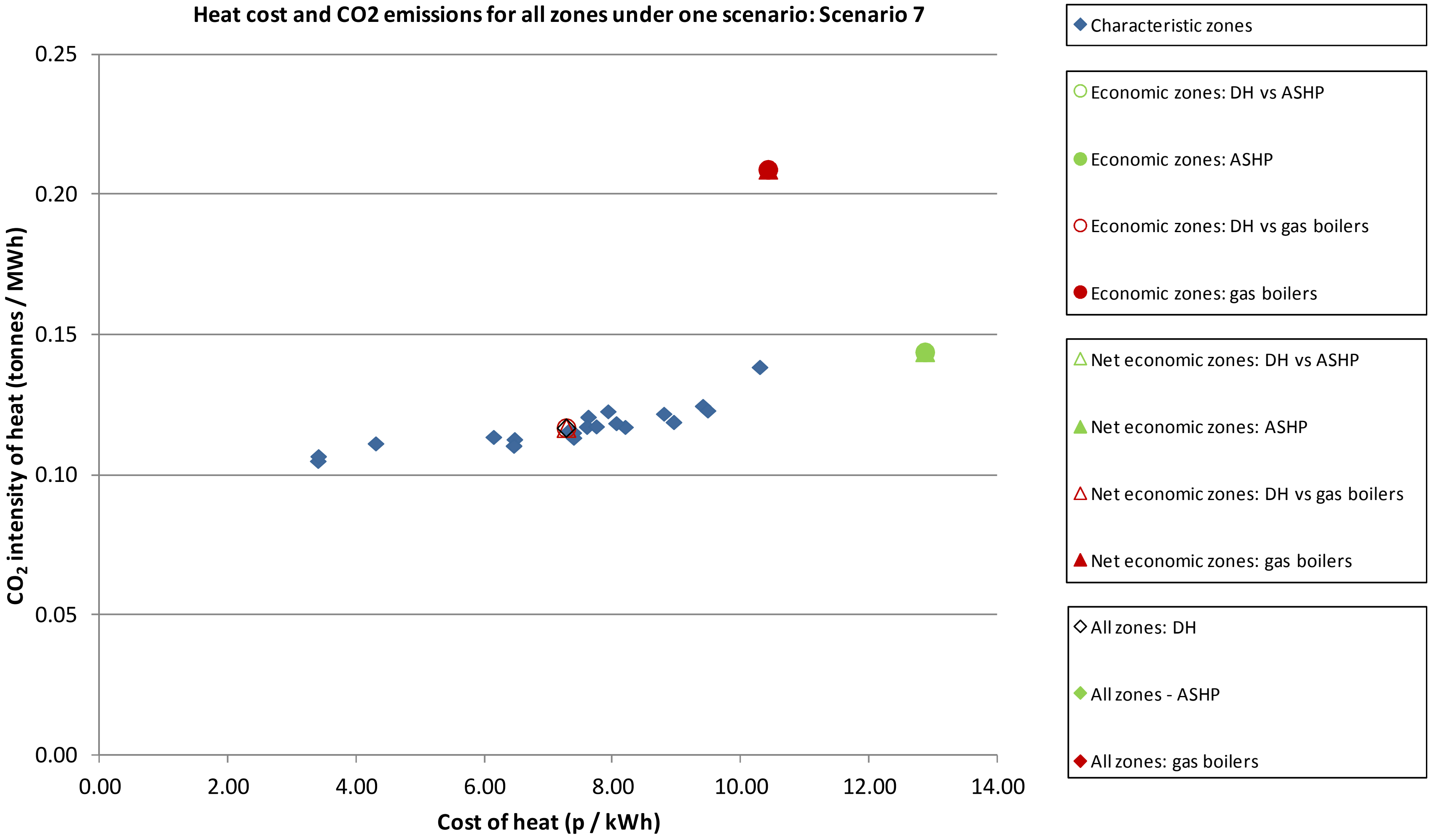


Figure 14: The carbon and cost performance of all CZs in the central case, scenario 7.

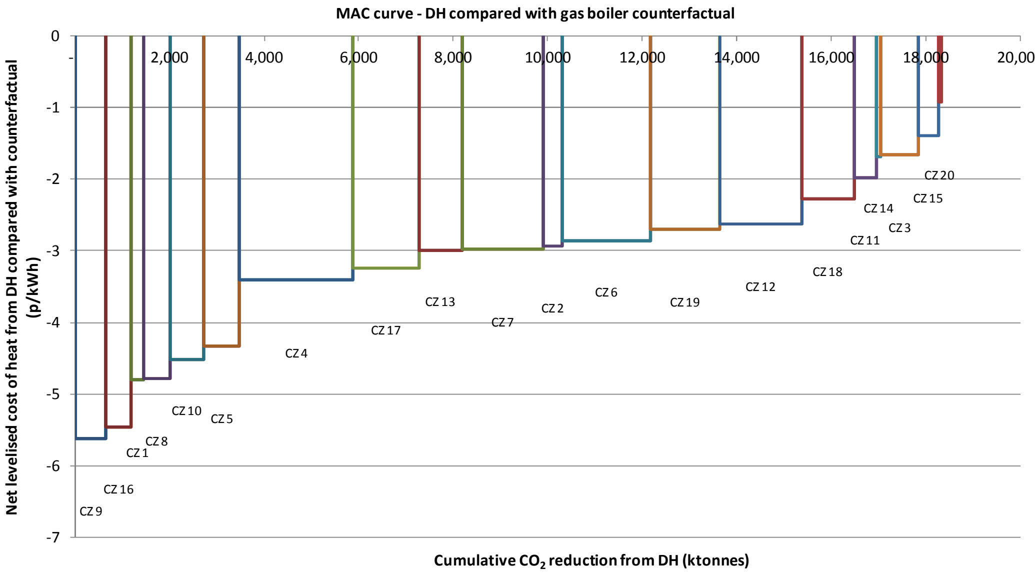


Figure 15: MAC curve showing central case DE results compared with gas boiler counterfactual

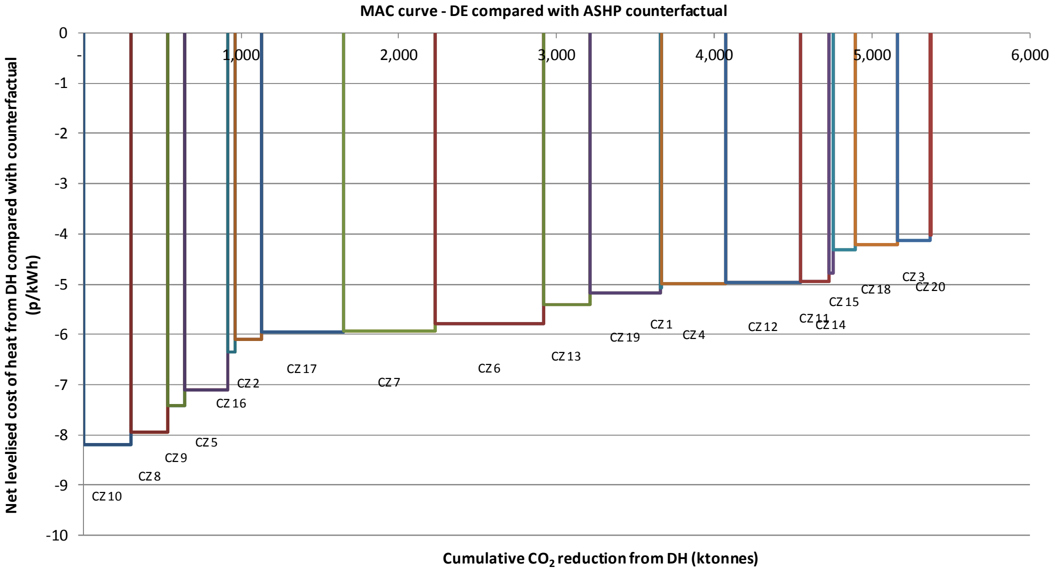


Figure 16: MAC curve showing central case DE results compared with ASHP counterfactual

The GB benefits case

Similarly to scenario 1, the optimised macro DE solution for all zones is economic compared against both counterfactuals. This means that the GB potential is identical for each of the benefit cases. For this reason, the average macro DE and average counterfactual results for each of the benefits cases in Figure 14 are identical. A summary of the GB potential is provided in Table 3.

Table 3: Summary of the GB benefits case for the central case, scenario 7.

	DE heat provision	DE heat provision	Commercial connections	Domestic connections	CO_2 reduction	CO_2 reduction	GB cost reduction
	TWh	% of GB heat	millions	millions	Mtonnes	%	£ billion
Counterfactual - gas boilers							
Case 1. Commercially driven uptake	199	43%	2.9	12.4	18.3	16%	6.3
Case 2. GB economy driven uptake	199	43%	2.9	12.4	18.3	16%	6.3
Case 3. Maximum CO2 reduction	199	43%	2.9	12.4	18.3	16%	6.3
Counterfactual - ASHP							
Case 1. Commercially driven uptake	199	43%	2.9	12.4	5.4	5%	11.1
Case 2. GB economy driven uptake	199	43%	2.9	12.4	5.4	5%	11.1
Case 3. Maximum CO2 reduction	199	43%	2.9	12.4	5.4	5%	11.1

The GB benefits case in the 2020s is identical from the 2010 scenario in terms of heat supply and the number of potential customers, with a total potential of 43% of the GB buildings heating market for all cases under both counterfactuals.

Against a gas boiler counterfactual, the GB CO_2 savings would be 18.3 Mtonnes per year, a large reduction from the 2010s figure of 43 Mtonnes, but still a significant 16% reduction in CO_2 emissions from GB heating.

Alongside the CO_2 reduction potential, macro DE could provide an annual saving in heating costs of £6.3 billion, an increase on the 2010 annual saving potential.

With an increase in macro DE heat CO_2 intensity combined with improved performance of ASHPs and lower electricity grid emissions factors, the GB CO_2 reduction potential is significantly reduced against an ASHP counterfactual to just 5% of heat emissions. This presents a worst case scenario and assumes that all buildings which would otherwise connect to the DHN have an ASHP. Assuming that ASHPs are deployed at a mass market scale and become an incumbent for stand-alone heating by the 2020s, the uptake is still likely to be relatively low with a large stock of gas boilers installed during the 2010s (and before) remaining in use. This would mean the potential CO_2 savings from macro DE deployed during the 2020s would be somewhere between 5% and 16% of the GB heat emissions.

Although macro DE offers only a small advantage in CO_2 performance against ASHPs, the deployment of macro DE still provides a large economic saving potential for GB, with an annual heat cost saving of circa £11.1 billion p.a. for schemes deployed in the 2020s.

Summary of scenario 7

The optimisation modelling demonstrates that the types of macro DE scheme providing optimal economic performance in the 2020s are likely to be similar to those in the 2010s, making use of modular natural gas CHP engines. The resulting schemes have virtually all their heat provided by the CHP engines with boilers used mainly for back up and negligible peak provision.

Macro DE remains economic in all of the CZs as with scenario 1, resulting in a GB Potential of 43% of the heat market which can be provided more economically by macro DE than either the gas boiler or ASHP counterfactuals. The CO_2 savings achievable are smaller than in scenario 1, primarily because of the reduced electricity grid emissions factor, but savings of between 16% (against gas boilers) and 5% (against ASHP) are still achievable.

These results demonstrate that, providing DHNs can be deployed at scale across entire zones, macro DE provides a more cost and carbon effective solution for urban areas in GB than the counterfactual options of gas boilers or heat pumps. This is true in both the 2010s (scenario 1) and the central case of the 2020s, where the relatively high carbon intensity of the electricity grid results in CO_2 savings from gas fired CHP. Post the 2020s (as investigated in scenario 12), the DHN can be used to provide future flexibility for other low carbon forms of generation. Macro DE could complement the deployment of micro scale DE technologies in less dense areas.

Sensitivity analysis – 2020s deployment

Introduction

This section presents results from the sensitivity modelling around the central case to assess how alternative scenarios may impact on the viability of macro DE schemes and therefore the GB benefits case.

A summary of the scenarios is repeated below (also shown in Figure 2).

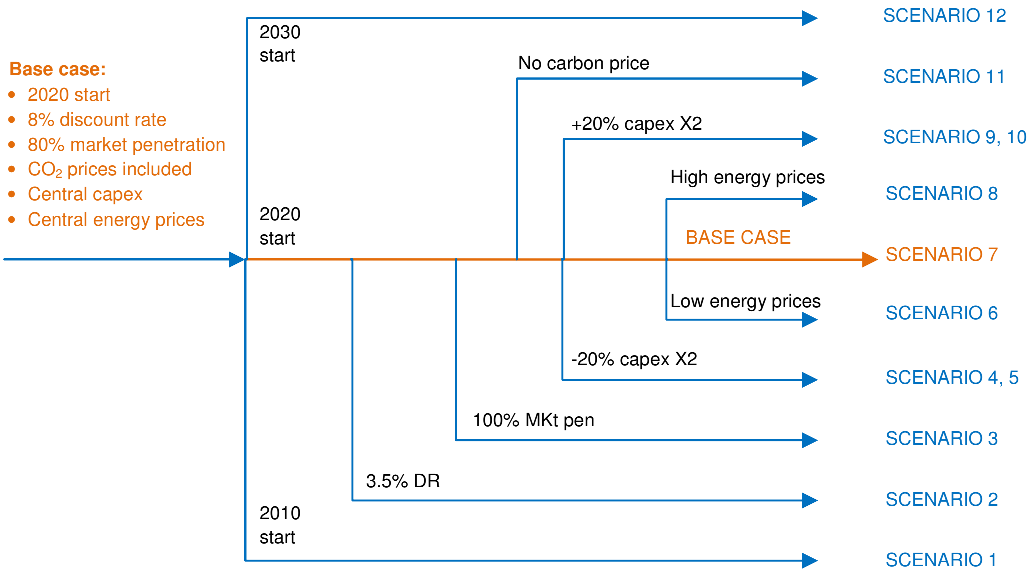


Figure 17. Schematic of the scenarios. Sensitivities are indicated around the base case. (Repeat of Figure 2).

Full results from each scenario for each CZ are provided in Appendix 3 and this section provides average results from across all CZs to allow trends to be observed.

Discount rate – Scenario 2

DE schemes can combine high capital investments with large ongoing operating costs and revenues. The discount rate applied to the analysis therefore can have a large impact on the economic viability.

The discount rate effectively represents the cost of finance. Applied to capital expenditure, it describes the interest paid on repayments. When applied to ongoing revenues and costs, it describes their value in terms of present day equivalence.

The central case discount rate of 8% represents a scheme which is primarily commercially led, but with a low risk due to the removal of many of the barriers associated with the deployment of macro DE, for example the access to heat markets, and ability to sell electricity. If a scheme was invested in by the public sector, then the requirement for returning a commercial profit is removed and lower cost sources of finance may be obtained. Both of these imply the use of a lower discount rate.

The results from scenario 2 show that reducing the discount rate to 3.5% results in the lowest cost of heat for macro DE from all scenarios [9]. From a central case scenario of around 7.3 p/kWh on average, the cost of macro DE heat is reduced to circa 5.4 p/kWh. The 3.5% discount rate is also used for the counterfactuals and as the gradient of the tails for the gas boiler and ASHP counterfactuals is lower than for the central case this shows that the costs for macro DE have reduced more than for the counterfactuals, increasing the net economic benefit.

All of the zones remain economic and so the three benefit case scenarios are the same, providing the same economic national penetration potential of 43% of heat provision as in scenario 7. The net GB economic benefit compared with gas boilers increases to £9.4 billion and against ASHPs to £17.4 billion.

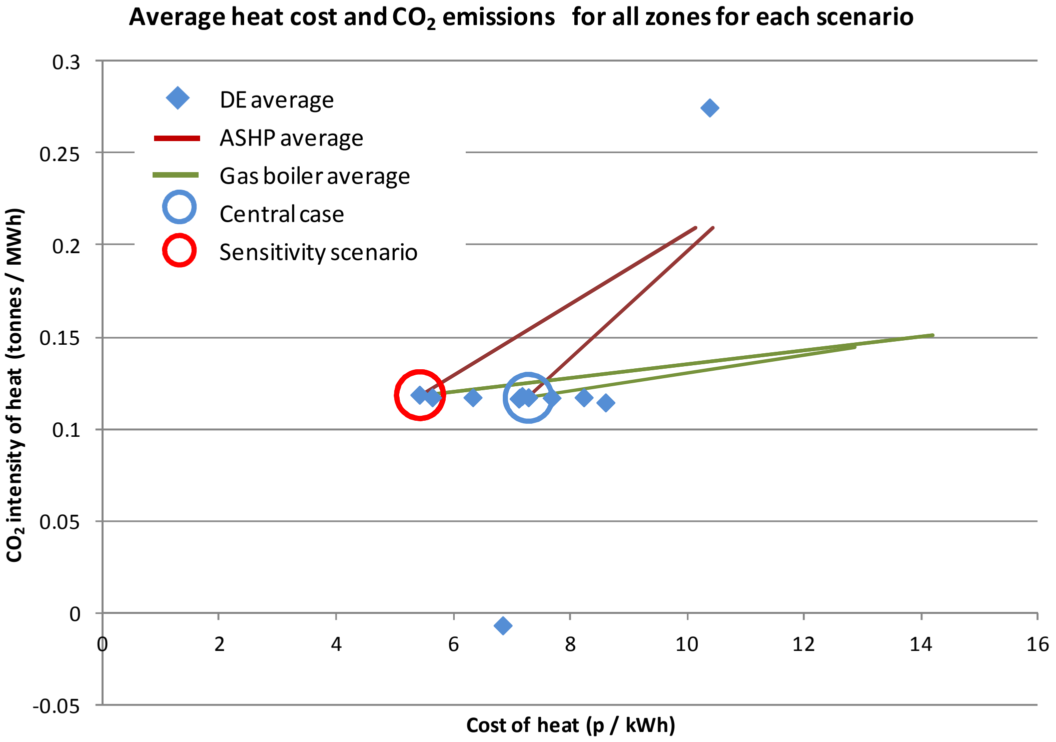


Figure 18: Average results for each scenario, with scenario 2 highlighted showing the impact of a reduced discount rate.

The results in Appendix 2 for scenario 2 show that reducing the discount rate results in a smaller range of heat cost across the zones. In the central case, the range of heat cost is circa 7 p/kWh, but in scenario 2 this reduces to circa 5 p/kWh. The reduction in range reflects the variance in capital expenditure between schemes, and a reduction in the costs associated with financing the capital investment.

Market penetration – Scenario 3

The central case assumes that 80% of connections within a zone are made. This market penetration therefore allows for some customers who either choose not to connect, or who are unable to connect to the DHN. By having less than 100% market penetration, certain components of the macro DE scheme can be reduced in size/number to match the 80% load. These include the energy centre, the local distribution network, and the building connections. It is assumed that the transmission components of the network are sized for 100% market

---

[9] The rate of 3.5% is provided by the UK Government HM Treasury Green Book and is the 'Social Time Preference Rate' The Green Book: Appraisal and Evaluation in Central Government.

penetration to allow for future connection (which may also require additional plant to be installed in the energy centre at a future date).

The results for scenario 3, highlighted in Figure 19, show that increasing the market penetration from 80% to 100% in each CZ reduces the cost of heat from the macro DE schemes by around 0.2 p/kWh on average. This demonstrates that the level of market penetration above 80% has a relatively small impact on the resulting cost of heat.

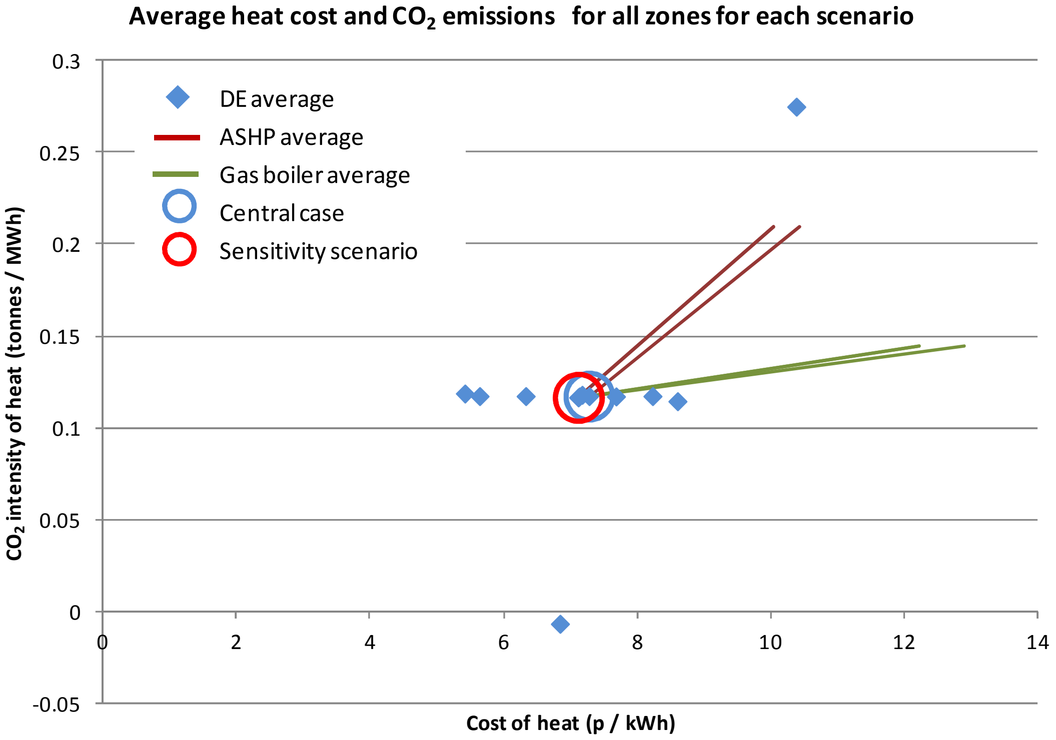


Figure 19: Average results for each scenario, with scenario 3 highlighted showing the impact of increased market penetration.

The result that market penetration above 80% has little impact on the economic viability of schemes has also been discussed in other research [10]. This research for the Department of Energy and Climate Change demonstrated that at high levels of penetration, above 80%, the resulting cost of heat will remain fairly constant. However at lower levels of penetration, a change in uptake within a zone has a much larger impact on the cost of heat. This is illustrated in Figure 20 taken from the research.

---

[10] The Potential and Costs of District Heating Networks. 2009. Poyry Energy Consulting and AECOM. Published by DECC.

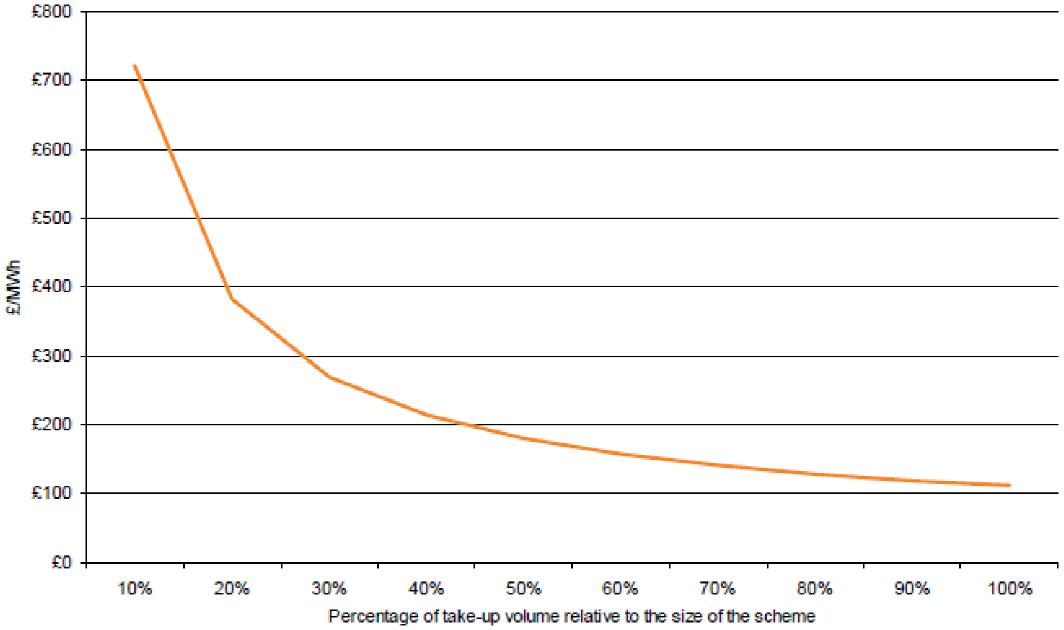


Figure 20: Variation in economic performance of a CHP district heating scheme with market penetration (Source – 'The Potential and Costs of District Heating Networks', 2009).

The results from this macro DE modelling and previous work demonstrates the importance in achieving a high level of market penetration in a zone to ensure that the scheme can operate economically, but that it is not vital for all customers to connect. This means that when schemes are identified and designed, they should aim to connect to the majority of customers (at 80% or above penetration), but allowing for either technically difficult loads, or unwilling customers not to connect. However, the design of the network should allow for future connection because the small amount of over-sizing of the main transmission pipes will have only a small impact on the economic performance. It also indicates that a build-up of demand from around 50% to 80% could be accommodated without a major economic penalty.

The dependence on penetration will be scheme specific based on a number of parameters:

- The mix and type of customers. Different levels of penetration in different customer types will impact the viability. In areas of low heat density, it will be important to maximise the number of connections, whereas in areas of high heat density, a reduction in penetration may have less impact.
- The size of customers. In schemes where there are a small number of relatively large customers, including potential anchor loads, the levels of penetration are likely to be discrete (a step function rather than a smooth curve as shown in Figure 20). This means that the loss or addition of a customer will have a larger impact on the viability in terms of heat loads and DHN layout.
- DHN layout. The location of loads needs to be considered. If a reduced penetration is caused by a loss of customers in one area, the DHN could be re-designed with minimal impact on viability. However if the loss of customers is spread across the network, there is no scope for re-design reducing in a lower heat density and lower viability.

The development of schemes needs to consider the potential levels of penetration and methods by which these can be maximised, for example through guaranteed connection contracts. Regulation could also be used to encourage or even mandate connections. It is also advisable that all scheme proposals are stress tested to understand the impact of changes in penetration, and how the DHN can be designed to be flexible to connection levels.

Energy centre capital expenditure – Scenarios 4 and 9

The economic analysis in this report includes all costs associated with constructing and equipping an energy centre. Whilst the central scenario assumes mid range costs, the costs could be subject to a number of sensitivities:

- The cost of plant. Gas engine CHP and boiler technology is very mature and it is unlikely there will be significant cost changes due to technology development. However cost variations could occur with changes in the international economy and exchange rates.
- Connection costs. The modelling implicitly assumes that gas and electricity connections are available for wide spread DE adoption. In certain areas, these services may be more or less accessible than average resulting in a cost variation.
- Energy centre building. Site specific conditions may impose different requirements on the energy centre building. In a largely industrial area, a simple industrial building may suffice with associated low costs. However in other areas, and in particular residential and commercial areas, additional conditions may be imposed on the building design in terms of design quality and materials resulting in increased costs.

Site. The modelling also implicitly assumes that suitable energy centre sites are available in the schemes. Whilst finding suitable locations can be challenging on smaller schemes, especially in city centres, the larger size of the zones considered in this study will mean that there will be greater scope for site selection. In some zones, it may be desirable to have more than one energy centre which may increase the costs by duplicating one-off costs such as connection to utilities.

These scenarios examine the sensitivity to energy centre cost with a simple +/- 20% adjustment on all the capital expenditure required for the energy centre, including replacement plant. Figure 21 shows the scenarios for both an increase and decrease in energy centre capital cost from the central scenario.

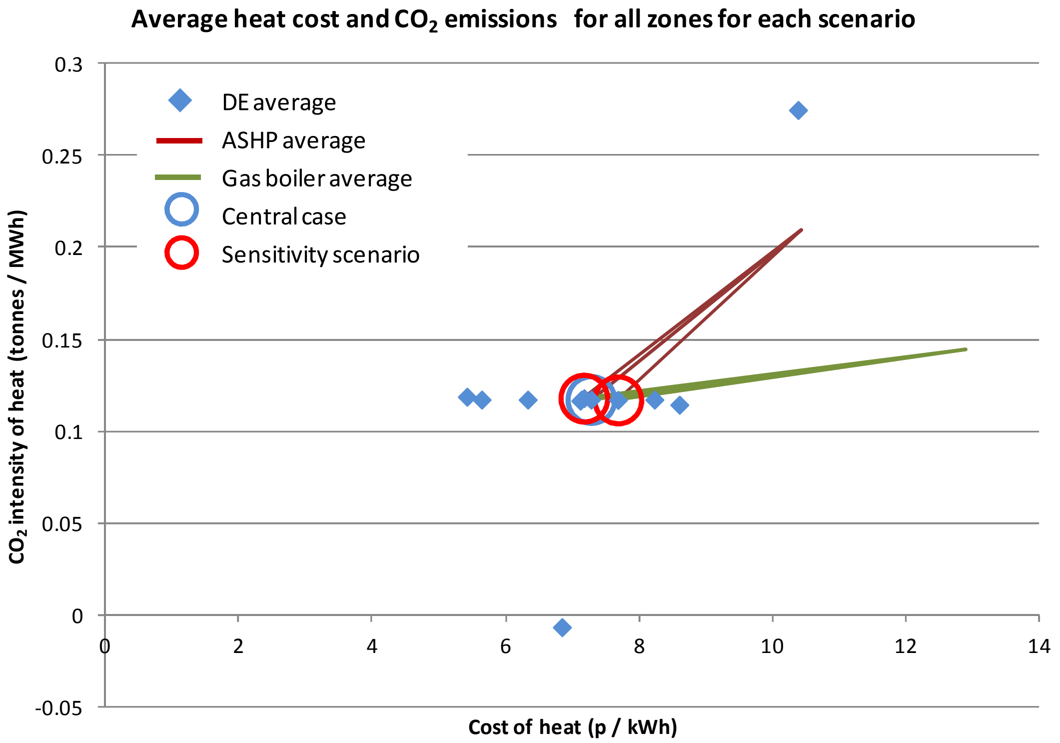


Figure 21: Average results for each scenario, showing the impact of capital adjustments to the energy centre of +/- 20%.

The results show that the capital cost of the energy centre has a relatively small impact on the overall cost of heat. The levelised cost reduces by 0.1 p/kWh with a lower energy centre cost, and increases by 0.3 p/kWh with a higher energy centre cost. Under both these scenarios, the levelised cost of macro DE heat remains lower than for either of the counterfactuals and therefore the GB potential remains unchanged from the central case.

Further analysis of scenarios 4 and 9 is provided in Appendix 5.

DHN Capital Expenditure – Scenarios 5 and 10

From the analysis of capital cost breakdown earlier, it is evident that the DHN capital cost represents around two thirds to three quarters of the overall capital expenditure in a macro DE scheme. Changes to DHN capital costs should therefore have a greater impact on levelised cost of heat than capital cost changes of the energy centre. The link between the DHN cost and the levelised heat cost is also likely to be more direct, with the network remaining unchanged in terms of layout and capacity regardless of its capital cost.

The average results across all CZs are shown in Figure 22 with scenarios 5 and 10 highlighted. A +/-20% change in DHN capital cost is equivalent to about +/-1 p/kWh on the levelised heat cost, giving a range of average costs between 6.3 p/kWh and 8.2 p/kWh. The cost reductions are more pronounced for the higher cost schemes, where the DHN represents a large fraction of the overall capital expenditure. For the lowest cost schemes (CZs 1, 9, and 16), the change is small as the capital cost of the DHN is a smaller proportion of the total.

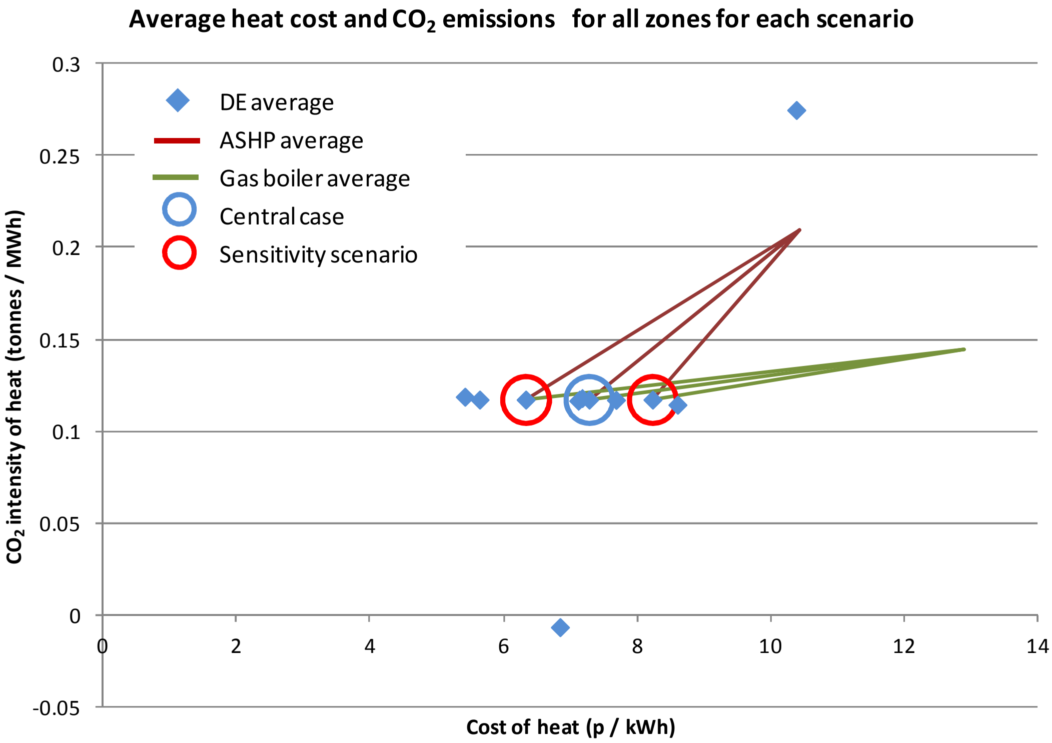


Figure 22: Impact of DHN cost adjustments on the average levelised cost of heat from macro DE schemes.

Despite an increase in 20% DHN costs, all CZs remain economic and the GB potential remains identical to the central case. A 20% increase in DHN cost results in around £2 billion reduction in economic benefit to GB compared with the central case.

The costs of the DHN can be used as a proxy for changes in thermal demand. When DHN networks are deployed, the network will be sized (and therefore costed) to meet the required thermal load. It would be prudent to ensure that all buildings have cost effective thermal efficiency measures included but it is unlikely that extensive and non-cost effective thermal improvements will be applied to all buildings. Once connected, the thermal efficiency of the connected buildings may be further improved over the DHN lifetime and new measures are developed and existing higher cost measures become more economic. This will reduce the thermal load for the DHN and heat revenues, and therefore electricity revenues will reduce. The result is in effect a smaller macro DE scheme but with an oversized (and therefore more expensive) DHN.

The impact of reducing thermal demands are not explicitly modelled in this study as agreed in the methodology approach with the ETI. This requires knowledge of the age, current performance standards, types of buildings connected and impact of energy efficiency upgrades. A detailed assessment of these factors is outside the scope of the project and is not compatible with the generalised CZ approach to represent all zones. However the increased capital cost DHN sensitivity provides an indication of the impact of thermal efficiency improvements.

The capital cost of DHN pipework is not directly related to thermal load – there is a fixed element to the costing (including the building connection cost and some fixed elements of the pipe network) and a variable element proportional to the pipe capacity. Given this, a 20% change in cost would represent more than a 20% change in thermal capacity. An alternative view is that a 20% change in thermal capacity would have a cost difference of less than 20% due to the components which are less capacity dependent in cost

This simple rule means that if thermal efficiency improvements provide 20% or more reduction in overall heating demands (considering the hot water component is unlikely to change much, this represents more than a 20% reduction in space heating demand), the cost spend on the oversized DHN which is not longer required (effectively a stranded asset) will be up to 20%, but not larger in percentage terms than the heating reduction. The resulting change in average levelised heat cost is only circa 1 p/kWh on average and so the GB economic potential remains unchanged.

These results suggest that the early deployment of macro DE schemes (alongside some thermal efficiency improvement) is compatible with subsequent further thermal efficiency improvements. The economics will change, but the schemes will remain economic, and further optimisation of the energy centre plant and its operation or an expansion of the scheme into other areas can be made in light of the reduced demands.

Energy costs – Scenarios 6 and 8

The decision on whether to invest in a DE scheme needs to consider the long term operation costs in addition to the capital investment. The two largest components over which the scheme has little control are the gas price for the boilers and CHP units, and the electricity revenue price gained for the electricity exports. The heat revenue price is also important, but this is typically linked to an alternative counterfactual such as gas boilers, and therefore in turn, the gas price. Of particular importance is the 'spark-spread' which describes the difference between the gas and electricity prices, and therefore the economics of generating electricity from gas in a CHP system.

The central case in this study assumes central price projections taken from the UK Government's Interdepartmental Analysts Group (IAG) guidance (see Appendix 3) [11]. However given the significant uncertainty over future prices and energy scenarios, this report also examines the potential for macro DE under the IAG High and Low price projections.

Low price projection

The results, presented in Figure 23, show that there is a small reduction in levelised heat cost of 0.15 p/kWh on average across all zones with the low price scenario. However the relation between electricity and gas prices means that the counterfactuals have a larger cost reduction of 1.6 p/kWh on average across all zones for both the ASHP and gas boiler options. This is a large enough difference to make CZs 14, 15, and 20 uneconomic compared with gas boilers as illustrated in Figure 24 (although all zones remain economic compared with ASHPs). These are three of the smallest zones and therefore the impact on the GB potential is not significant, with a reduction from 43% to 42% of the overall heat market.

It is also clear from comparing Figure 24 with Figure 15 that the low energy price scenario has a large impact across all CZs, with the central MAC curve CZs now having a levelised cost of around 1.5 p/kWh lower than for gas boilers compared with the central case of about 3 p/kWh. This is manifested by circa £3 billion reduction in GB economic potential over both counterfactuals.

---

[11] Valuation of Energy Use and Greenhouse Gas Emissions for Appraisal and Evaluation. DECC and HM Treasury. 2011.

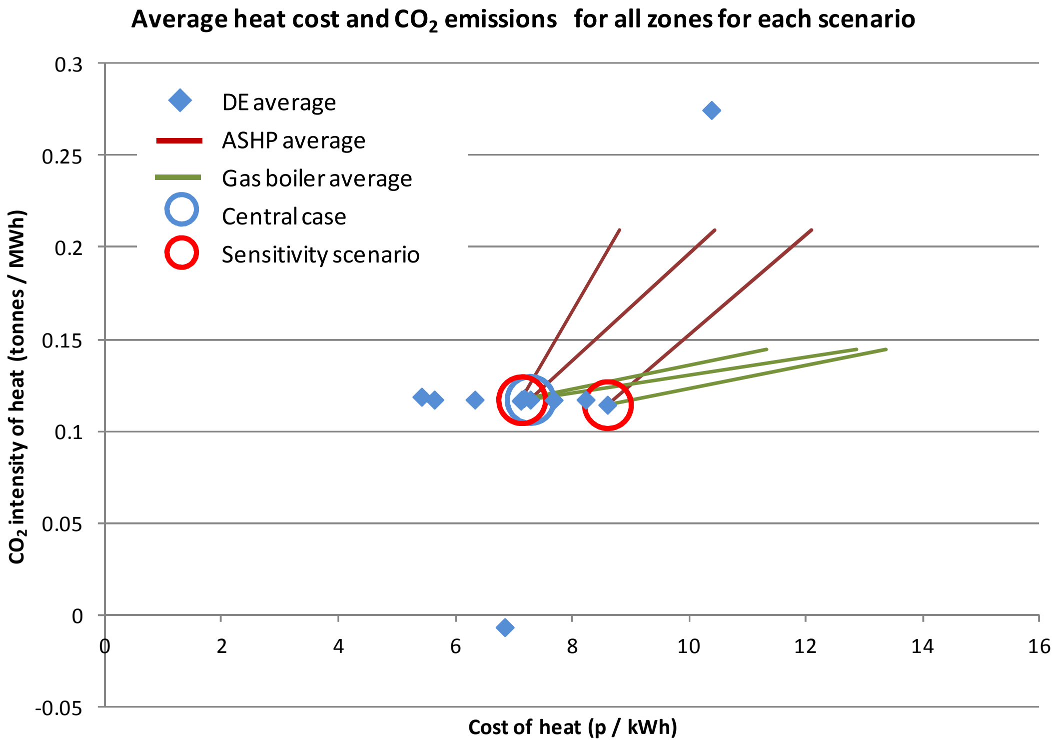


Figure 23: Comparison of average levelised cost under high and low energy price scenarios compared with the central case.

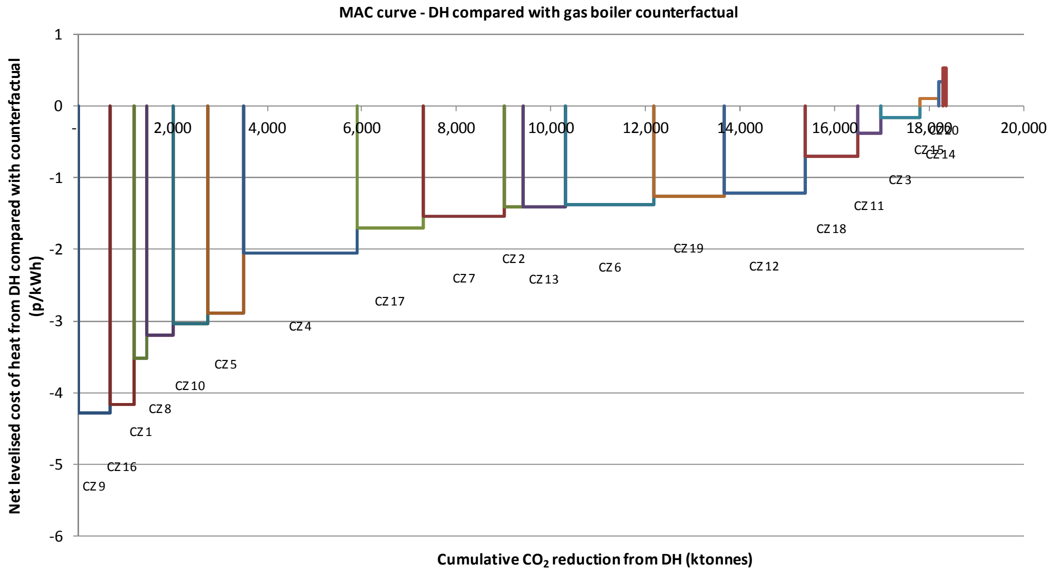


Figure 24: MAC curve showing the impact of low energy prices on macro DE. (This can be compared with Figure 15 for the central scenario).

High price projection

The efficiencies offered by CHP mean that its economic performance will generally improve for higher energy price levels. In the scenario 8 results, the average levelised cost of heat from macro DE increased by 1.3 p/kWh, a far larger change than in the low price scenario. However the counterfactual costs for boilers increase by more (1.6 p/kWh) and ASHPs by 0.5 p/kWh. This means that macro DE becomes more cost effective against gas boilers in a high price scenario with a GB potential saving of £6.9 billion, an increase of £0.6 billion. Whilst the cost benefit over ASHPs is reduced, the GB economic benefit is still large at £9.5 billion.

These results show the robustness of the economics of macro DE in a range of future energy price scenarios. If energy prices follow the Governments low projection, macro DE remains economic against gas boilers in most zones maintaining almost full market potential, albeit with a GB economic benefit of around half the central case. With high energy prices the performance of macro DE improves further, maintaining full economic potential and increasing the GB economic benefit by £0.6 billion. In both scenarios, ASHPs are not predicted to be economically competitive against macro DE or gas boilers across all zones.

The consideration of lifecycle costs will have an impact on the design of the scheme and may result in re-optimisation of the energy centre. Further discussion is provided in Appendix 5.

Removal of carbon price – Scenario 11

The central case includes a carbon price based on a £ per tonne of CO_2 using the IAG social cost of carbon [12]. These are projected to range from £55 per tonne in 2010 to £212 per tonne in 2050. The net effect of this is to provide macro DE schemes with an additional revenue based on the overall CO_2 savings.

There are a number of mechanisms for charging for emissions of CO_2, including direct mechanisms like the CRC, and indirect mechanisms such as the climate change levy and the EU Emissions Trading Scheme. Whilst these charging mechanisms will probably continue to change into the future through a range of incentives and schemes, it is likely that the overall effect will be for some form of continual CO_2 charge. However as a sensitivity to this, scenario 11 examines the impact that the removal of CO_2 charges could have on macro DE. Figure 25 shows the average results from each scenario with scenario 12 highlighted.

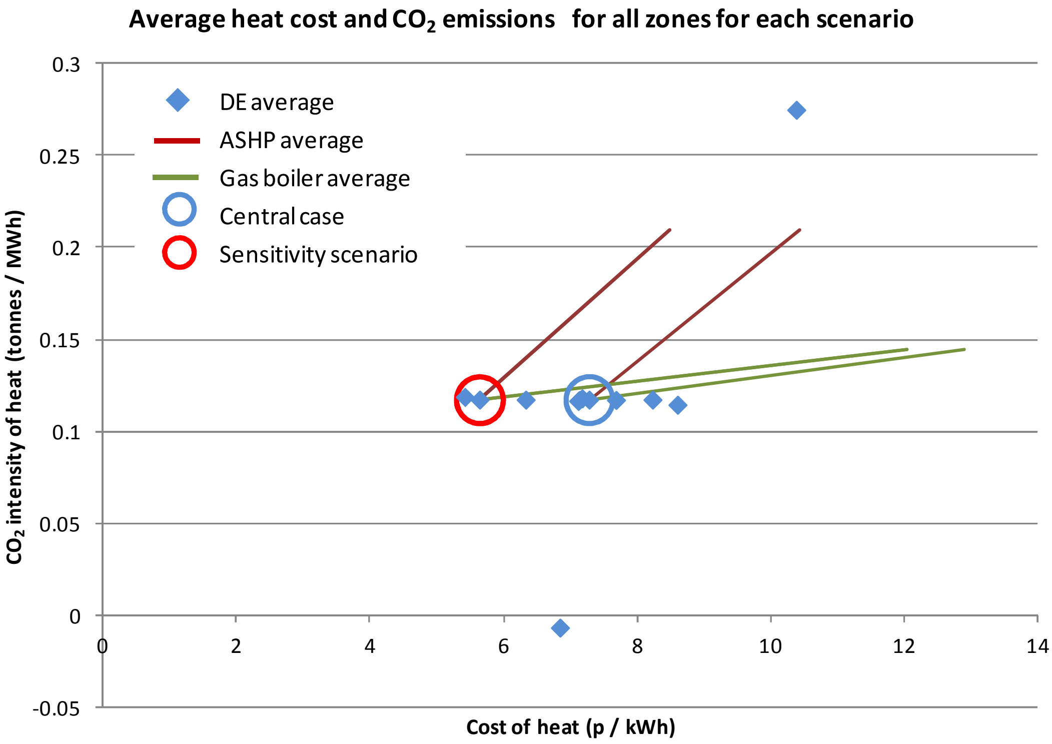


Figure 25: Average results from across all CZs in each scenario, highlighting the impact of CO_2 charge removal.

---

[12] See footnote 11.

The results show that that the removal of CO_2 prices results in a large reduction in the levelised heat cost from macro DE, from around 7.3 p/kWh in the central scenario to around 5.6 p/kWh in scenario 11. This produces the second lowest levelised heat cost from all the scenarios, the lowest resulting from reduced discount rates. However, the counterfactual costs also reduce, in the case of gas by a similar amount so that the macro DE option remains economic.

It is important to note, as detailed in Appendix 3, that the CO_2 calculations for this study are based on a 10 year average for the first 10 years of the scheme. This is to allow schemes to be tested on the merits of the first energy centre technology option to be installed, which may then change in the future. However the economic analysis is based on a 25 year cashflow to allow assessment of the DHN life, but also replacement technologies. In general the discrepancy between these two assessment lifetimes is acceptable, because the economics and CO_2 savings are assessed independently. However carbon pricing is the one sensitivity which is affected by both. Further details are provided in Appendix 5.

Summary

The results in this section show the impact of a number of sensitivities around a central case for deployment in the 2020s. These are perhaps the most important results of the study as they represent the period when mass scale deployment of macro DE may occur in GB.

The results al demonstrate that if macro DE can be deployed at a reasonable scale, with large DHNs across the zone classes modelled, then it remains cost effective in virtually all areas under all the sensitivities. The potential of 43% of the GB heat market remains under most scenarios, with only around 1 percentage point change. Macro DE is therefore a robust heating solution for urban areas into the 2020s and performs economically in the majority of cases against both gas boiler and ASHP counterfactuals.

The lowest levelised costs and greatest economic benefit (to the heat market) is obtained by reducing the discount rate applied to the economic analysis. This suggests that public sector finance should be an important feature of macro DE delivery. Of course the wider economic benefits to the GB economy may not be as great if the reduced discount rate represents a reduced income to GB based financiers and this would need to be examined further in an impact assessment.

In terms of capital costs, reduction in DHN costs, either through lower price equipment or more efficient network design, has a greater impact on the levelised cost than the same changes to the energy centre costs. Cost reductions in energy centre equipment are often not seen directly as a proportionally lower levelised cost, but result in a re-optimisation of the scheme. For example, a lower specific capital cost for CHP potentially may lead to additional CHP capacity.

Market penetration is often viewed as a critical factor for the success of macro DE schemes. This analysis, supported by other studies, demonstrates that it is not important to have all customers in an area connected, but around 80% of customers should connect to achieve a viable scheme. This means that schemes will need to be effectively marketed, and incentivise customers to connect, or rely on regulation, but it will be permissible for a small number of customers who are either unwilling, or unable to connect to remain with another heating solution. It is recommended that further work examines the impact of market penetration, based on analysis of example zones to allow investigation of the different factors which can influence penetration and its impact.

Sensitivity analysis – 2030s deployment

Introduction

If the 2020 represents the mass deployment stage for macro DE, the 2030s represent a period of transition where further remaining areas may be equipped with DHNs, and existing schemes built in the 2010s and 2020s may be modified to use alternative heat sources.

Due to the lifetime of DHNs, and the significant investment, the networks need to perform acceptably with both current and future technologies. A key consideration is the move to a lower carbon electricity grid and therefore heat supply technologies are needed which can provide heat to the network whilst still providing CO_2 savings.

Work package 5.3 of this report investigates new and immature technologies which may be suitable for this period. In this section of the report, the performance of the mature technologies from WP3.2 technology library is assessed with a view to how these could be used for projects started in 2030.

All of the results presented here represent a new macro DE scheme with full investment in the DHN and energy centre. This is appropriate for new schemes built in the 2030s, but early schemes being retrofitted will only require new energy centre plant and not a DHN replacement. Therefore the costs and economic benefits presented here represent a conservative case, and for a replacement of energy centre equipment only, the economic benefits will be greater.

Scenarios modelled

Scenario 12 is based around the central case (scenario 7) but with a 2030 starting point, and therefore CO_2 emission factors and energy costs relating to the later starting date. The electricity emission factor assumed is 0.16 kg/kWh.

The following variations of scenario 12 have been modelled.

- Scenario 12.0. Central case with a 2030 start. Heat pumps are excluded from the model to assess how gas engine CHP systems will perform compared with the 2020s case.
- Scenario 12.1. As for 12.0, but with the inclusion of heat pumps in the technology choice.
- Scenario 12.2. An additional constraint that the macro DE emissions must be 50% or less than the gas boiler counterfactual emissions to ensure a significant use of heat pumps This prevents higher CO_2 options being selected based on economic performance alone.
- Scenario 12.3. The CO_2 reduction constraint is tightened to target an 80% reduction in emission over the gas boiler counterfactual.

Scenario 12.0 – Central case with a 2030s deployment

The minimum cost optimisation still identifies gas-engine CHP to be the most cost effective solution when heat pumps are removed from the choice of technologies available in the model. Similarly to the 2020s schemes, most CZs make use of multiple units operating in a modular fashion, allowing the majority or all of the heat to be provided by the CHP units. However for some zones, the optimisation results in a smaller number of units, and a corresponding reduction in CHP heat. In particular, CZ 7 and 12 have a significant drop, with only 14% and 30% of the heat being supplied by the CHP units, the remainder from the gas-fired boilers.

The economic and environmental performance of the schemes is now very different to the 2020s schemes, as illustrated in Figure 26. All of the schemes have higher CO_2 emissions than both the gas boiler and ASHP counterfactuals, primarily due to the reduction in grid electricity CO_2 intensity. There is also a much wider range of levelised costs, caused by relative changes in the gas and electricity prices (the spark-spread) and the reduced CHP output, with a corresponding reduction in electricity revenue.

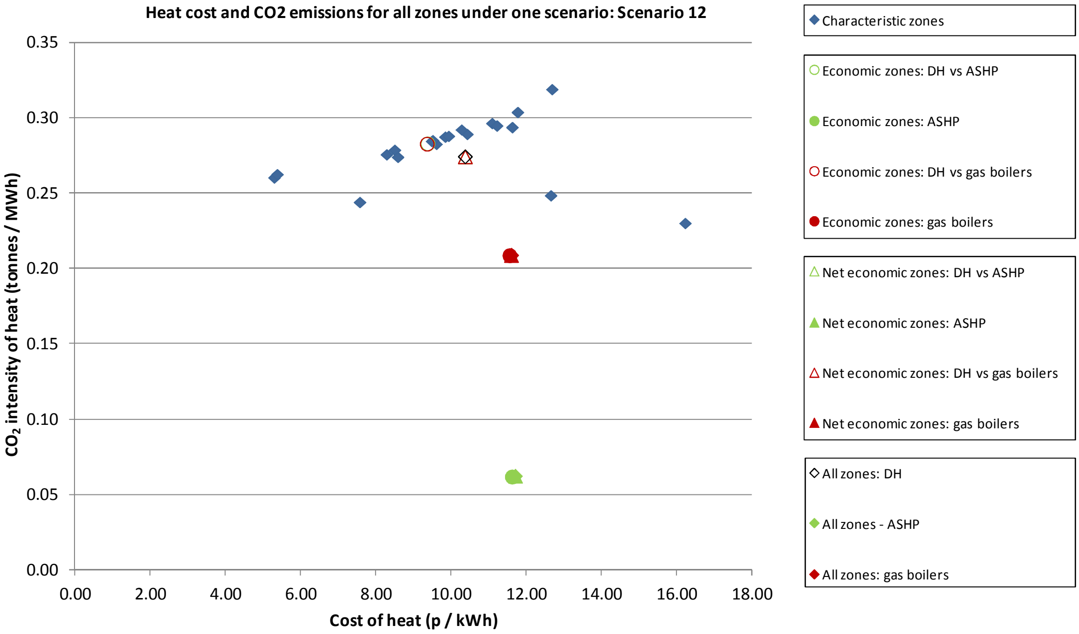


Figure 26: Economic and environmental performance of macro DE schemes in the 2030s based around gas engine CHP.

With the increase in costs, CZs 7, 12, and 20 are no longer economic as stand-alone schemes. This reduces the economic GB potential for heat provision and overall economic benefit as shown in Table 4. The economic benefit against both counterfactuals is similar at between £3.5 billion and £3.6 billion for the commercial benefits case, and between £2.4 billion and £2.7 billion for the GB economy and the maximum CO_2 savings (although there are no CO_2 savings) benefits cases. If only economic zones are included, then the proportion of heat demand met by macro DE drops to 35%.

The counterfactuals have also changed with the ASHP costs falling so that they are similar to gas boilers and the ASHP now showing a significant CO_2 advantage as the electricity that supplies them is lower carbon. The levelised cost of heat from ASHPs has fallen due to improvements in performance, and relative changes to gas and electricity prices result in a smaller difference still against gas engine macro DE.

Table 4: Summary of the GB benefits case for scenario 12.

	DE heat provision	DE heat provision	Commercial connections	Domestic connections	CO_2 reduction	CO_2 reduction	GB cost reduction
	TWh	% of GB heat	millions	millions	Mtonnes	%	£ billion
Counterfactual - gas boilers							
Case 1. Commercially driven uptake	159	35%	2.4	9.9	-11.8	-10%	3.5
Case 2. GB economy driven uptake	199	43%	2.9	12.4	-13.0	-11%	2.4
Case 3. Maximum CO2 reduction	199	43%	2.9	12.4	-13.0	-11%	2.4
Counterfactual - ASHP							
Case 1. Commercially driven uptake	160	35%	2.4	9.9	-35.1	-31%	3.6
Case 2. GB economy driven uptake	199	43%	2.9	12.4	-42.1	-37%	2.7
Case 3. Maximum CO2 reduction	199	43%	2.9	12.4	-42.1	-37%	2.7

These results demonstrate the need for an alternative option to gas engine CHP-only systems in the 2030s to achieve CO_2 reduction, and this is examined in the sensitivities around scenario 12.0. As the gas-engine CHP is still the most cost-effective solution and economic compared to the counterfactuals in most cases, it is likely that a gas-engine CHP scheme would continue in operation even though it is not saving CO_2; some intervention in the market at this point would be necessary. However. it is important to note that there is still potentially a role for gas CHP in the 2030s and beyond, working in parallel with other technologies, supporting electricity generation in times of peak demand, and therefore displacing generation from higher CO_2 fossil powered peak generation plant. At these times, the marginal electricity factor which the CHP is offsetting is likely to be considerably higher than the average marginal emissions factor used in this report. This form of operation would require careful control of when the gas CHP system is operated and when the alternative forms of generation are operated. This will mean some form of central information collection and distribution which provides information about the CO_2 level of the grid and what systems should be operated, in a similar manner to the existing national grid control systems.

Scenario 12.1 – Inclusion of heat pumps in the technology choice

If large-scale heat pumps are included in the technology choice, but with no constraints on CO_2 emissions, the cost optimal schemes remain largely composed of gas engine CHP units, with heat pumps only appearing in the largest schemes as shown in Figure 27.

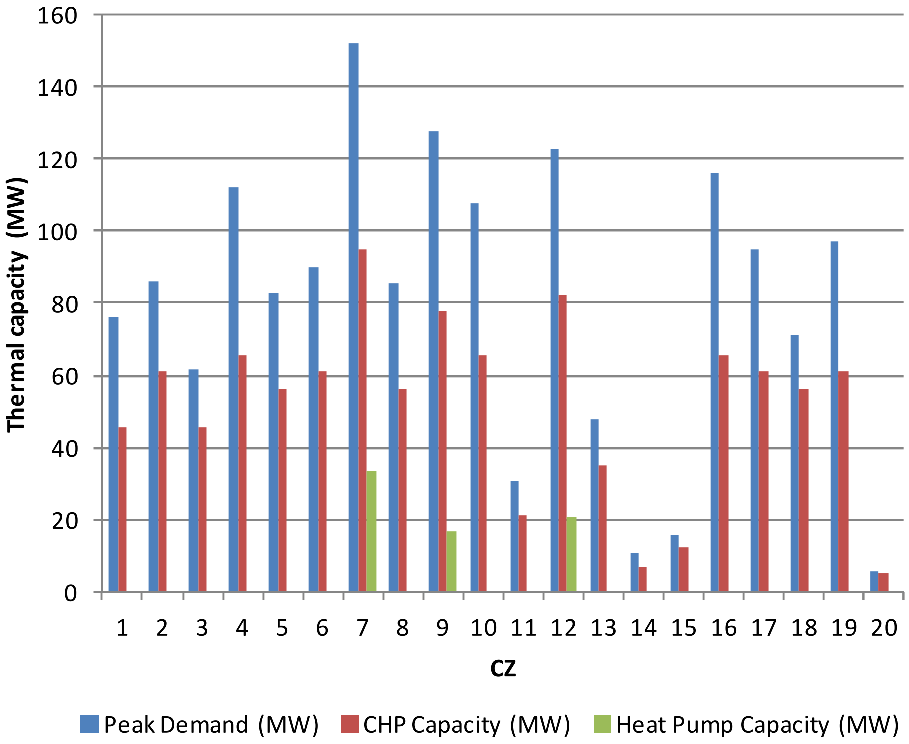


Figure 27: Capacity of gas engine and heat pumps for each CZ showing limited uptake of heat pumps.

The heat pumps allow cost optimisation reducing the levelised cost of heat in the more expensive schemes. With their inclusion, all CZs become economic, resulting in a net GB economic benefit of between £4.1 billion and £4.3 billion against the respective gas boiler and ASHP counterfactuals. However limited use of heat pumps does not provide much lower carbon heat, and there remains a CO_2 deficit similar to scenario 12.0.

These results show that the use of large-scale heat pumps on macro DE schemes can allow the deployment of cost effective macro DE across all types of zone in the 2030s, but without further constraints, the cost optimised schemes will not result in lower carbon heat.

Scenario 12.2 – Constraining CO_2 emissions to 50% of the gas boiler counterfactual

If the emissions are constrained to target 50% of the gas boiler counterfactual emissions or less, then the majority of CZs use a number of heat pumps in a modular fashion. Gas CHP engines remain in some CZs to help improve the economics if the CO_2 constraint can still be met.

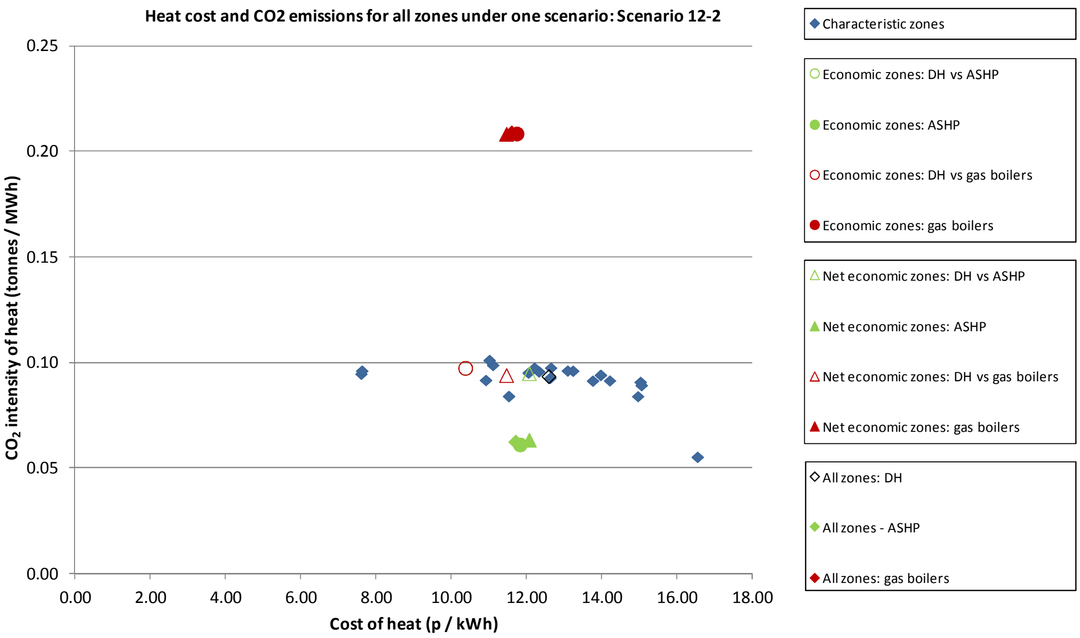


Figure 28: Economic and environmental performance of macro DE schemes in the 2030s with the CO_2 intensity of heat constrained to 50% or less of gas boiler counterfactual.

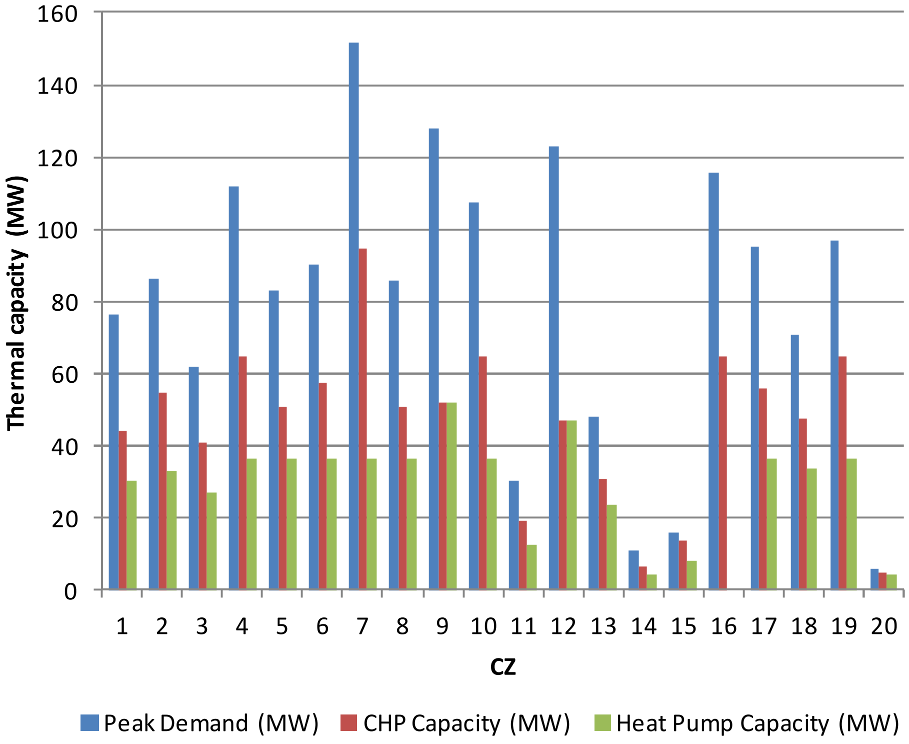


Figure 29: Capacity of gas engine and heat pumps for each CZ with CO_2 emissions constrained to 50% of the gas boiler counterfactual.

The results from scenario 12.2 provide an important perspective on macro DE schemes in the 2030s. They demonstrate that using a combination of large-scale heat pumps in combination with gas engine CHP systems, significant CO_2 reductions can be made over the gas boiler counterfactual. The combination of the two technologies could be viewed as a transition where some gas engine CHP units from earlier schemes are replaced by heat pumps or operated in conjunction with heat pumps. The combination of the two working together could allow for ‘smart’ operation, allowing heat pumps to operate at times of excess electricity on the grid (thus using low carbon excess renewable generated electricity), and the gas CHP systems operating at times of peak demand on the grid, thus offsetting higher carbon electricity from fossil peaking plant.

The results also show that in the 2030s macro DE schemes will be under increasing competitive pressure from individual ASHPs which in some cases will be lower cost and in all cases will deliver lower CO_2 emissions.

This combination of technologies is not economic in all zones, and the GB potential for macro DE is reduced as shown in Table 5, with only 6% of the GB heat market being commercially viable with macro DE and 21% allowing for cross subsidy. The CO_2 reduction and economic benefit is correspondingly small at a GB scale. The zones which remain economic in comparison with the gas boiler counterfactual are CZs 1, 5, 8, 10, and 16. However if the inclusion of heat pumps is viewed as a replacement technology on an existing DE scheme, then the economics will be much improved as the entire DHN cost does not need to be recovered, and the payback will be on the energy centre alone. It is recommended that further work examines the transition of technologies in schemes in more detail, allowing the investigation of technology changes during the lifetime of the DHN and the split of investment and payback.

Table 5: Summary of the GB benefits case for scenario 12.2.

	DE heat provision	**DE heat provision**	**Commercial connections**	**Domestic connections**	**CO_2 reduction**	**CO_2 reduction**	**GB cost reduction**
	TWh	% of GB heat	millions	millions	Mtonnes	%	£ billion
Counterfactual - gas boilers							
Case 1. Commercially driven uptake	29	6%	1.0	2.0	3.2	3%	0.4
Case 2. GB economy driven uptake	96	21%	1.9	5.9	11.0	10%	0.0
Case 3. Maximum CO2 reduction	199	43%	2.9	12.4	23.0	20%	-2.0
Counterfactual - ASHP							
Case 1. Commercially driven uptake	29	6%	1.0	2.0	-1.1	-1%	0.4
Case 2. GB economy driven uptake	93	20%	1.7	6.4	-2.9	-3%	-0.0
Case 3. Maximum CO2 reduction	199	43%	2.9	12.4	-6.2	-5%	-1.8

Scenario 12.3

Scenario 12.3 examined a constraint on CO_2 emissions from the macro DE schemes of 20% (80% reduction) of the gas boiler counterfactual. For all zones, no solutions existed which could meet this constraint.

It is recommended that further work examines the setting of constraints between a 50% and 80% reduction in CO_2 emissions, to assess the level of CO_2 savings which can be achieved with the combination of heat pumps and has CHP, and whether this can save CO_2 against the ASHP counterfactual as well as the gas boiler counterfactual. Further improvements in CO_2 savings using this combination allow the carbon saving lifetimes of macro DE schemes to be extended further into the future without the need for lower carbon forms of generation.

Summary

The 2030s will require a transition in macro DE technology from gas engine CHP systems to other, lower carbon forms of energy as a result of the grid decarbonisation. Without a requirement for reducing CO_2 emissions, gas engine CHP will remain the most cost effective solution, although now only provides an economic solution for 32% of the heat market.

It is not predicted that large scale heat pumps will be taken up if cost is the prime driver, and additional CO_2 constraints are required to ensure that macro DE schemes are developed which save CO_2 compared to the counterfactuals. With a constraint limiting the macro DE heat to 50% or less than the gas boiler counterfactual, a combination of heat pumps and gas engine CHP can always provide a technical solution, but the price penalty means that the GB potential for new macro DE schemes is significantly reduced. On existing schemes using heat pumps as a replacement heat source, the economics will be improved, creating a larger economic market and greater CO_2 reduction.

In order to maintain a larger share of the heat market, the 5.1 modelling demonstrates that further technology development and potentially newer technologies will be required to ensure that schemes can remain economic and provide acceptable CO_2 reductions. This will be examined in the 5.3 report and analysis.

The GB benefits case

Introduction

The wide scale deployment of macro DE can provide a number of benefits to GB. Many of these benefits have been mentioned in the discussion so far, and include:

- The provision of heat from centrally managed highly efficient macro DE schemes.
- Energy security
- Reduction in CO_2 emissions
- Economic performance and benefits for the heat market, including reducing fuel poverty.
- Technology opportunities and development of a new business opportunity

The analysis in this report provides a range of scenarios and associated impact on the level of uptake viable. Alongside this technical and economic assessment, a number of other factors also need considering which are outside the scope of this study, but which may impact on the development potential. Many of these other factors are "soft" barriers which can potentially be overcome through improvements to the policy and regulatory frameworks.

Heat provision

The modelling in this report demonstrates that up to 43% of the current GB buildings heat market can be connected economically to macro DE schemes, resulting in overall cost savings. The following charts present this as part of the total GB heat demand for each scenario against both counterfactuals.

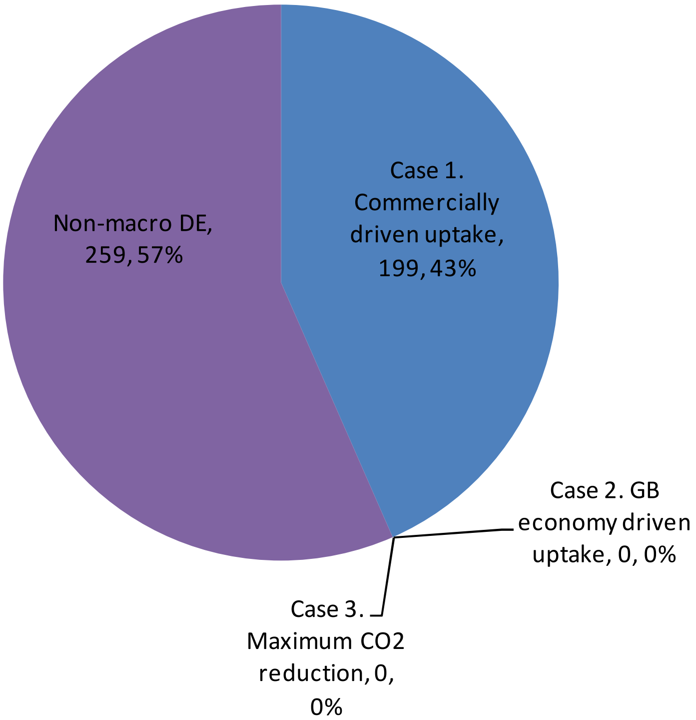


Figure 30: GB Potential for macro DE in the central case against both counterfactuals. Heat in TWh p.a. With all schemes being economic, there is no additional potential for the GB economy benefits case, or the maximum CO_2 reduction case.

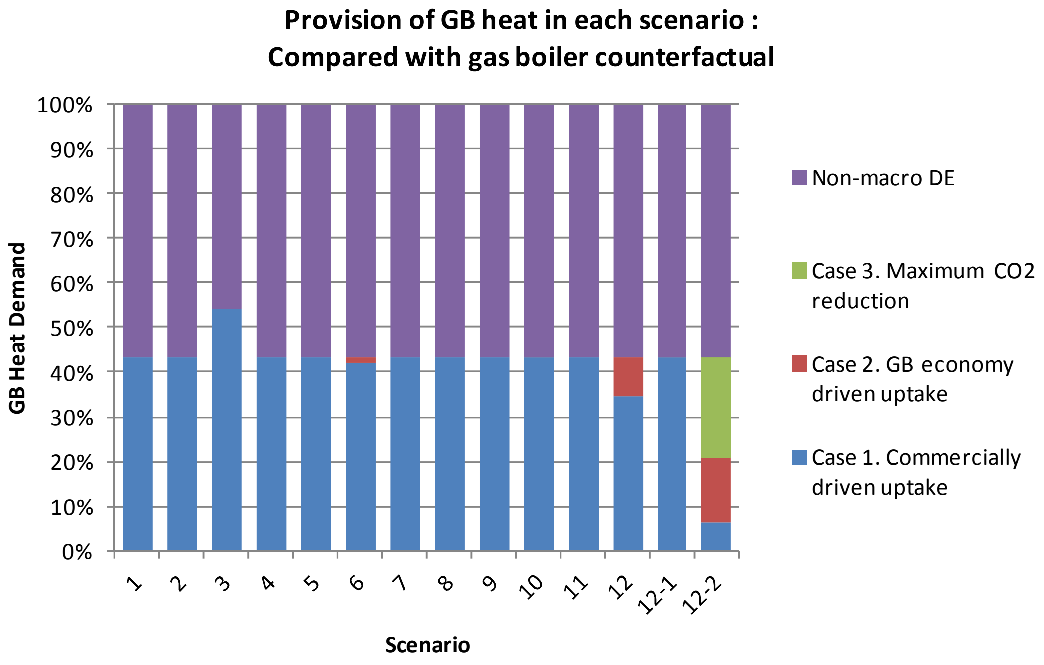


Figure 31: Provision of heat from macro DE compared with the gas boiler counterfactual for each scenario

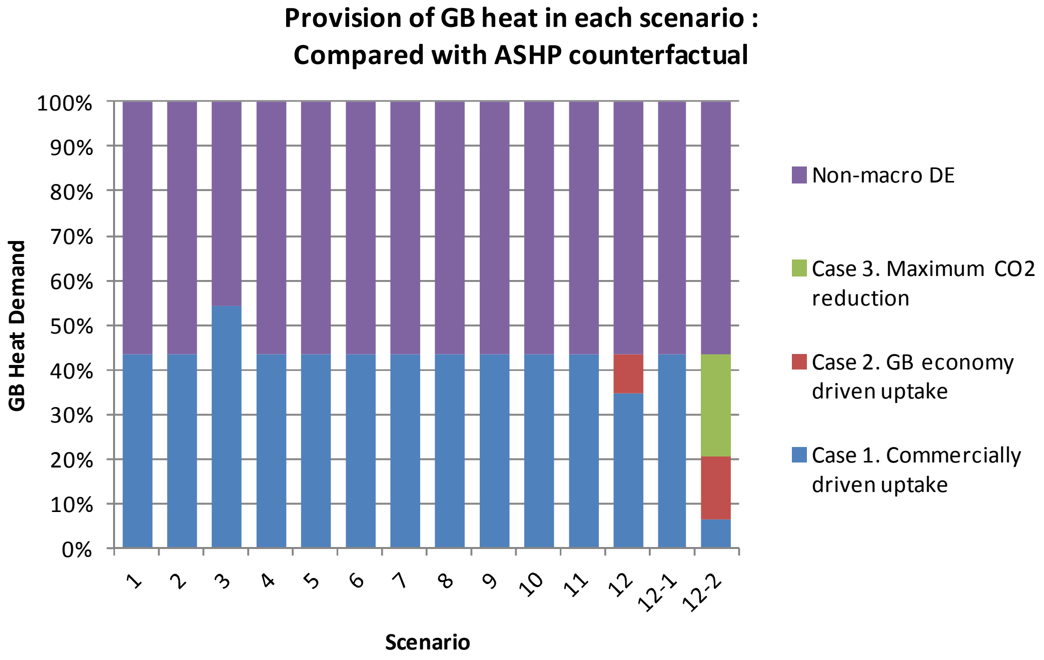


Figure 32: Provision of heat from macro DE compared with the ASHP counterfactual for each scenario

The 43% achieved under the central scenario represents 12.4 million homes and 2.9 million non-domestic connections, all of whom will benefit from lower heating costs. Achieving this level of uptake may be economically and technically viable, but will require the many barriers to macro DE to be addressed, to enable the levels of penetration required, and facilitate the development of schemes in a timely manner.

Energy security

The issue of energy security is becoming more important for GB as increasing amounts of fossil fuel are imported to meet a reduction in national gas and oil outputs. With a strong reliance on natural gas for electricity generation, and around 80% of heating being provided by natural gas (almost all in urban areas), the future availability of gas presents an energy security risk.

A transition to macro DE provides opportunities for improving energy security. Firstly, the development of cost effective gas engine CHP schemes in the 2010s and 2020s improves the overall efficiency of energy generation and therefore reduces the demand for gas. The modelling for 2010 in scenario 1 demonstrates that gas engine macro DE schemes could save 49% in primary energy compared with a gas boiler counterfactual, and 31% compared with an ASHP counterfactual. Even with improvements to ASHP performance by the 2020s, the saving in primary energy is still 27%.

This benefit is provided by gas engine CHP schemes in both the 2010s and 2020s. To some extent it will continue into the 2030s depending on what the marginal electricity generation is and how gas engine CHP units are operated. By combining with heat pumps, it may be possible to optimise schemes in a ‘smart’ configuration which react to other generation on the electricity network.

The use of DHNs will provide greater opportunities for energy security than individual counterfactual systems. By maximising the GB potential, and having 43% of the building heating load on DHNs, all of the buildings may be retrofitted with alternative heat generation technologies. Some new and novel technologies are assessed in work package 5.3, but others may exist which are currently not even considered. With individual counterfactual systems, either fuel has to be delivered to each building (such as gas) or electricity will be required. The delivery of fuel can be complex and the types of technologies which can burn the fuel are limited. For example, it is not possible to burn waste at a domestic house scale. If electricity is used for heating, it is likely that a component of the generation will be thermal, either nuclear, fossil, biomass, or energy from waste, allowing connection to a DHN providing greater efficiencies.

DHNs provide a benefit in both of these scenarios. They open opportunities for using larger scale generation technologies which are suited to alternative fuel types. One obvious example is incineration of waste which has strong synergies with large populations and dense urban areas. They also provide a means for taking excess heat from thermal power generation and using this for heating. A number of other benefits are also possible for example optimising different forms of generation in relation to external factors, such as the heat pumps and gas CHP combination.

Contrary to this view, there could be an argument the DHNs lock areas into fossil generation, and alternatives such as building scale ASHPs, connected to a low carbon grid, are a more suitable option with greater flexibility offered by the electricity grid. The benefits of DHNs are then in the ability to make use of larger technologies which are generally more efficient than the building scale alternatives, alongside making use of low carbon electricity heating sources, and capturing excess heat from industrial processes.

Therefore in terms of improving energy security, DHNs will potentially be an important component irrespective of other strategic energy decisions.

Reduction in CO_2 emissions

The primary energy efficiency improvements facilitated by macro DE enable CO_2 savings to be made when compared with the counterfactuals in the 2010 and 2020 cases. The CO_2 savings depend on the type (and fuel) of the technology selected, the optimised solution, and the CO_2 intensity of the energy being displaced. In this study, the counterfactuals are gas boilers (which do not change in CO_2 intensity over time), ASHPs and grid electricity (which do change over time).

The total CO_2 emissions associated with heating buildings in GB are currently estimated to be 113 Mtonnes. Table 6 provides a summary of the potential CO_2 reduction available against this total from the scenarios modelled in work package 5.1.

Table 6: Summary of annual CO_2 reduction potential from macro DE across GB. All figures in Mtonnes. (note values are shown to 2 decimal places to allow observation of changes between scenarios)

	Compared with gas boiler counterfactual			Compared with ASHP counterfactual		
	Commercially driven uptake	GB economy based approach	Maximum CO_2 reduction	Commercially driven uptake	GB economy based approach	Maximum CO_2 reduction
2010s						
Scenario 1	42.98	42.98	42.98	42.96	42.96	42.96
2020s						
Central – scenario 7	18.33	18.33	18.33	5.38	5.38	5.38
Minimum (scenario)	17.79 (6)	18.03 (2)	18.03 (2)	5.22 (6)	5.23 (4)	5.23 (4)
Maximum (scenario)	23.08 (3)	23.08 (3)	23.08 (3)	6.89 (3)	6.89 (3)	6.89 (3)
2030s						
Scenario 12.2 (50% reduction constraint)	3.22	10.97	22.97	-1.05	-2.94	-6.17

The results for the 2010s (scenario 1) show that the savings from macro DE are almost identical against both the gas boiler and ASHP counterfactuals. This is due to the similar CO_2 intensities of heat from both these technologies. The savings are equivalent to a 38% reduction in CO_2 from CO_2 emissions associated with heating buildings.

In the 2020s, the savings against gas boilers are much larger than against ASHP due to the reduction in grid electricity CO_2 intensity. The minimum savings in the 2020s are only slightly less than the central case. Against the gas boiler counterfactual, the minimum reductions are obtained for scenario 6 (low energy prices) and scenario 2 (reduced discount rate). Both of these scenarios result in lower electricity revenues, and therefore there is less incentive for operating the CHP plant. Against the ASHP counterfactual, minimum CO_2 emissions are also obtained under scenario 4 (20% reduction in energy centre cost). Inspection of the optimised systems reveals that with a reduction in CHP cost, additional smaller units are installed for peak loads, but their lower efficiency results in smaller carbon savings. Maximum CO_2

savings against both counterfactuals are achieved with the increased market penetration (scenario 3). This is clearly due to the 20% increase in heat load.

In the 2030s, it will be possible for macro DE to produce CO_2 savings compared with the gas boiler counterfactual by including heat pumps in systems if a CO_2 constraint is imposed (up to 50% of gas boiler equivalent emissions as modelled). The maximum savings are similar to the 2020s, but require investment in schemes which are not considered economic. If a cross subsidy approach is used, the CO_2 savings are circa 11 Mtonnes (or 10% of heat emissions), which reduces to 3.2 Mtonnes for economic zones only. It is not predicted that a macro DE scheme in 2030 will make CO_2 savings compared to the ASHP counterfactual with the technologies available as modelled in the scenarios, but further sensitivity analysis assessing CO_2 constraints between 50% reduction and 80% reduction from the gas boiler counterfactual are recommended to examine the level of savings which can be made.

Overall it is clear that the greatest opportunity for making CO_2 savings from macro DE is now rather than in the future, suggesting that schemes should be initiated earlier. This will also have a large impact on cumulative CO_2 emission reductions.

Economic benefits

This report assesses the change in GB heat costs with the adoption of macro DE. These benefits are effectively the reduced heat cost to homes and businesses across GB, and not necessarily a national economic benefit. Where savings are made through the adoption of macro DE, other sectors, such as major power station developers, individual boiler manufacturers and maintainers, may lose trade. Therefore a full impact assessment is required to assess the true value to the GB economy.

Table 7: Summary of annual economic benefit from macro DE across GB. All figures in £ billions.

	Compared with gas boiler counterfactual			Compared with ASHP counterfactual		
	Commercially driven uptake	GB economy based approach	Maximum CO_2 reduction	Commercially driven uptake	GB economy based approach	Maximum CO_2 reduction
2010s						
Scenario 1	5.6	5.6	5.6	15.4	15.4	15.4
2020s						
Central – scenario 7	6.3	6.3	6.3	11.1	11.1	11.1
Minimum (scenario)	3.4 (6)	3.3 (6)	3.3 (6)	8.3 (6)	8.3 (6)	8.3 (6)
Maximum (scenario)	9.4 (3)	9.4 (3)	9.4 (3)	17.4 (3)	17.4 (3)	17.4 (3)
2030s						
Scenario 12.2 (50% reduction constraint)	0.4	0.0	-2.0	0.4	0.0	-1.8

The results presented in Table 7 demonstrate that the savings in heat cost with the adoption of macro DE schemes are higher against ASHPs than the gas boiler counterfactuals for both the 2010s and 2020s. By the 2030s, the savings are significantly reduced, and similar against both counterfactuals.

A simple calculation suggests that the savings per a domestic customer are circa £62 per year per £1 billion saving, and for non-domestic customers £79 per year per £1 billion saving[13]. This means that in scenario 1, the average home connected could save approximately £350 per year annualised cost against gas boilers and £950 per year annualised cost against ASHPs.

Market potential

The term ‘economic benefit’ has been used in this report to describe the reduction in overall heating costs to GB consumers. However the widespread adoption of DH will provide additional support to the GB economy through the need for supply chains of DE components.

The costs of technology units and DHN components are discussed in the work package 3 reports in detail. By sizing the DHNs and sizing and optimising the energy centre components (in WP 3 and WP 4), and then aggregating these CZ specific costs to a GB level, the market size can be identified.

Using the central case as an example to understand the order of magnitude of the market size, the following figures are obtained:

- The total investment potential in energy centres is circa £35 billion. This includes the plant (and replacement during a schemes lifetime), energy centre building, and associated services.
- The total investment potential in DHNs is circa £93 billion.
- The total potential for installed CHP capacity is circa 47 GW thermal.

These values show that the potential market for macro DE equipment and services is significant enough to support extensive up-scaling of relevant industries in the GB if local manufacture and supply chain is to be developed. Sectors that could particularly benefit are: steel pipe, gas-engines and generators, civil engineering construction, domestic plumbing components and installers.

Achieving this potential requires many of the barriers to macro DE to be overcome, not least achieving the desired levels of uptake. For a GB industry to be able to respond to this investment potential, there will need to be confidence that the market will develop, and it will be crucial that long-term policy is developed which consistently supports, or even regulates, the development of macro DE schemes.

---

[13] The optimisation of the macro DE schemes is based on the total energy loads and therefore is it not possible to accurately calculate the savings for each customer. The figure presented here allocate the overall savings based on the split between total domestic and non-domestic heat loads, and the number of each type of customer.

Applying the analysis to other areas

The optimisation modelling used in this report to assess the GB benefits case is based on the simulation of macro DE on individual CZs. This work has been conducted under WP 4 of the macro DE study, with additional modelling conducted in WP 5.1 to scale these results to a GB level.

By using smaller individual CZs as the basis for the modelling, the optimisation and analysis can equally well be applied to smaller areas, and even individual schemes. The route chosen will depend on the level of detail available from the areas of interest, and to some extent, the level of information required form the model.

For larger scale studies, for example the examination of a large urban conurbation, or sub-region in GB, it may be most appropriate to select a number of CZs which represent these areas, and simply take the existing CZ optimised results, and scale up to the desired area (see Figure 33). This requires knowledge of which CZs most appropriately represent the assessment area, and how they scale. Information provided in the WP2 reporting can be used to help with this identification process, including the use of maps which show the distribution of the classes and character areas geographically.

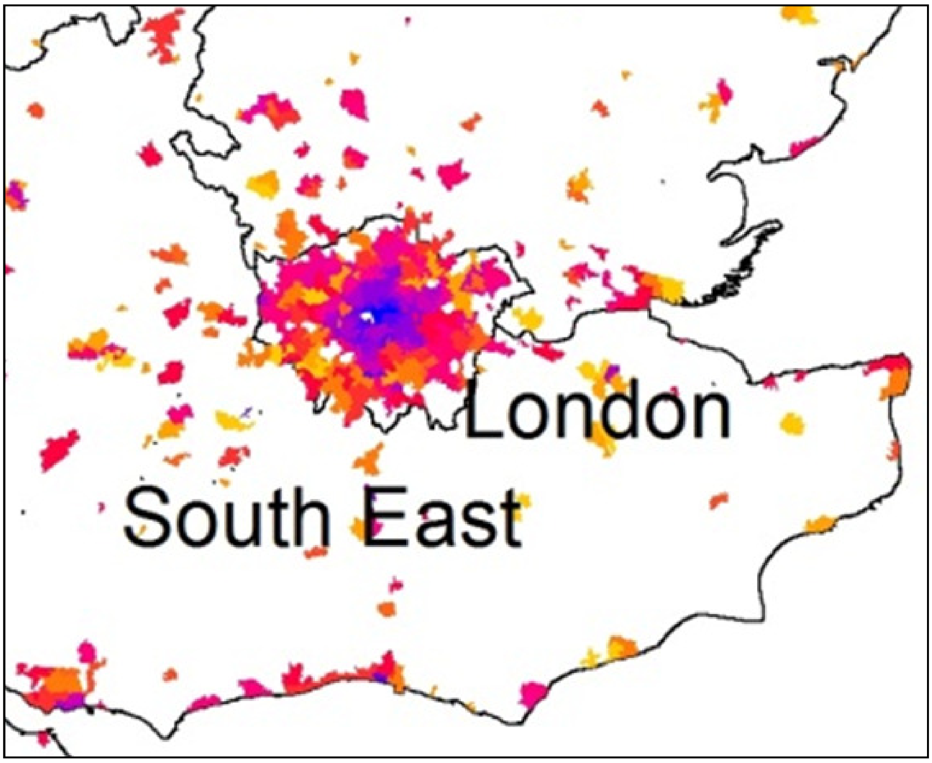


Figure 33: Close up showing zones and classes in London. By selecting the class types and number and size of zones in each class, it is possible to assess the benefits case and optimised schemes for defined areas.

An alternative option is to develop specific zones for the optimisation, and optimise the scheme base on these specific characteristics. WP 3 reports describe the data requirements for calculating the costs of the DHNs, and WP 4 reporting provides an overview of the optimisation and the input requirements for operating the tool.

Conclusions

(1). There is a very large potential for macro DE using gas fired CHP in the 2010s and 2020s.

This report demonstrates that up to 43% of the GB heat market, consisting of 12.4 million homes and 2.9 million non-domestic connections, could be economic for macro DE schemes using gas engine CHP. This is predicted under the central assumptions of an 8% discount rate, 80% market penetration, and central energy price projections. This provides a large economic benefit to customers with a saving of £5.6 billion in heat cost against a gas boiler counterfactual (equivalent to a 29% reduction in cost) and £15.4 billion saving against an ASHP counterfactual (equivalent to a 53% reduction in cost) in the 2010s. Large CO_2 reductions are also achievable of 38% of the current emissions associated with heating buildings. The cost and carbon savings available from macro DE schemes are largest in the 2010 scenario suggesting that GB should be investing and installing macro DE schemes as soon as possible. This will provide the largest annual benefits, but also the largest cumulative benefits over the lifetime of the schemes. This is particularly important in the context of climate change where a reduction in cumulative emissions (i.e. early savings) is more important than annual savings (i.e. late savings).

The macro DE schemes are predicted to save circa 50% in primary energy compared with a gas boiler counterfactual, and 31% compared with an ASHP counterfactual. The flexibility offered by the DHNs provides future opportunities for new technologies and alternative energy and fuel sources, allowing energy and CO_2 savings to be retained in the future compared with the counterfactual building scale options.

In the 2010s and 2020s, virtually all zones are economic for all scenarios compared with both counterfactuals, resulting in heat cost savings of between 30% and 50%. The savings per a domestic customer are circa £62 per year per £1 billion GB saving, and for non-domestic customers £79 per year per £1 billion GB saving. This means that in scenario 1, the average home connected could save approximately £350 per year annualised cost against gas boilers and £950 per year annualised cost against ASHPs.

Using the central case as an example to understand the order of magnitude of the market size, the following figures are obtained:

- The total investment potential in energy centres is circa £35 billion. This includes the plant (and replacement during a schemes lifetime), energy centre building, and associated services.
- The total investment potential in DHNs is circa £93 billion.
- The total potential for installed CHP capacity is circa 47 GW thermal.

These values show that the potential market for macro DE equipment and services is significant enough to support extensive up-scaling of relevant industries in the GB if local manufacture and supply chain is to be developed. Sectors that could particularly benefit are: steel pipe, gas-engines and generators, civil engineering construction, domestic plumbing components and installers.

(2). Despite the technical and economic potential, many barriers exist which future policy aimed at supporting macro DE can help overcome.

By overcoming the barriers associated with macro DE schemes, in particular facilitating strong levels of uptake to access the heat market, and providing a fair electricity price for CHP generated electricity through changes to the electricity market, macro DE can be economic in all the classes identified in both the 2010s and 2020s. The importance of a favourable electricity price is demonstrated in the modelling, with a reduction in revenue of 20% reducing the GB potential for economic macro DE schemes to around half. This has a larger effect than carbon pricing therefore suggesting that policy which only considers carbon pricing may have limited impact on the viability of macro DE if electricity revenues are not also directly supported.

Achieving a high market penetration will be important, and policy could be used to assist with this. The modelling demonstrates that provided a high proportion (typically around 80% but scheme dependent) of the market can be achieved, it is not necessary to access all customers allowing for some flexibility, but these types of penetration levels, especially in the private sector and domestic sectors will require policy support. Schemes will need to be effectively marketed, and customers potentially incentivised, or the use of regulation to encourage connection.

These conditions combined with large scale deployment and diversified schemes, results in optimised schemes where large proportions of the heat can be provided by the CHP units, improving the overall efficiency and primary energy savings.

(3). Macro DE may be a significant contributor to GB electricity supply with wide spread deployment.

Achieving the economic potential of macro DE will result in high levels of electricity generation of up to 62% of the total GB demand. It will be important to understand how feasible this is, although there will be good synergies between heat generation and electricity demand, especially if non-macro DE areas take up heat pumps. The performance of the grid in the modelling is independent of the amount of macro DE generated electricity and these need to be examined together in future work.

(4). DHN costs dominate the capital expenditure and access to low cost finance can help reduce this impact.

The economic and environmental performance of macro DE in the 2020s will be affected by a number of factors. The lowest levelised costs are achieved with access to lower discount rates of 3.5% in scenario 2, demonstrating the importance of controlling the cost of capital finance. This represents significant public sector investment in schemes. The DHN costs typically represent around two thirds of the overall capital expenditure, except in commercial/institutional building orientated zones (where they can be considerably lower). Therefore changes in DHN costs (scenarios 5 and 10) have a greater impact than energy centre costs (scenarios 4 and 9). WP1 also identified that DHNs may cost more in the UK than in Continental Europe and so this disparity needs investigating. Importantly, macro DE remained economic in virtually all zones across all scenarios, demonstrating the robustness of the solution.

(5). The CO_2 savings from gas CHP will reduce in the 2030s, but alternative forms of generation can make use of the flexibility offered by DHNs.

In the 2030s, gas CHP remains the most economic technology for macro DE schemes, but is no longer predicted to save carbon. It is not predicted that large scale heat pumps will be taken up if cost is the prime driver, and additional CO_2 constraints and market interventions are required to ensure that macro DE schemes are developed which save CO_2 compared to the counterfactuals. The combination of large scale heat pumps and gas engine CHP allows CO_2 savings of greater than 50% compared with gas boilers to be achieved in this period, with a commercial GB Benefits Case potential of 6% of the heat market, and an economic GB Benefits Case of 21% of the heat market.

If heat pumps are used as a replacement on existing macro DE schemes, the economics will be improved due to the prior payback of part or all of the DHN, creating a larger economic market and greater CO_2 reduction.

In order to maintain a larger share of the heat market, the 5.1 modelling demonstrates that further technology development and potentially newer technologies will be required to ensure that schemes can remain economic and provide acceptable CO_2 reductions. This will be examined in the 5.3 report and analysis.

Recommendations for further work.

This report presents the GB benefits case for macro DE, and is part of the larger ETI macro DE study. Throughout the work a number of areas have been identified where further work could be conducted to further understanding in the area of macro DE. In this section, recommendations are made on issues identified in this report, based around the GB potential.

The following recommendations are made:

i. The modelling suggests that gas engine CHP could provide up to 62% of the GB electricity demand. It is recommended that further work examines the potential of the electricity network to accept this level of distributed electricity generation, and assessed how this scale of generation can be accommodated alongside other sources of generation and the demand profile. Further modelling by the ETI using the ESME model will help to substantiate the need for this analysis. It is likely (and currently in the DECC roadmaps) that some form of fossil fuelled thermal electricity generation will be in operation until 2050. Whilst this is the case, it makes sense for this to be distributed allowing capture of the waste heat for macro DE. Therefore if macro DE schemes are deployed at a large scale, CHP is likely to have a long term future.

ii. The high levels of electricity generation could have a strong synergy with heat pumps being used in non-macro DE areas and other future electricity demands (such as electric vehicles). It is recommended that this is examined further to understand the relative scales of deployment of macro DE (urban areas) and micro DE (rural areas), and the corresponding changes in electricity demand and generation. With macro DE predicted to be a major electricity producer if fully deployed to potential, finding economic uses for this electricity (potentially in micro DE, but also electric vehicles) will be important.

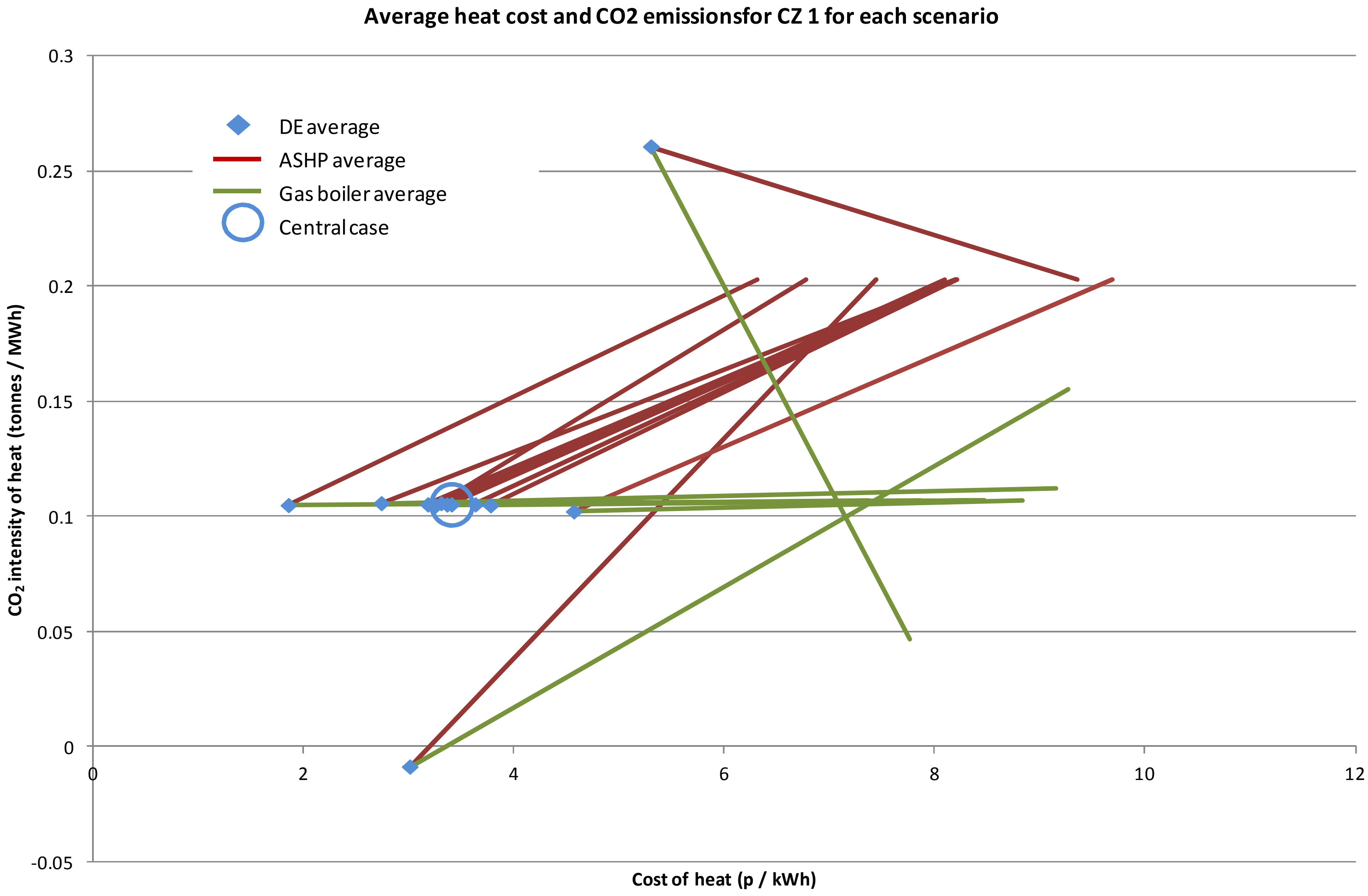
iii. During the 2030s, there is a role for both gas engine CHP and heat pumps on macro DE schemes. This modelling assumes a simple average marginal electricity grid factor, but the schemes could be operated in a smart manner to use the most appropriate technology depending on grid conditions. For example at times of high demand and low wind output gas CHP would be used and at times of low demand and high wind output heat pumps would be preferred. It is recommended that a "smart mode" of operation is examined including the use of tighter CO_2 constraints in the 2030s, to refine and optimise the concept of a combined gas CHP and heat pump system. This could include the examination of control parameters, technology and communications options, and systems and mechanisms currently used elsewhere, such as the national grid. This analysis will also need to include an understanding of how future energy demand patterns may change (see point ii).

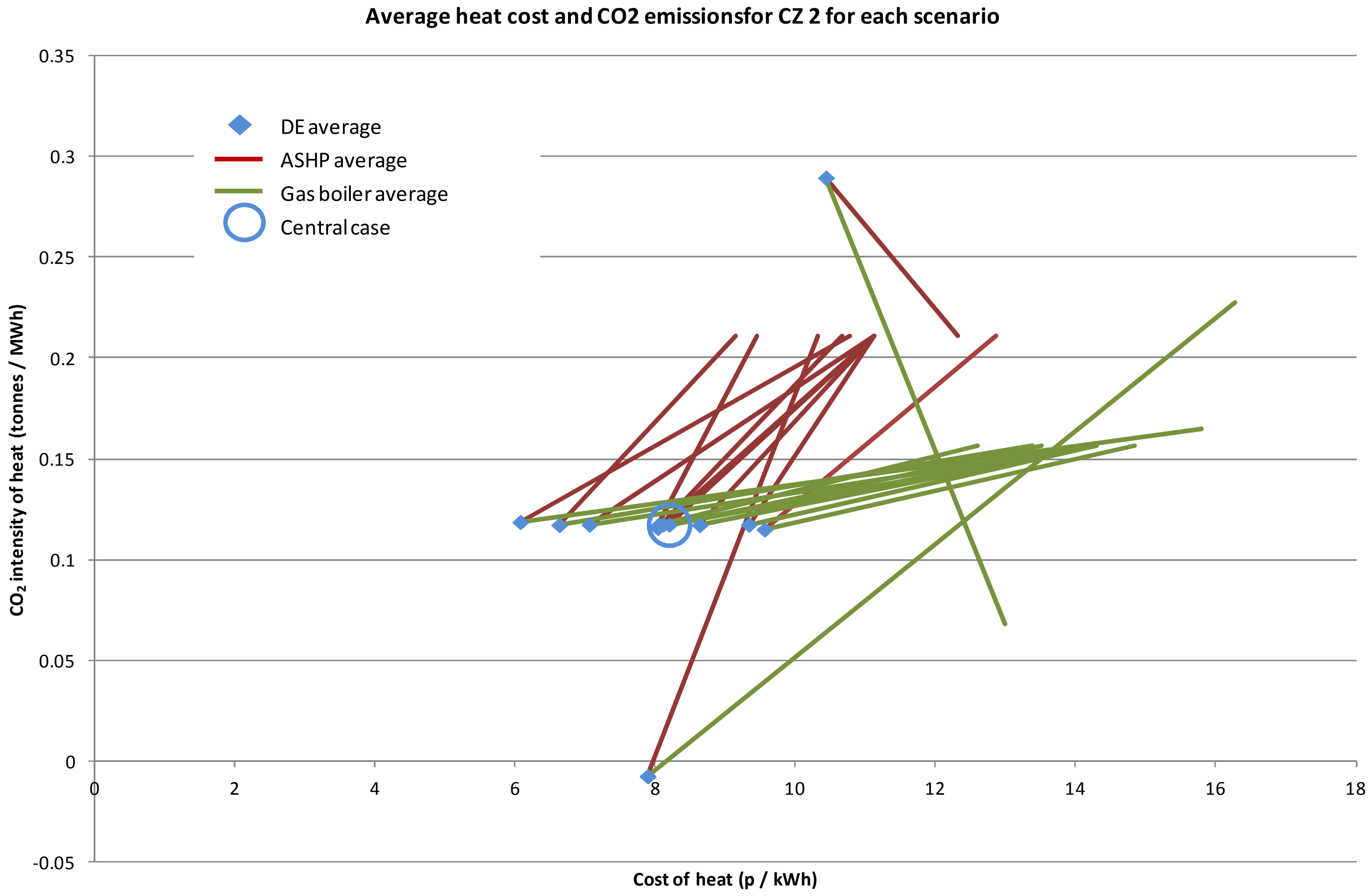
iv. The modelling in this work is based around a central market penetration level of 80% with a sensitivity of 100%. The central case represents a high uptake whilst allowing for some flexibility, but may require policy to incentivise or regulate connection to achieve. At lower levels of penetration, it is unlikely that schemes will attract investment unless future guarantees of connection increases are provided. It is recommended that further work assesses the sensitivities around market penetration levels in more detail, including benchmarking penetration levels against existing schemes, and taking some example schemes to understand how scheme specific factors such as DHN layout and customer types could influence this.

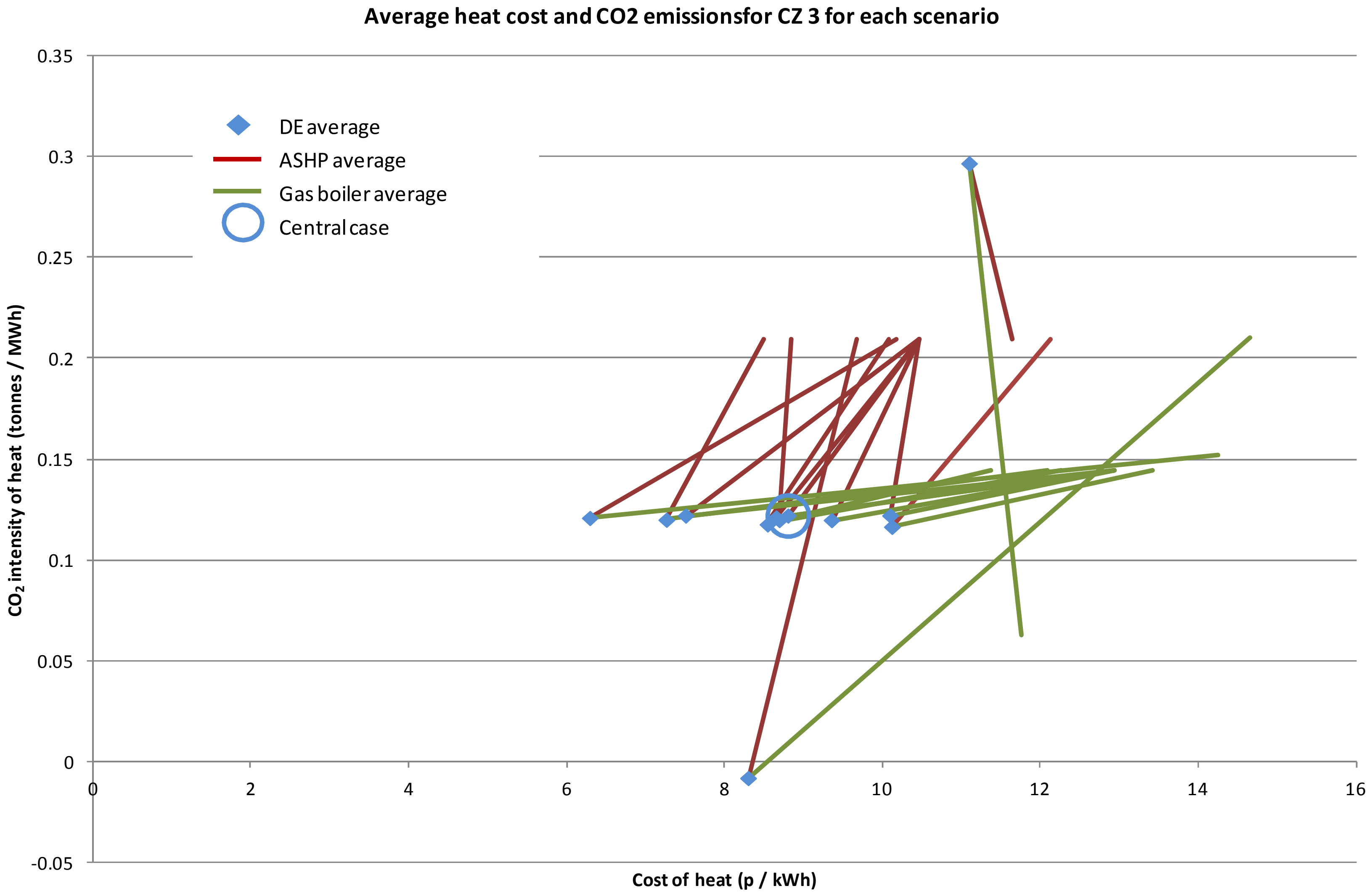
Appendices

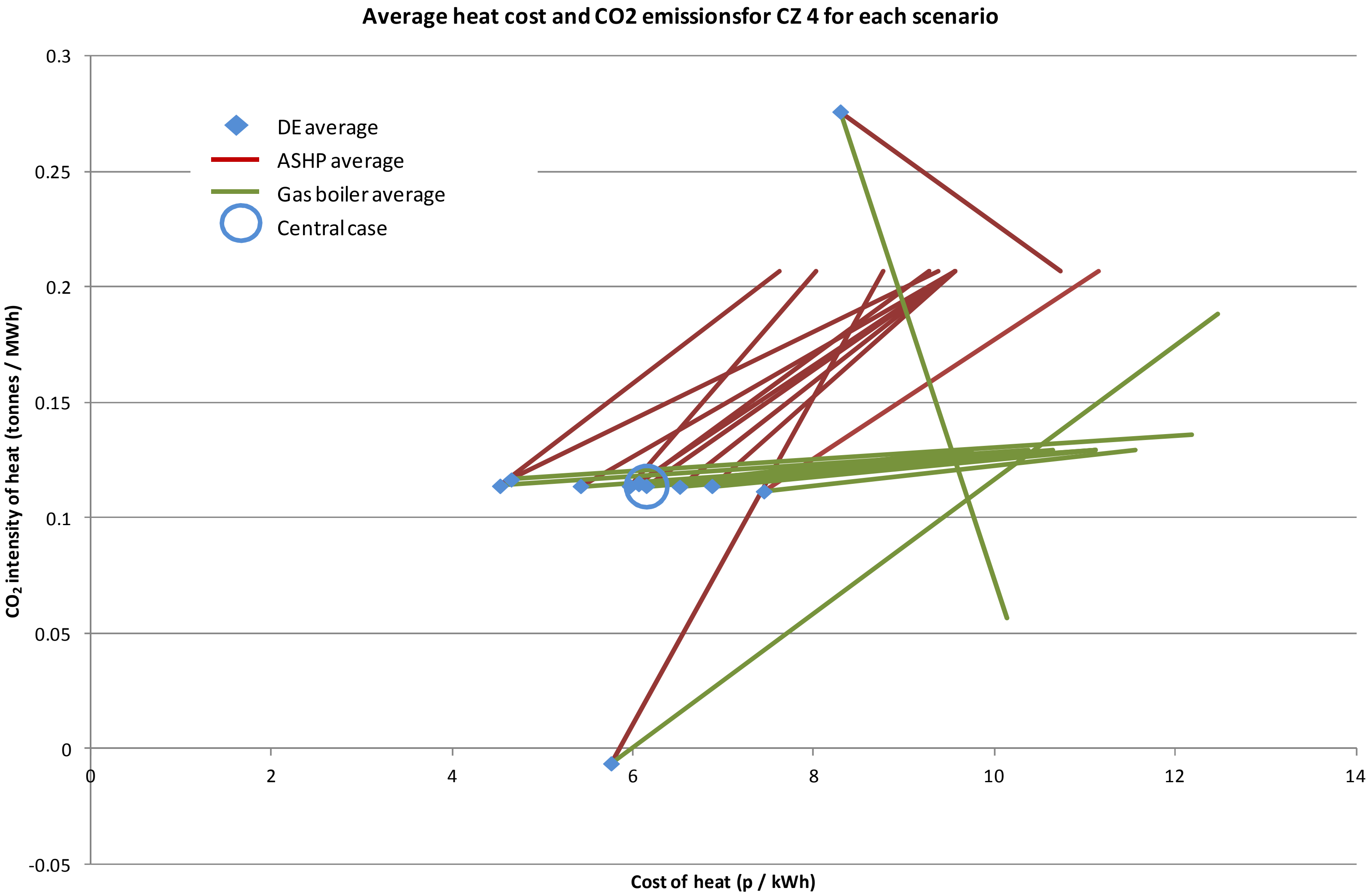
Appendix 1 – Results by characteristic zone

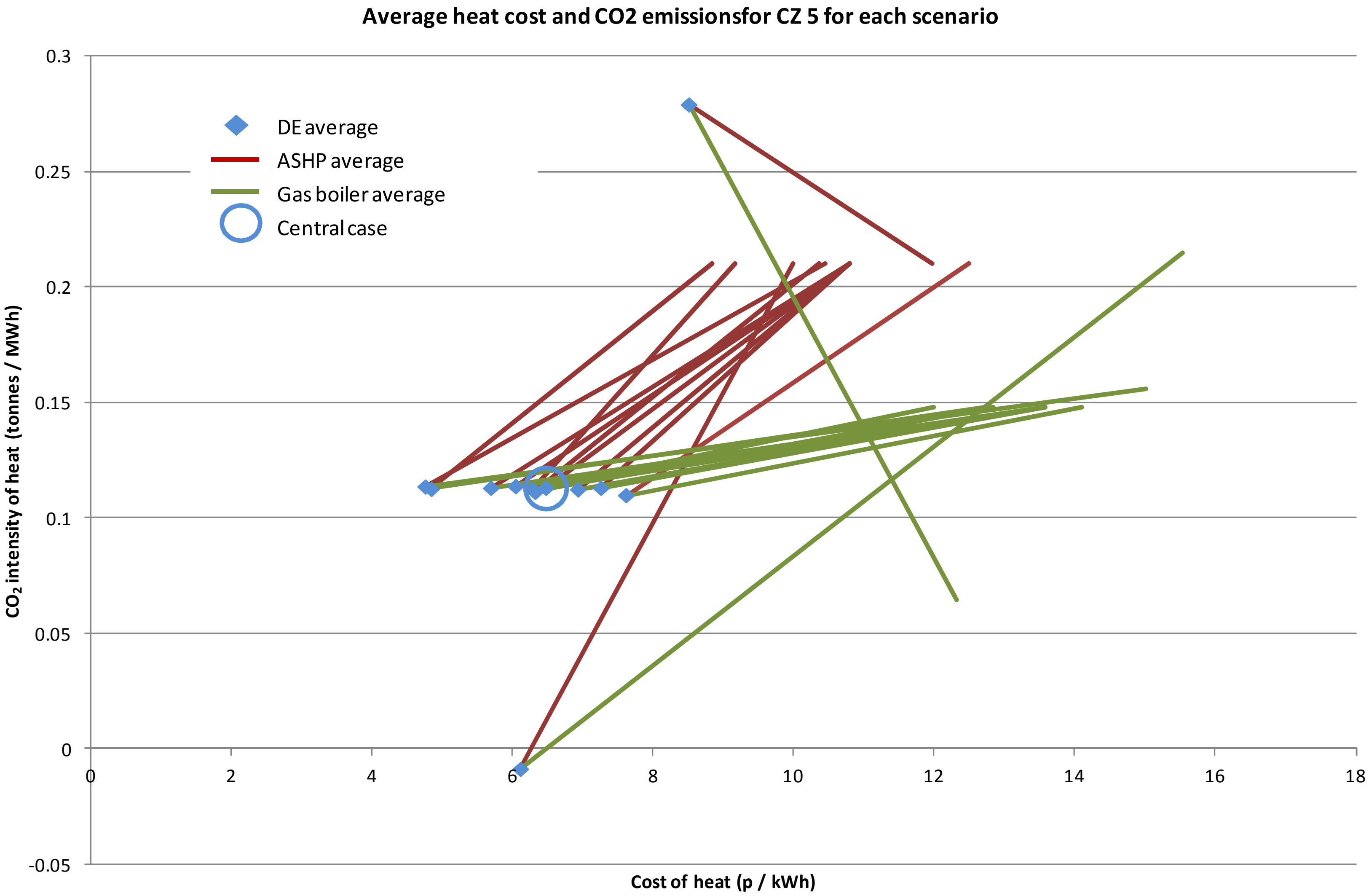
The following charts show all the scenario results for a single CZ, using tails to show the relative change in macro DE schemes and the counterfactuals. To interrogate the data further, the datasets provided alongside this report should be referred to.

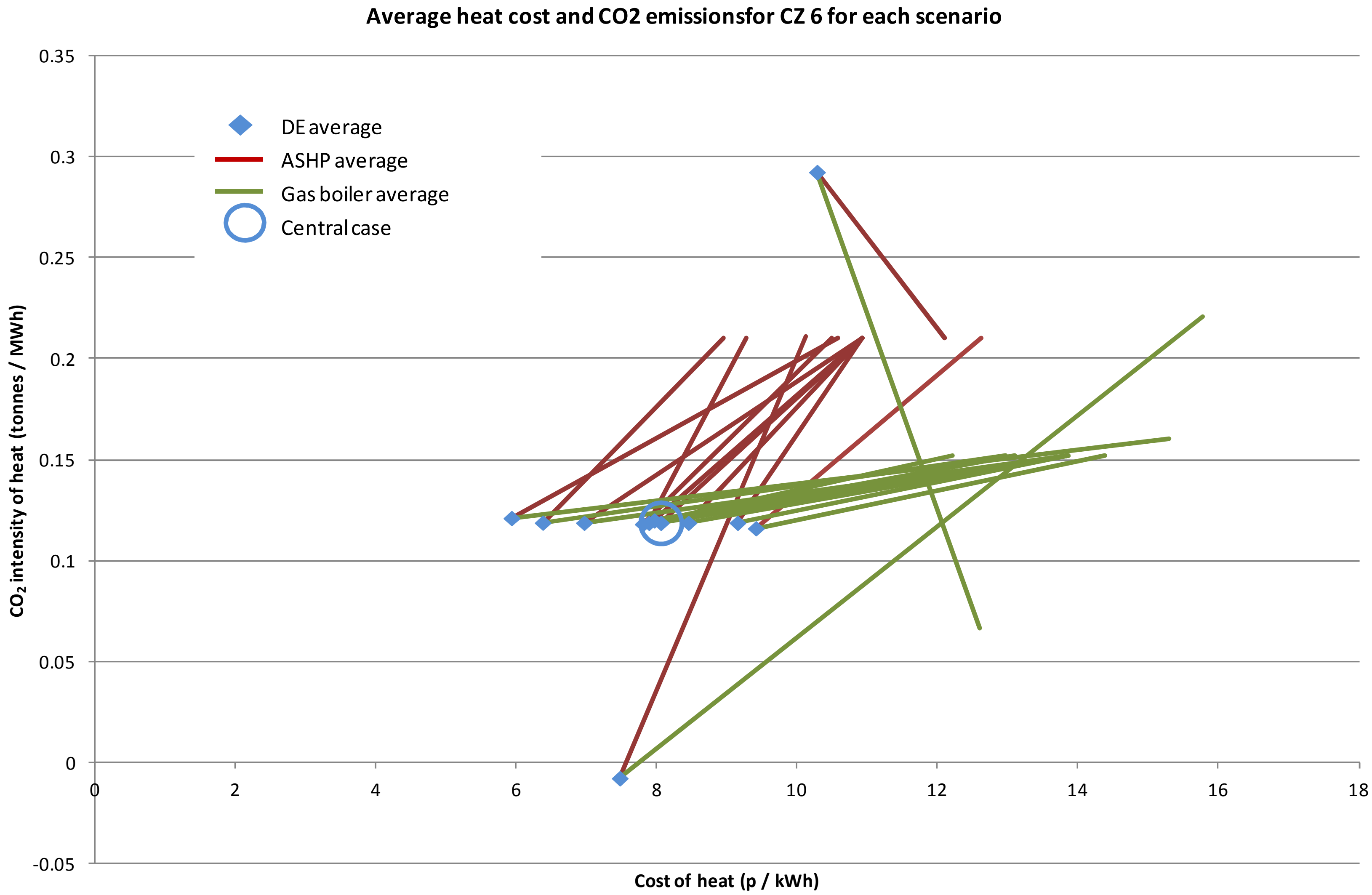

Average heat cost and CO2 emissionsfor CZ 1 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO₂ intensity of heat (tonnes / MWh)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
Cost of heat (p / kWh)

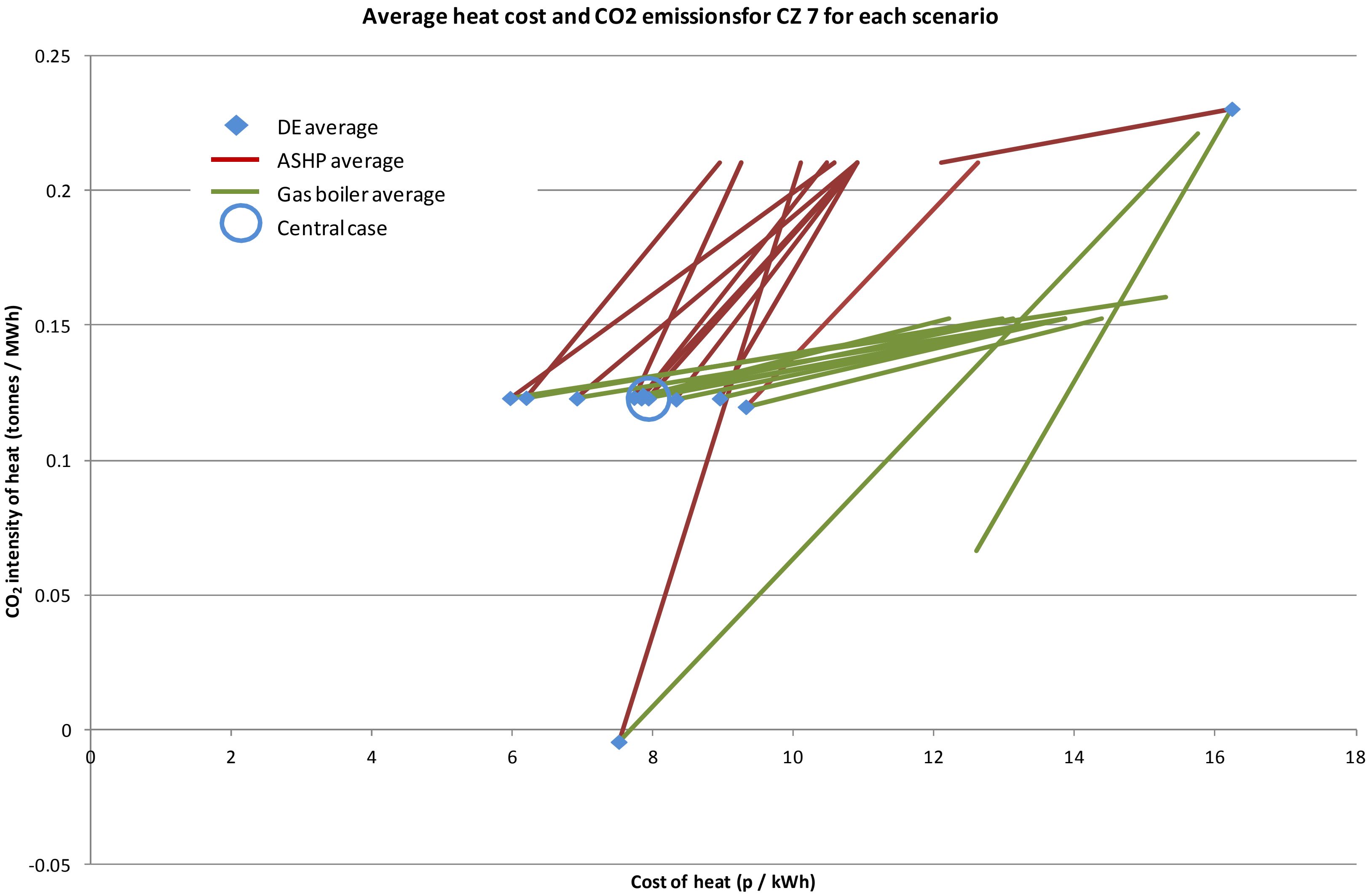

Average heat cost and CO2 emissionsfor CZ 2 for each scenario
DE average
ASHP average
Gas boiler average
Central case
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
18
CO_2 intensity of heat (tonnes / MWh)
Cost of heat (p / kWh)

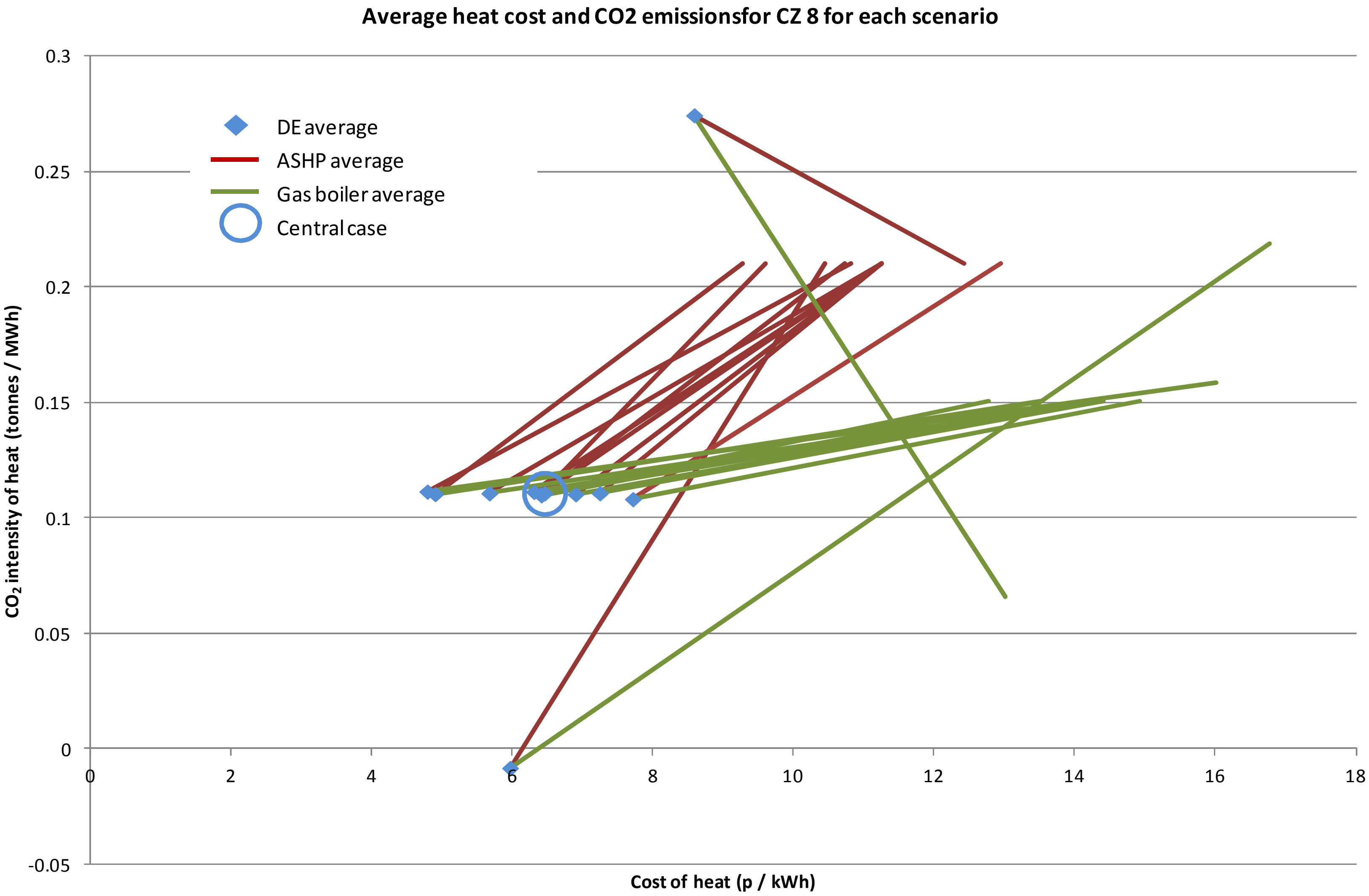

Average heat cost and CO2 emissionsfor CZ 3 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO_2 intensity of heat (tonnes / MWh)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
Cost of heat (p / kWh)

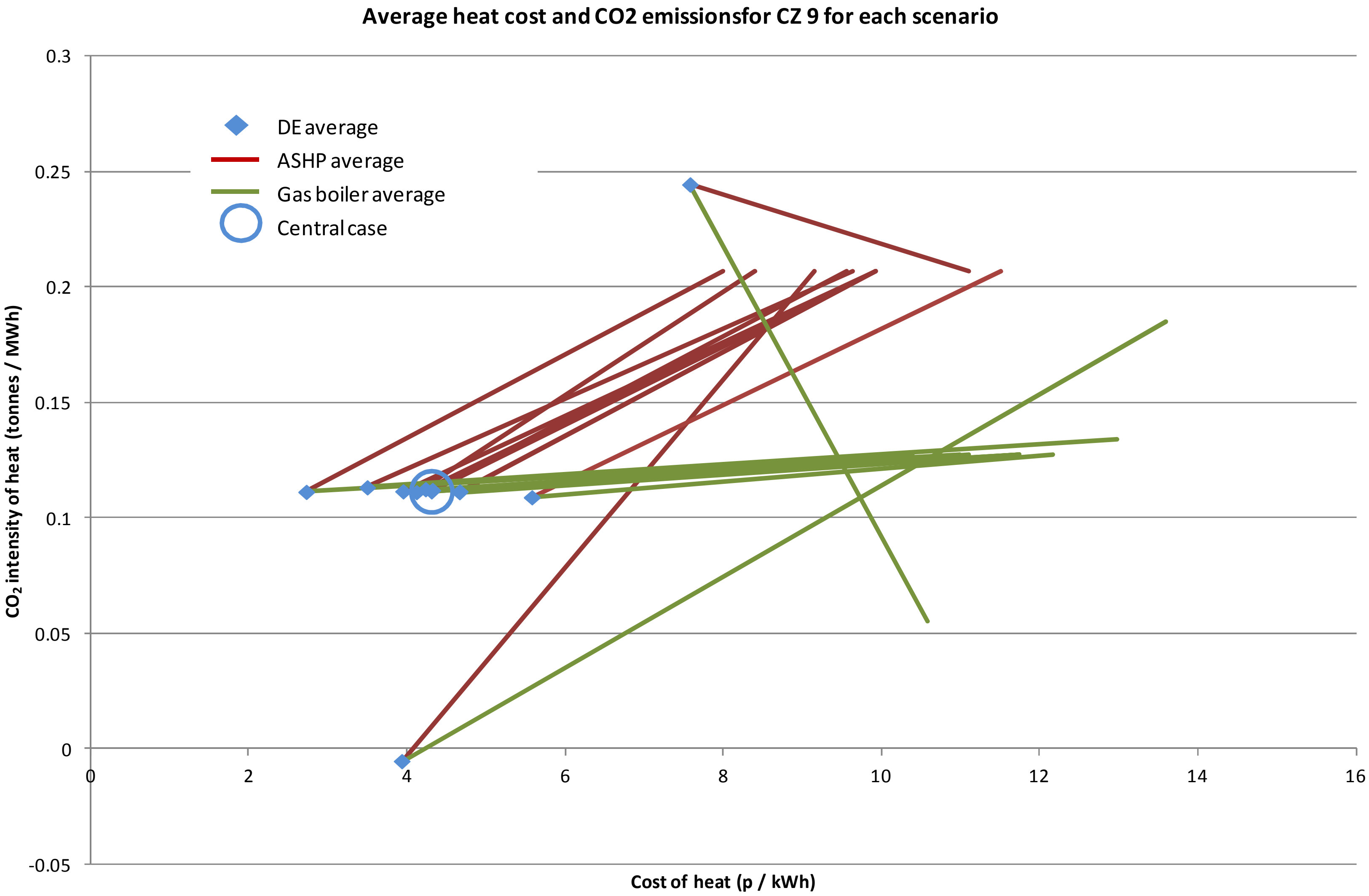

Average heat cost and CO2 emissionsfor CZ 4 for each scenario
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
DE average
ASHP average
Gas boiler average
Central case
CO2 intensity of heat (tonnes / MWh)
Cost of heat (p / kWh)

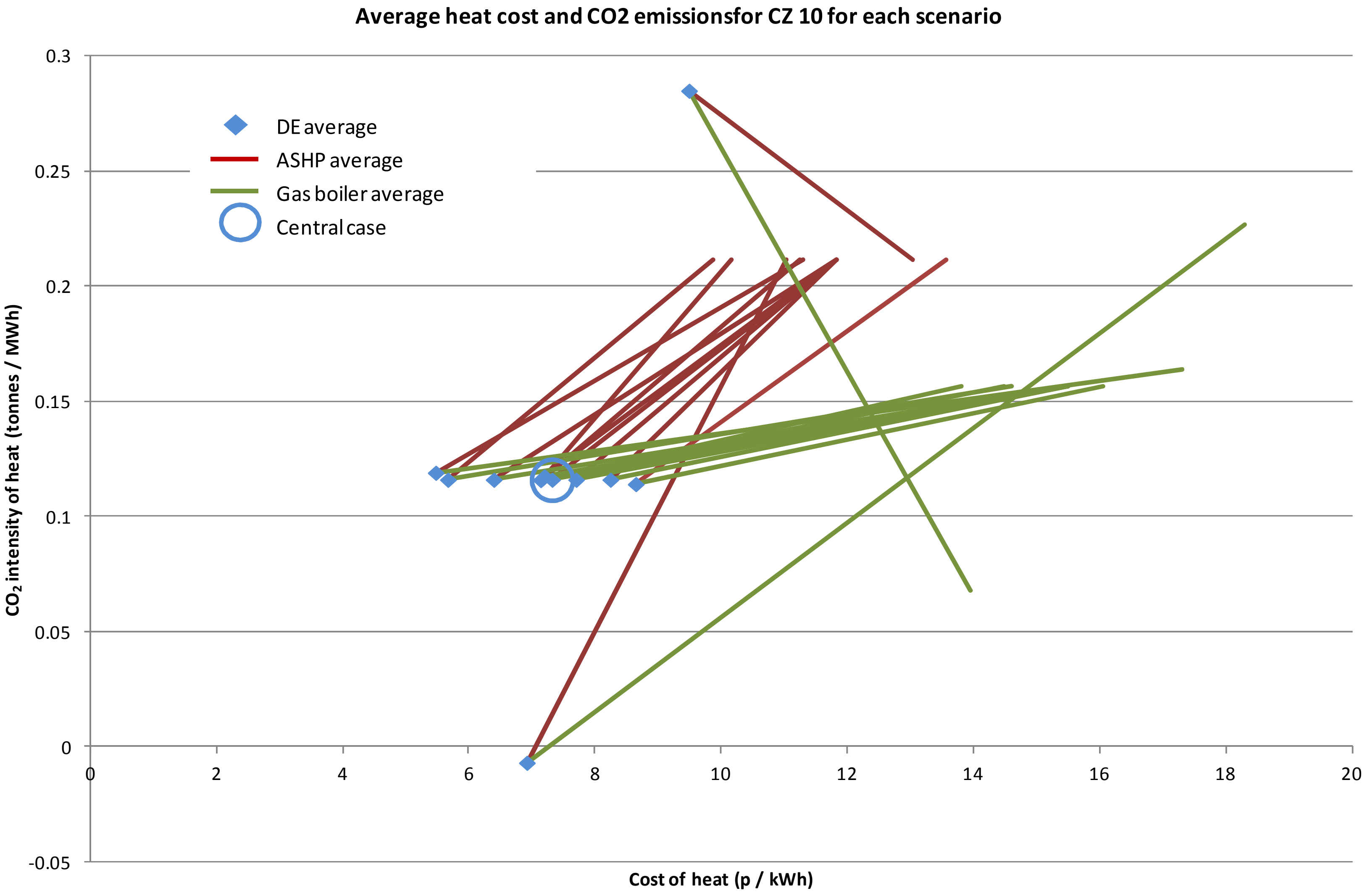

Average heat cost and CO2 emissionsfor CZ 5 for each scenario
CO₂ intensity of heat (tonnes / MWh)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
18
Cost of heat (p / kWh)
DE average
ASHP average
Gas boiler average
Central case

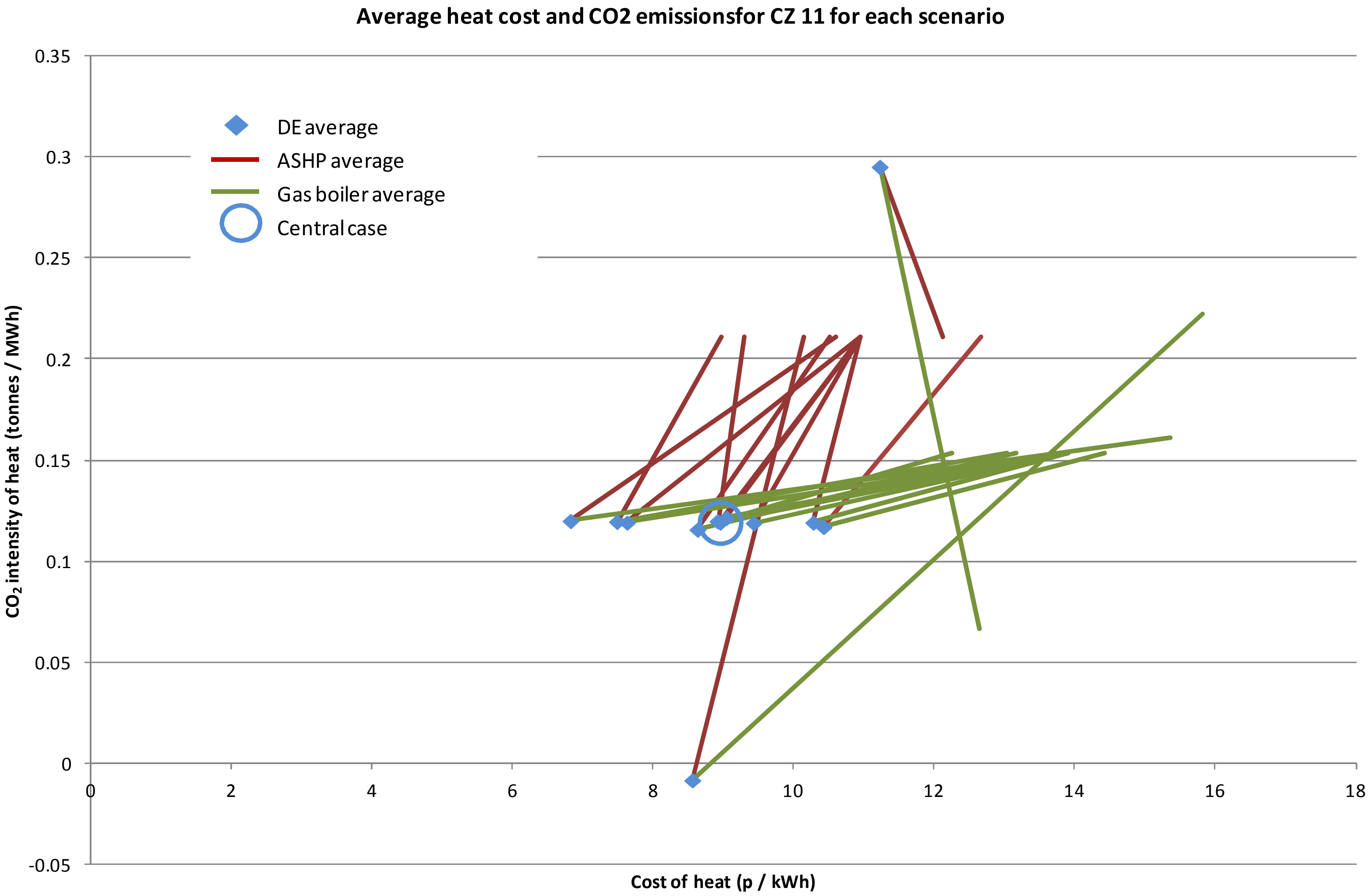

Average heat cost and CO2 emissionsfor CZ 6 for each scenario

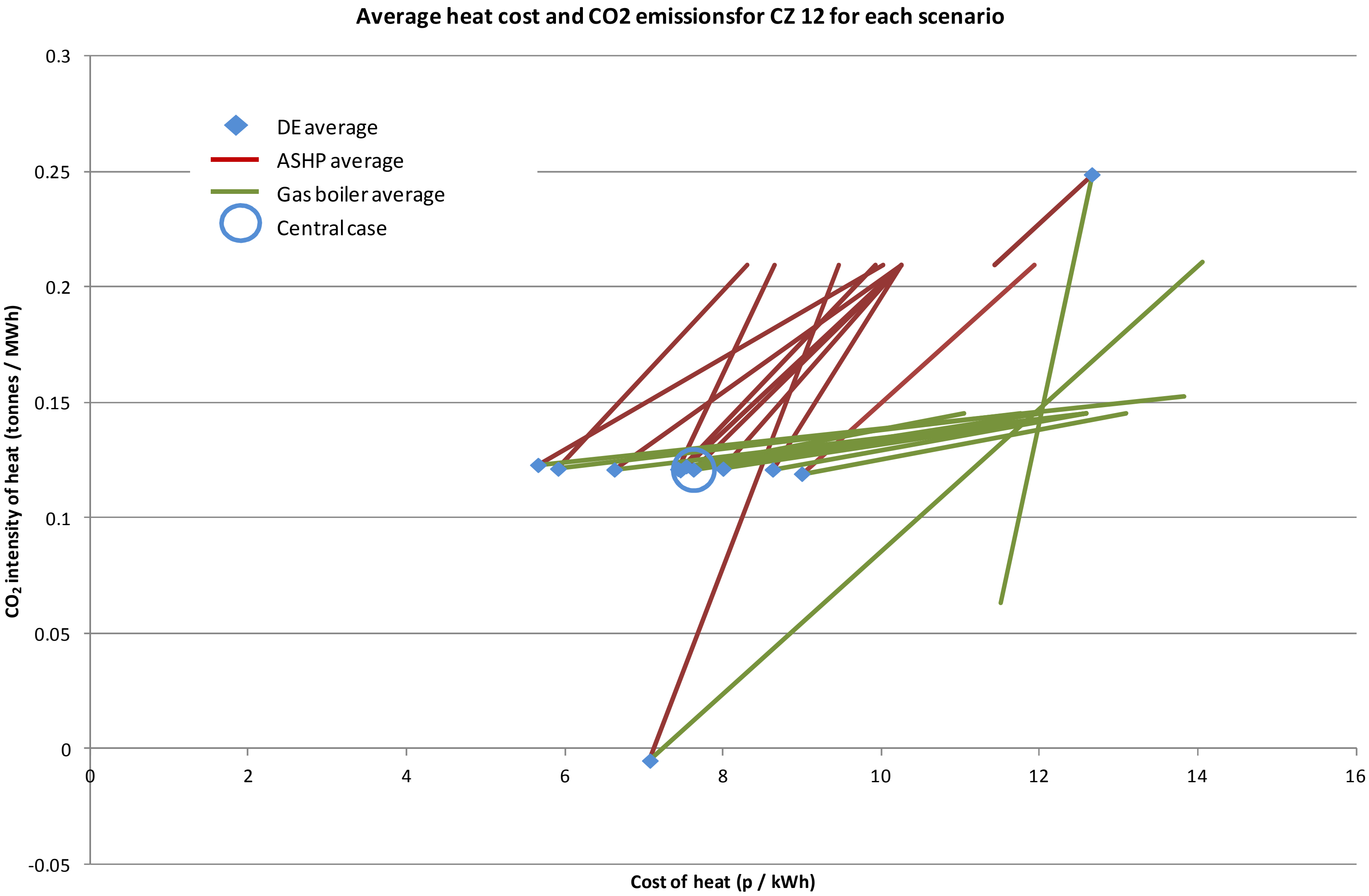

Average heat cost and CO2 emissionsfor CZ 7 for each scenario
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
18
DE average
ASHP average
Gas boiler average
Central case
CO_2 intensity of heat (tonnes / MWh)
Cost of heat (p / kWh)


Average heat cost and CO2 emissionsfor CZ 8 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO$_2$ intensity of heat (tonnes / MWh)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Cost of heat (p / kWh)
0
2
4
6
8
10
12
14
16
18

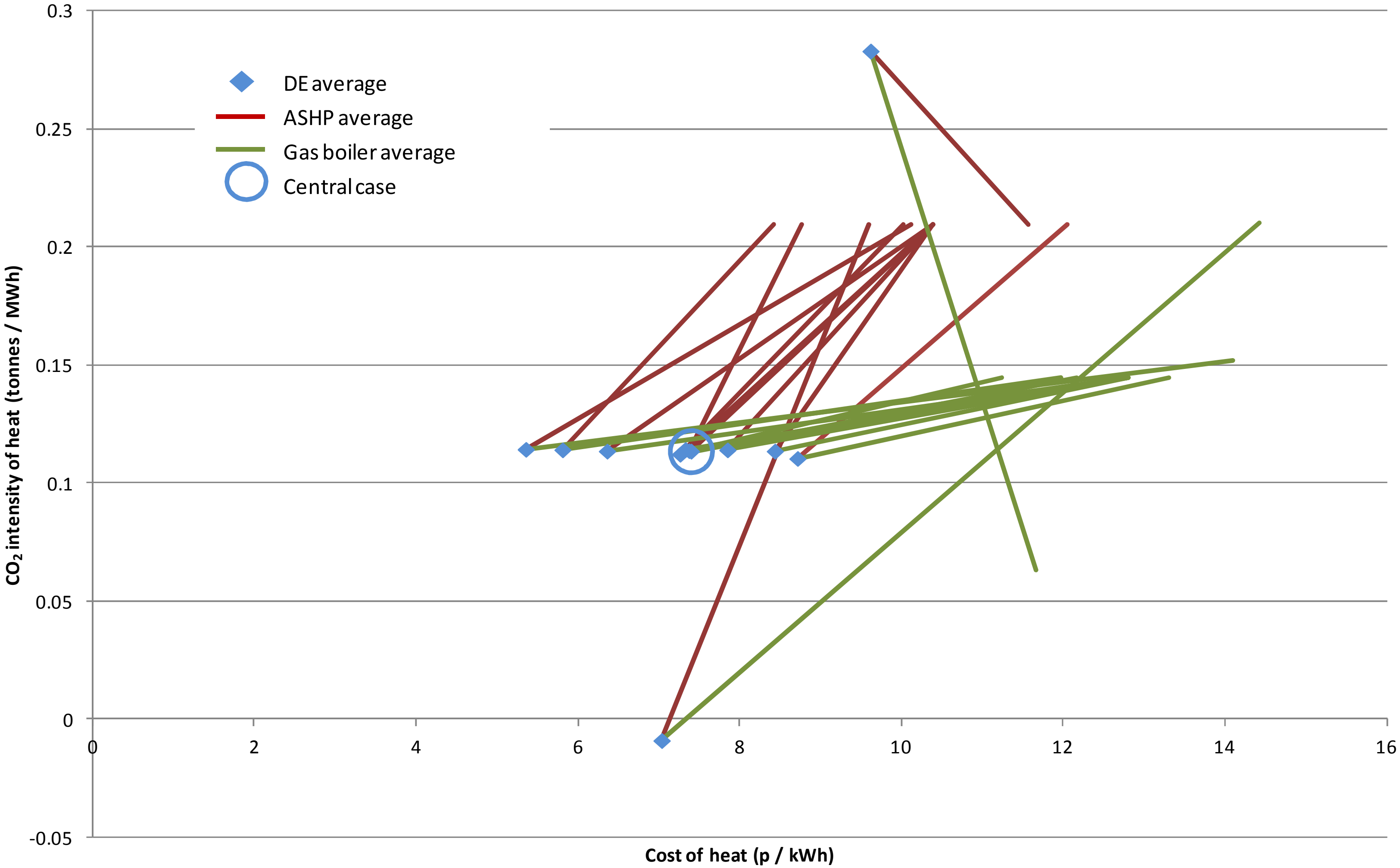

Average heat cost and CO2 emissionsfor CZ 9 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO₂ intensity of heat (tonnes / MWh)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
Cost of heat (p / kWh)

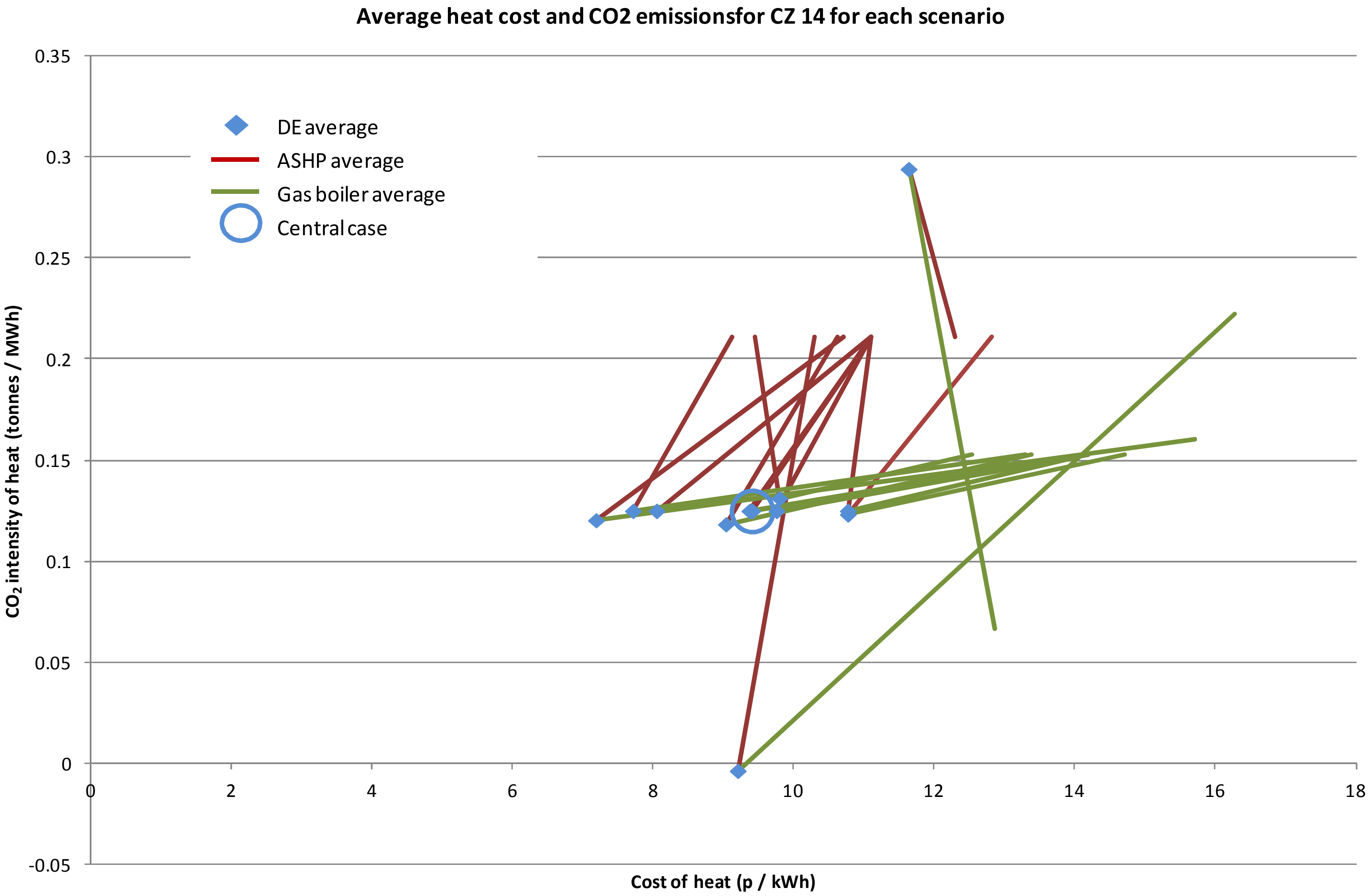

Average heat cost and CO2 emissionsfor CZ 10 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO2 intensity of heat (tonnes / MWh)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
18
20
Cost of heat (p / kWh)


Average heat cost and CO2 emissionsfor CZ 11 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO$_2$ intensity of heat (tonnes / MWh)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
18
Cost of heat (p / kWh)

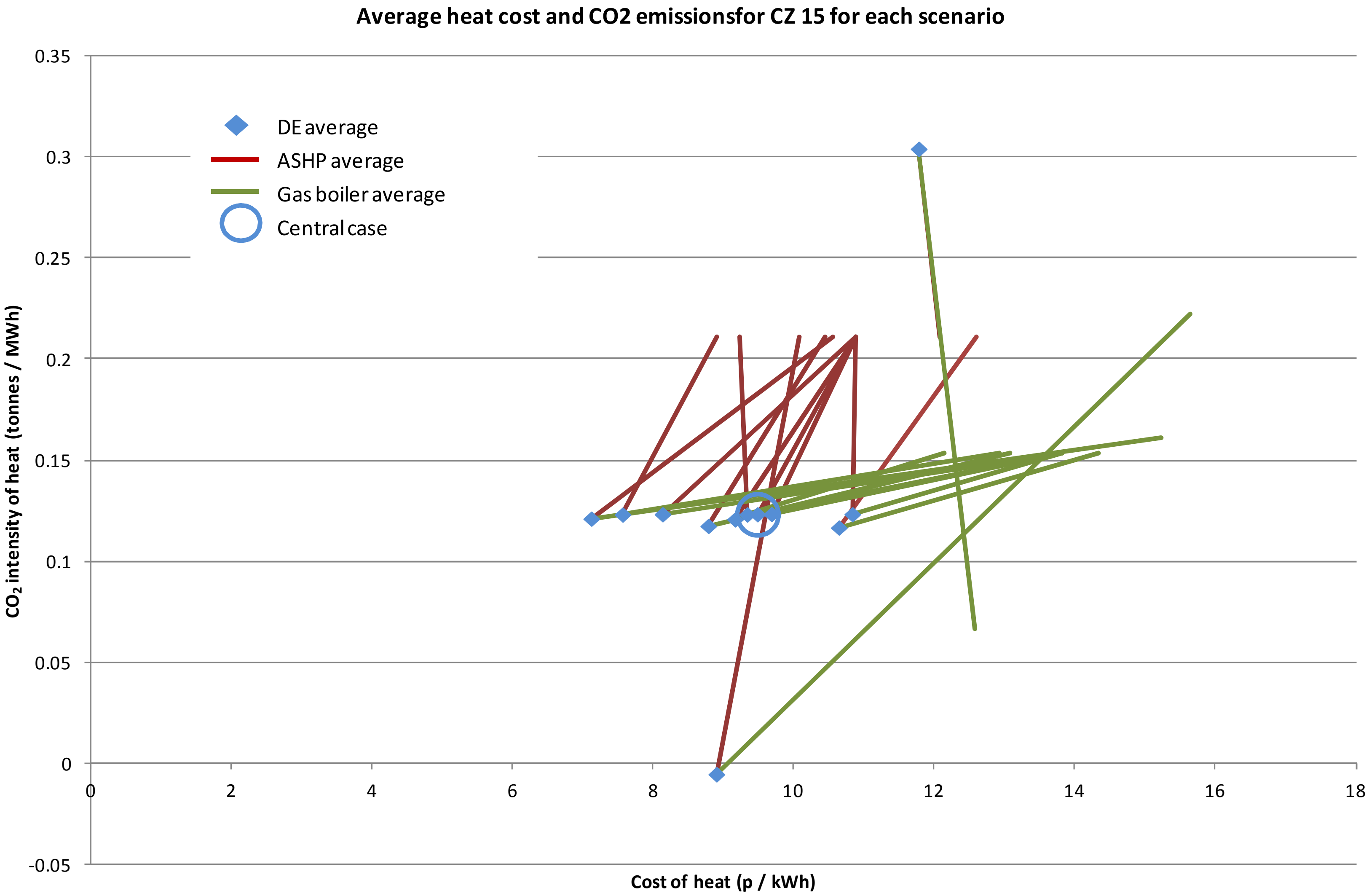

Average heat cost and CO2 emissionsfor CZ 12 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO_2 intensity of heat (tonnes / MWh)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
Cost of heat (p / kWh)

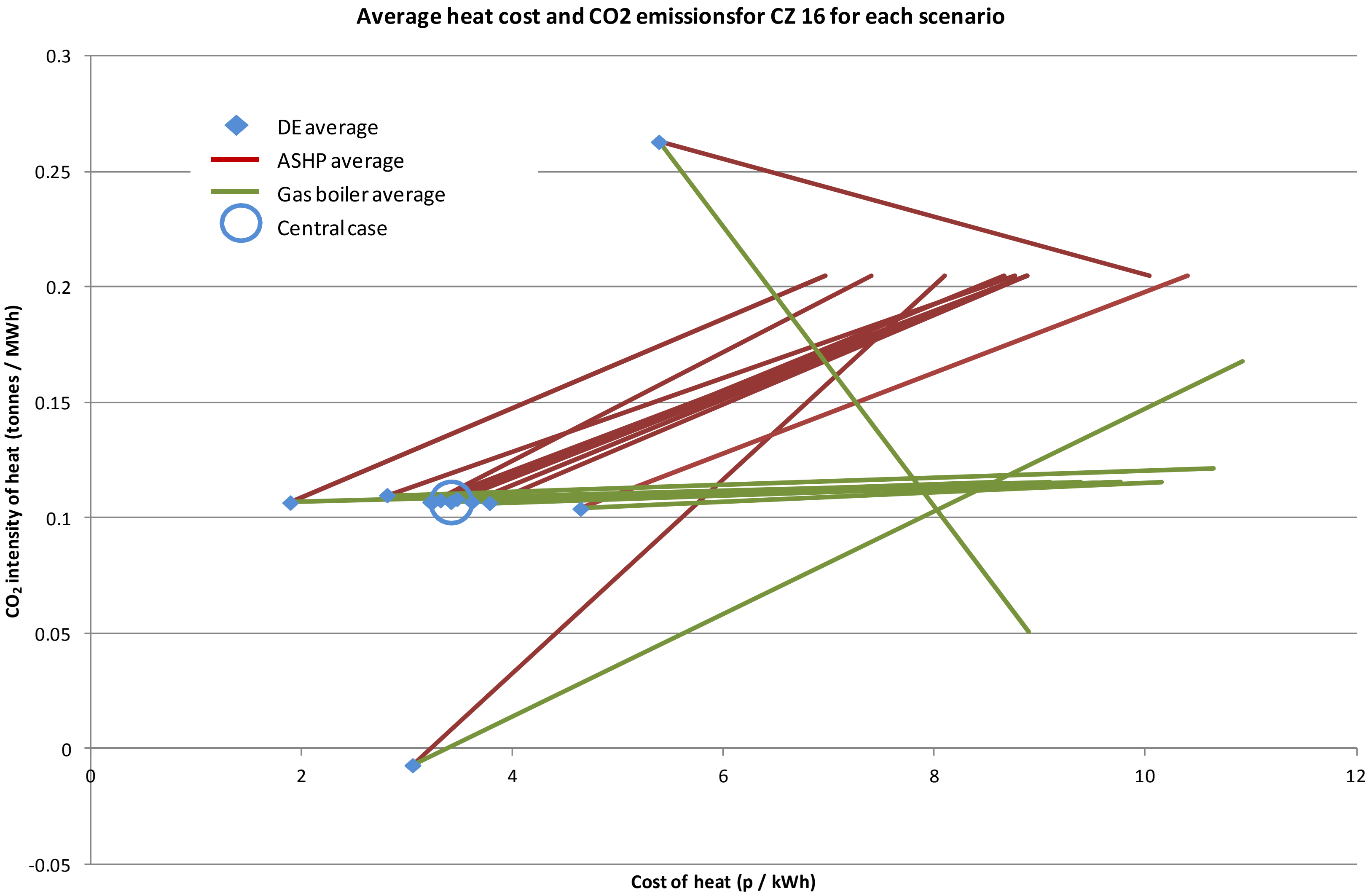
Average heat cost and CO2 emissionsfor CZ 13 for each scenario

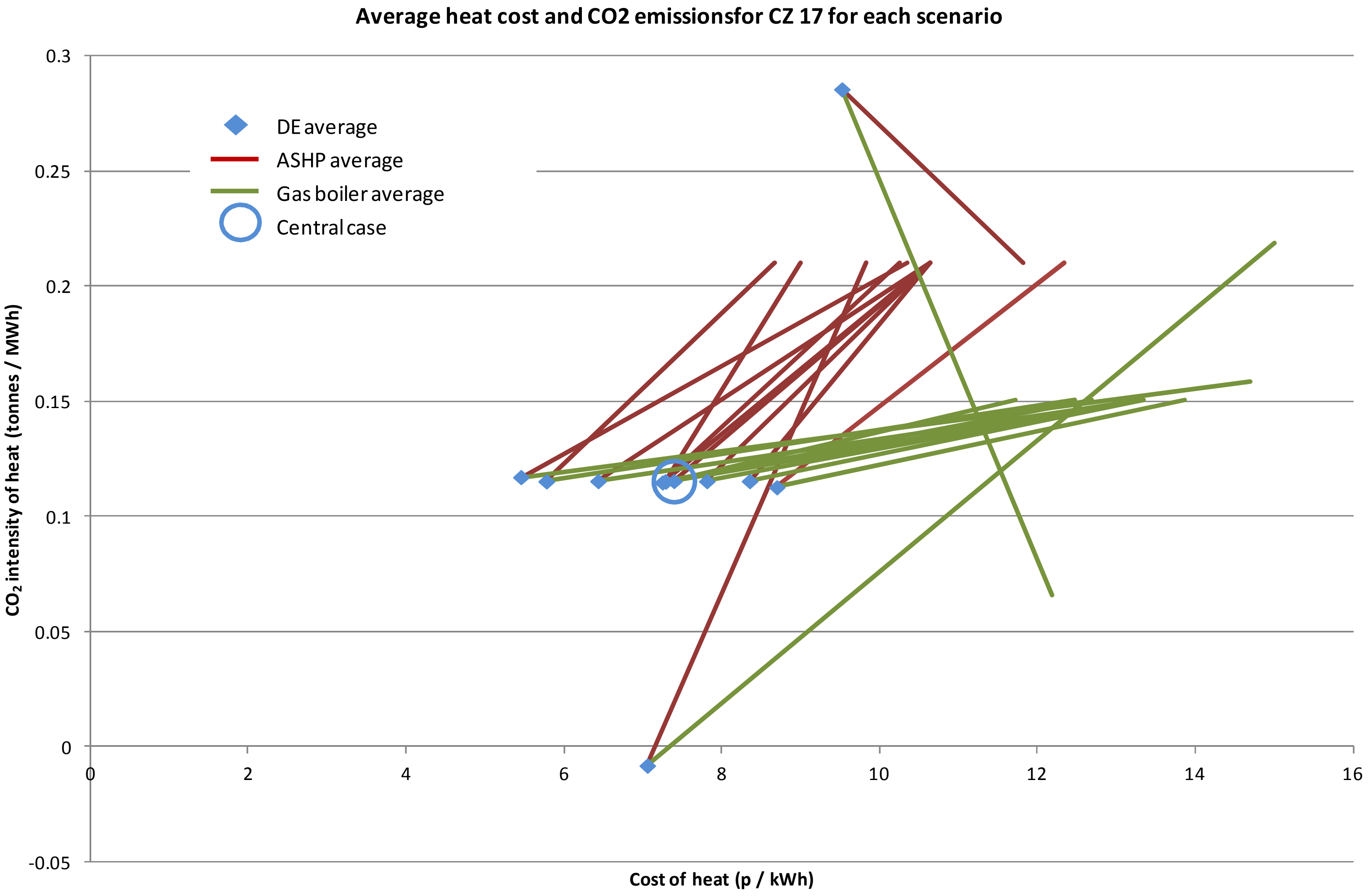


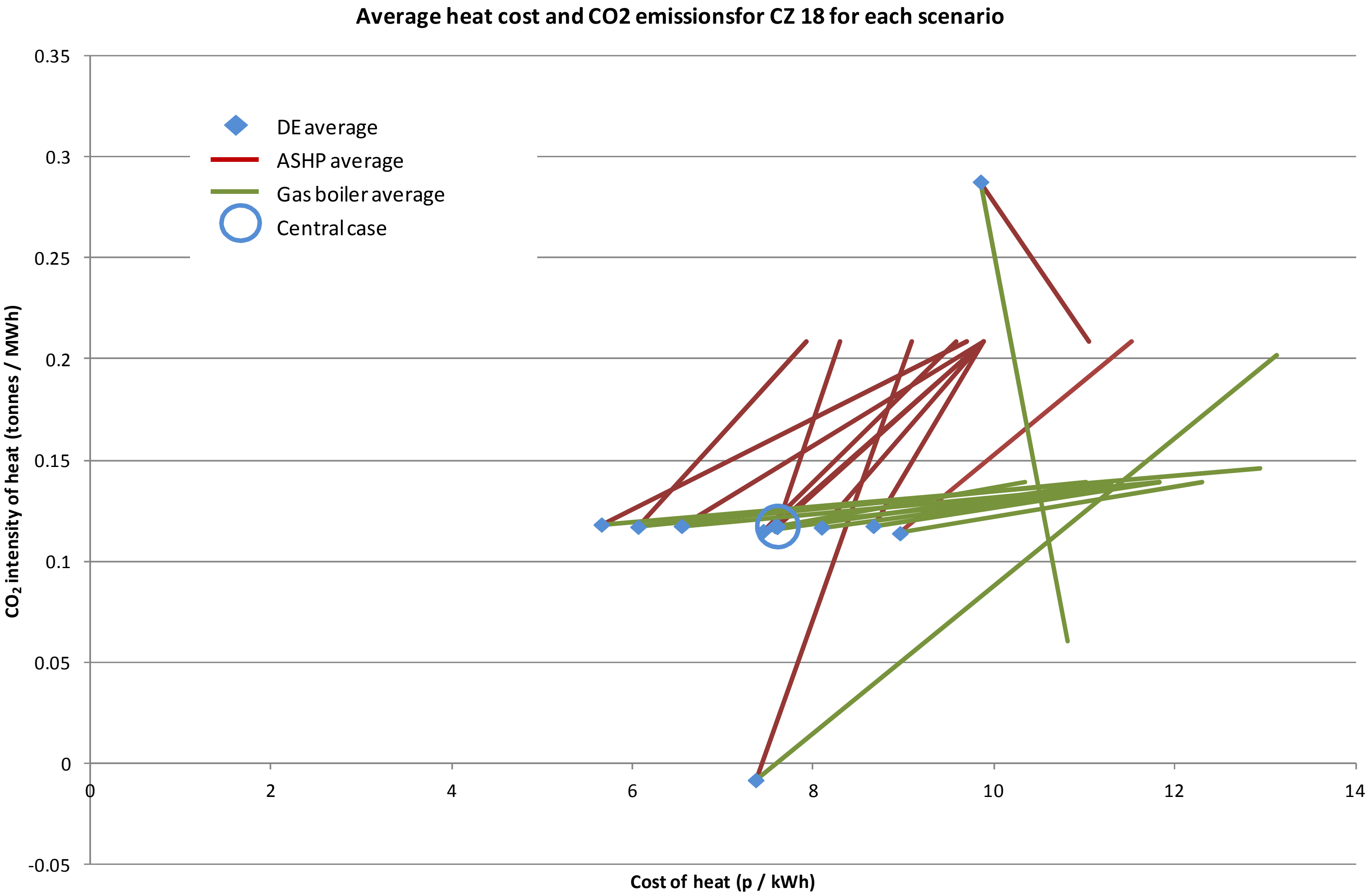


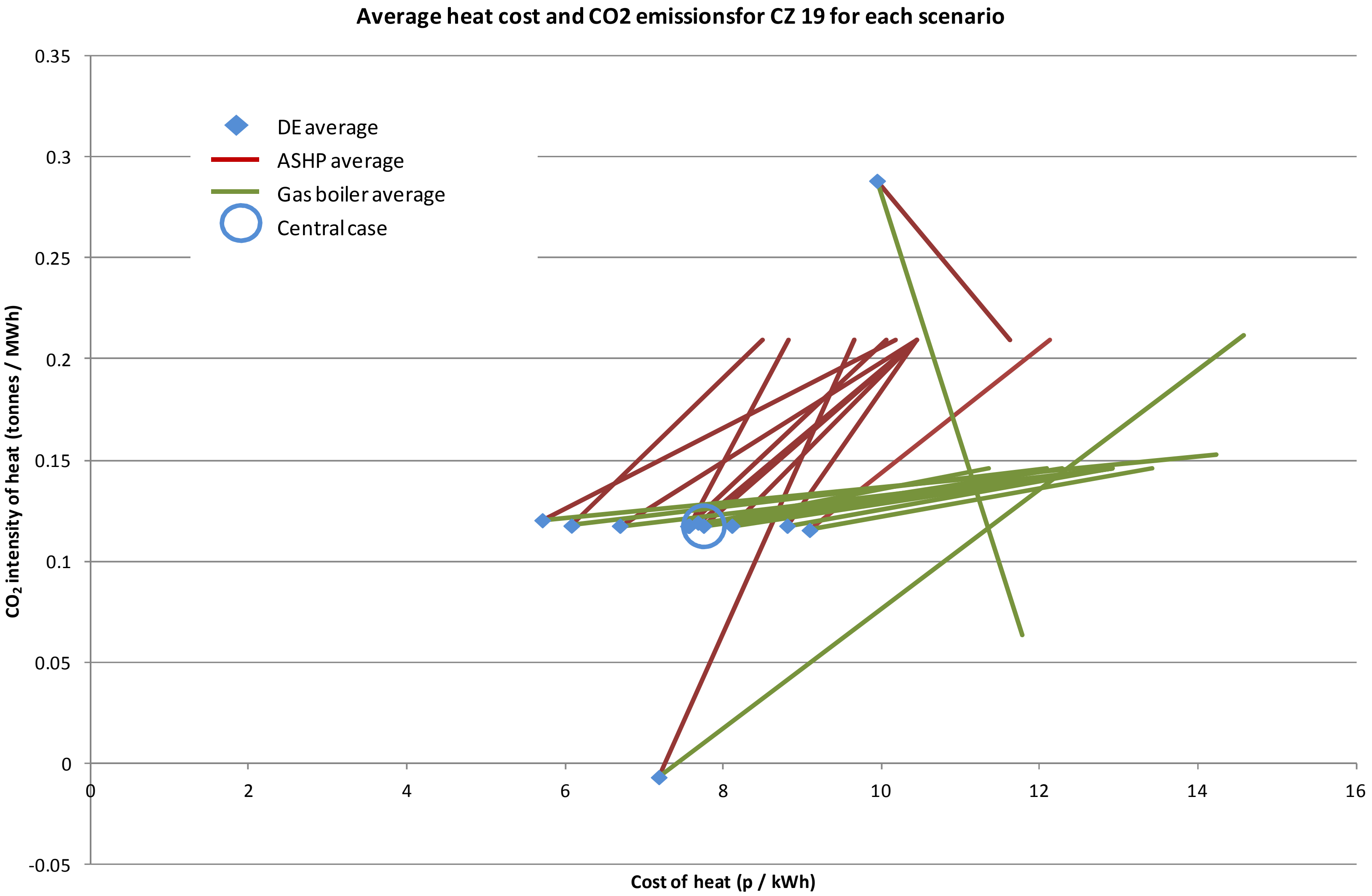
Average heat cost and CO2 emissionsfor CZ 14 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO_2 intensity of heat (tonnes / MWh)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
18
Cost of heat (p / kWh)

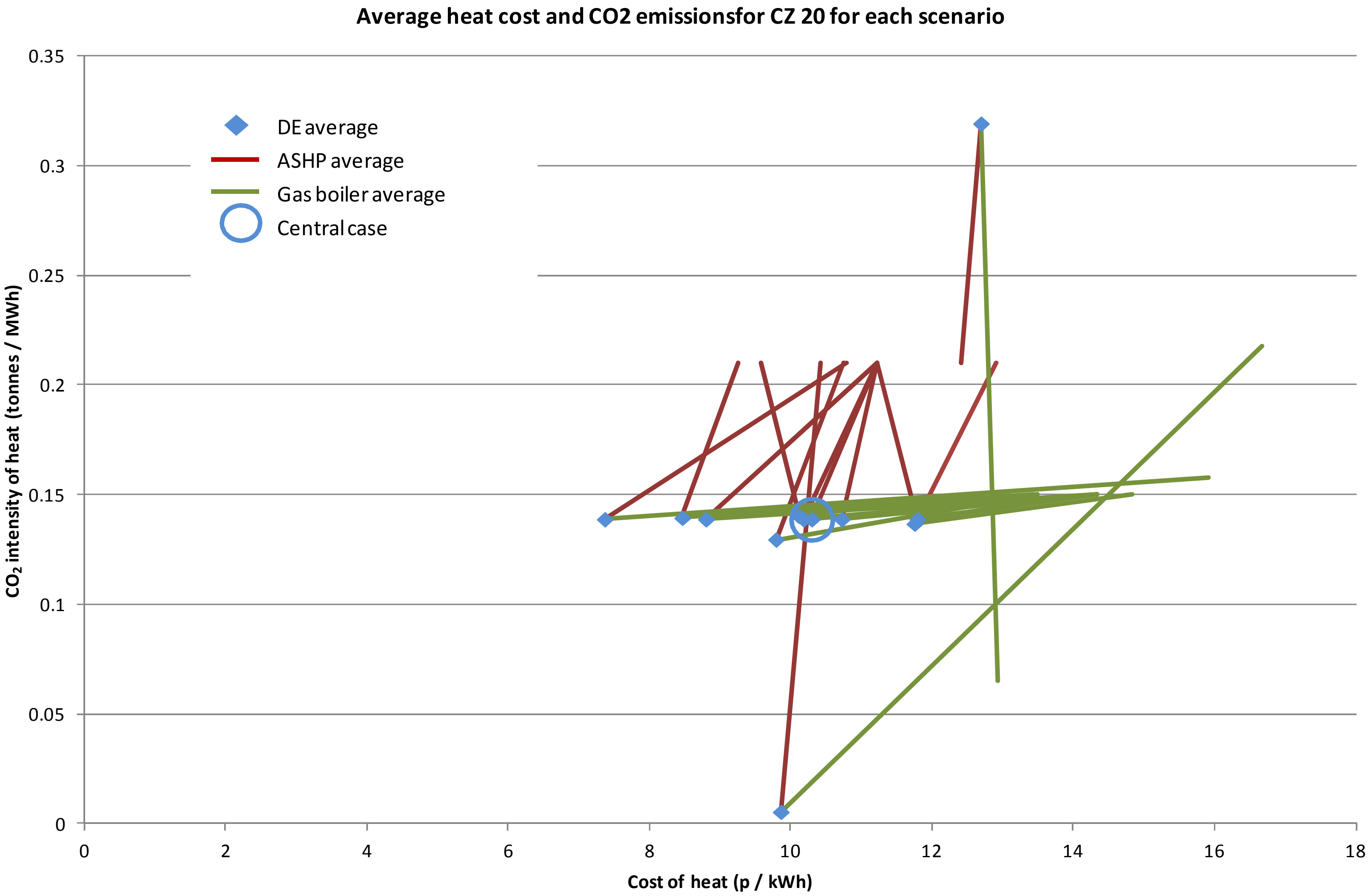

Average heat cost and CO2 emissionsfor CZ 15 for each scenario
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16
18
DE average
ASHP average
Gas boiler average
Central case
CO$_2$ intensity of heat (tonnes / MWh)
Cost of heat (p / kWh)


Average heat cost and CO2 emissionsfor CZ 16 for each scenario
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
DE average
ASHP average
Gas boiler average
Central case
CO₂ intensity of heat (tonnes / MWh)
Cost of heat (p / kWh)


Average heat cost and CO2 emissionsfor CZ 17 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO$_2$ intensity of heat (tonnes / MWh)
Cost of heat (p / kWh)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
16

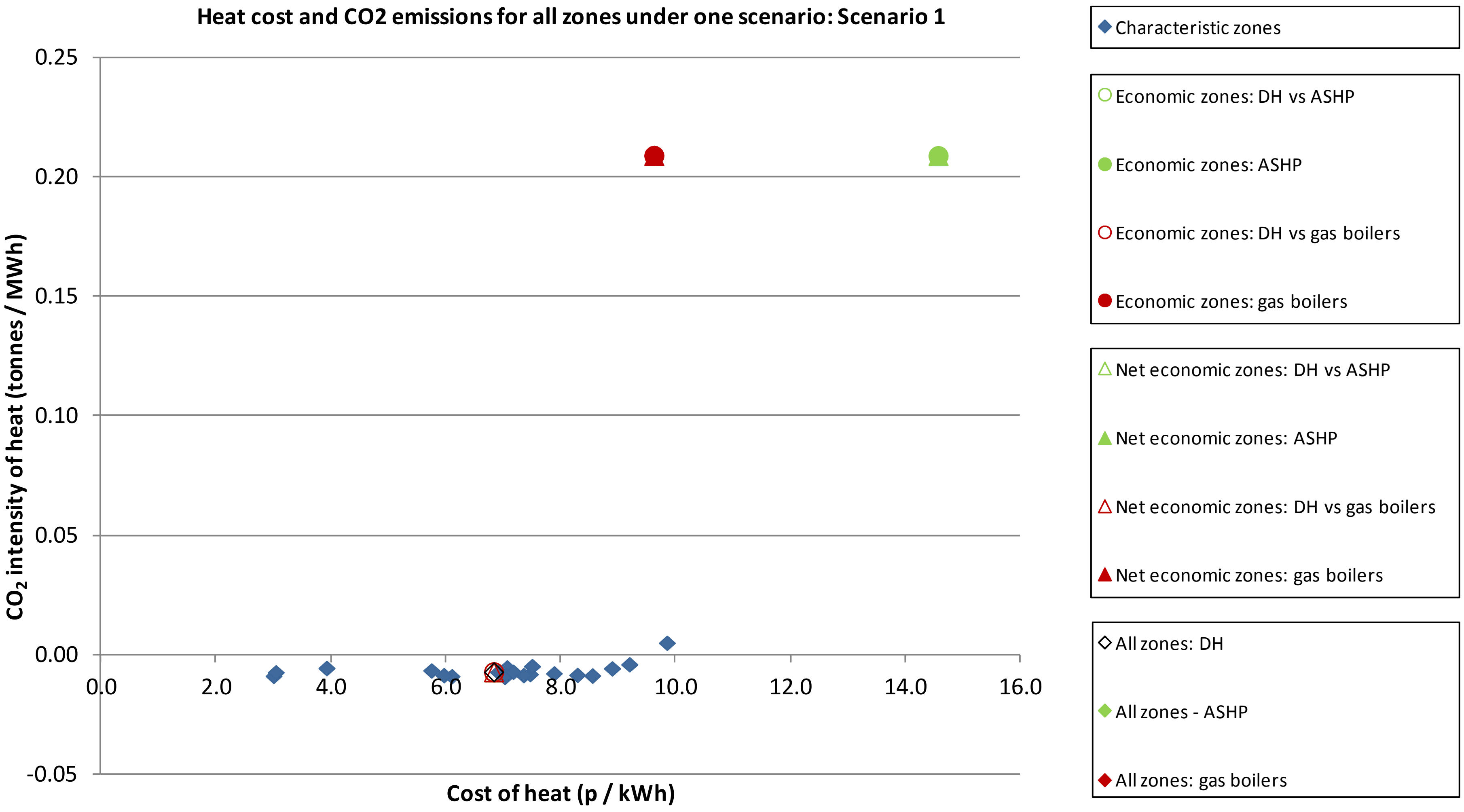

Average heat cost and CO2 emissionsfor CZ 18 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO₂ intensity of heat (tonnes / MWh)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
0
2
4
6
8
10
12
14
Cost of heat (p / kWh)

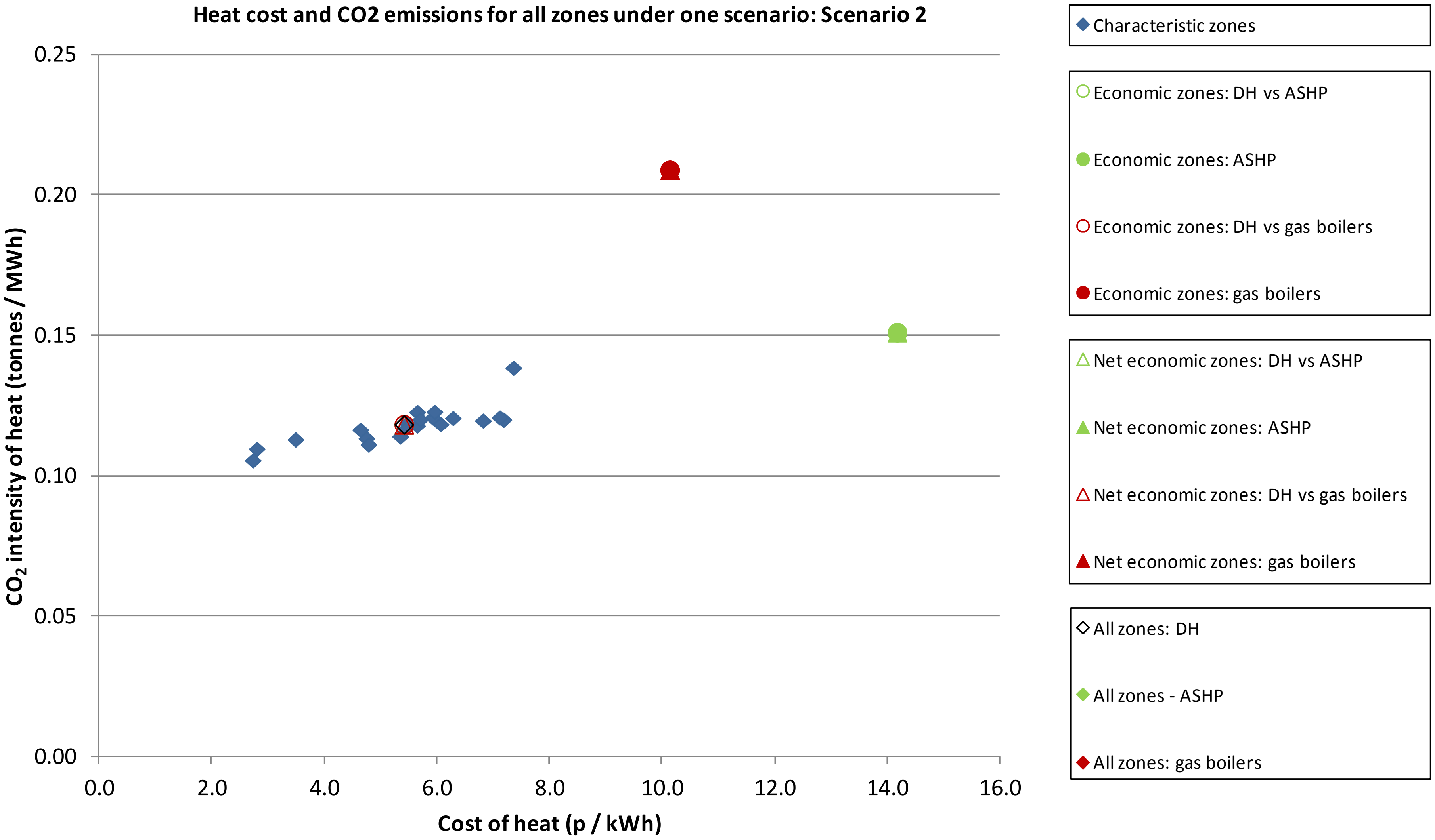

Average heat cost and CO2 emissionsfor CZ 19 for each scenario
DE average
ASHP average
Gas boiler average
Central case
CO$_2$ intensity of heat (tonnes / MWh)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
Cost of heat (p / kWh)
0
2
4
6
8
10
12
14
16


Average heat cost and CO2 emissionsfor CZ 20 for each scenario
DE average
ASHP average
Gas boiler average
Central case
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
12
14
16
18
Cost of heat (p / kWh)
CO₂ intensity of heat (tonnes / MWh)

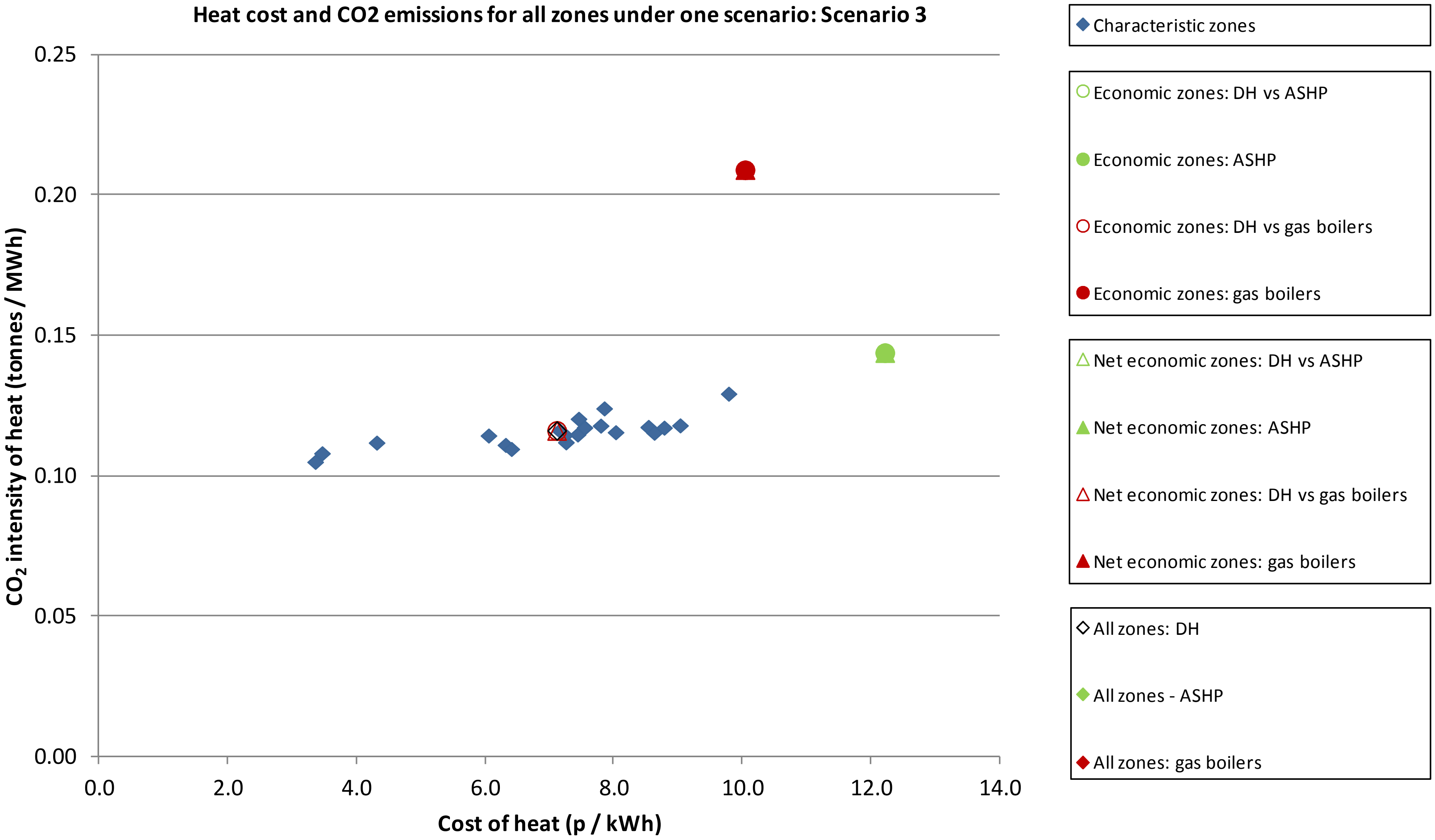
Appendix 2 – Results by Scenario

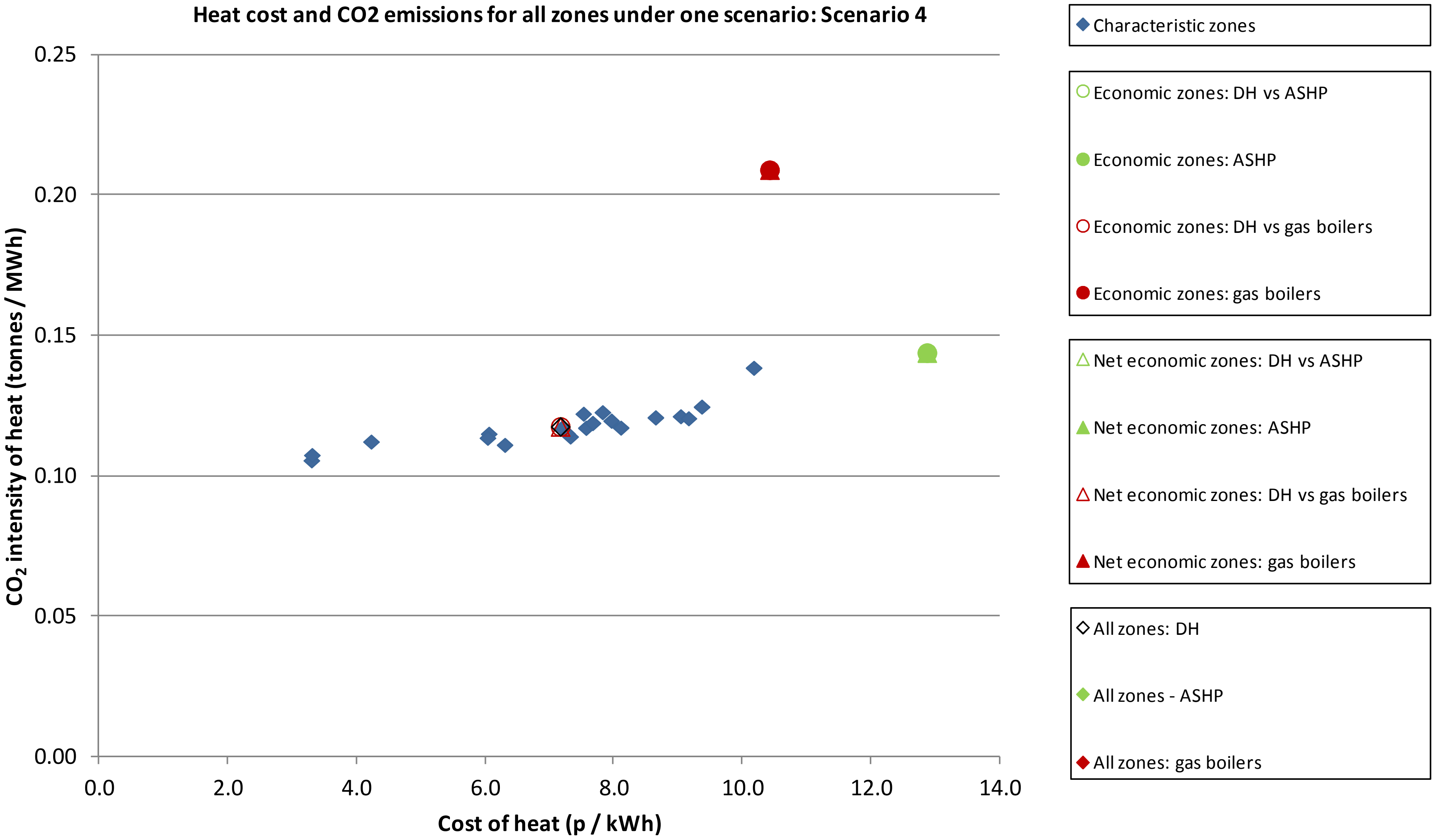
The following charts show all the CZ results in a single scenario. To interrogate the data further, the datasets provided alongside this report should be referred to.

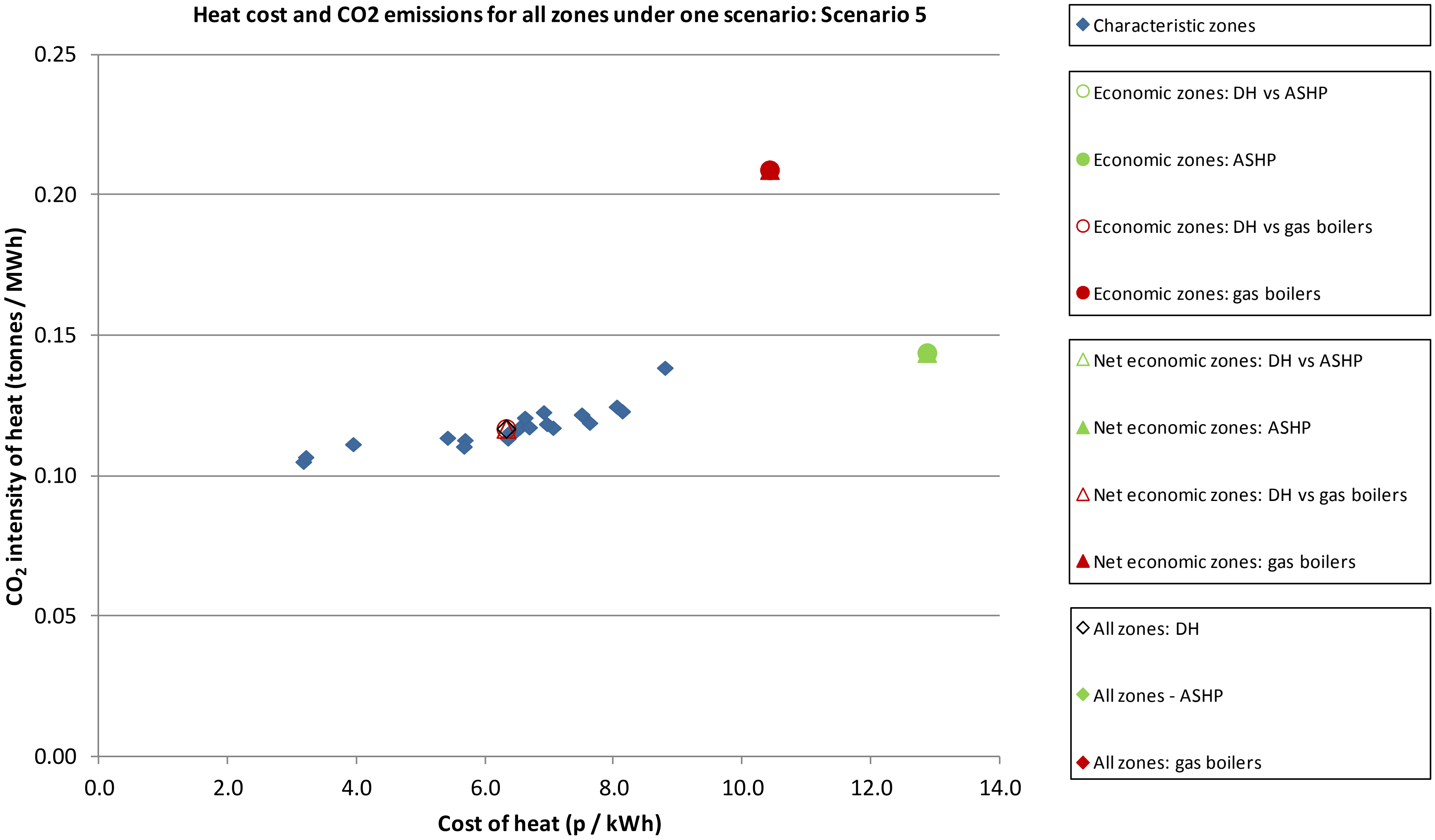

Heat cost and CO2 emissions for all zones under one scenario: Scenario 1
CO$_2$ intensity of heat (tonnes / MWh)
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Cost of heat (p / kWh)
◆ Characteristic zones
○ Economic zones: DH vs ASHP
● Economic zones: ASHP
○ Economic zones: DH vs gas boilers
● Economic zones: gas boilers
△ Net economic zones: DH vs ASHP
▲ Net economic zones: ASHP
△ Net economic zones: DH vs gas boilers
▲ Net economic zones: gas boilers
◇ All zones: DH
◆ All zones - ASHP
◆ All zones: gas boilers

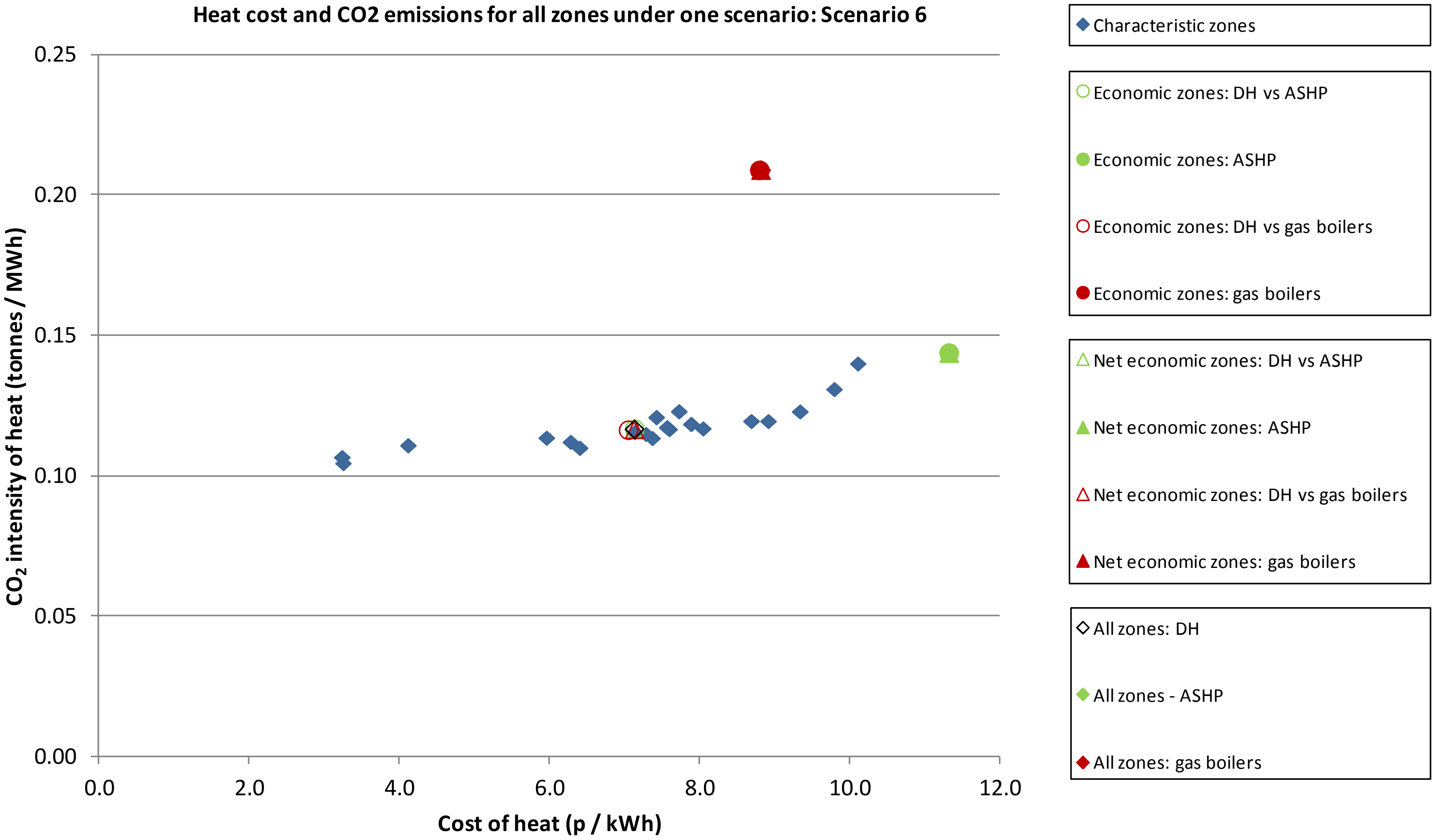


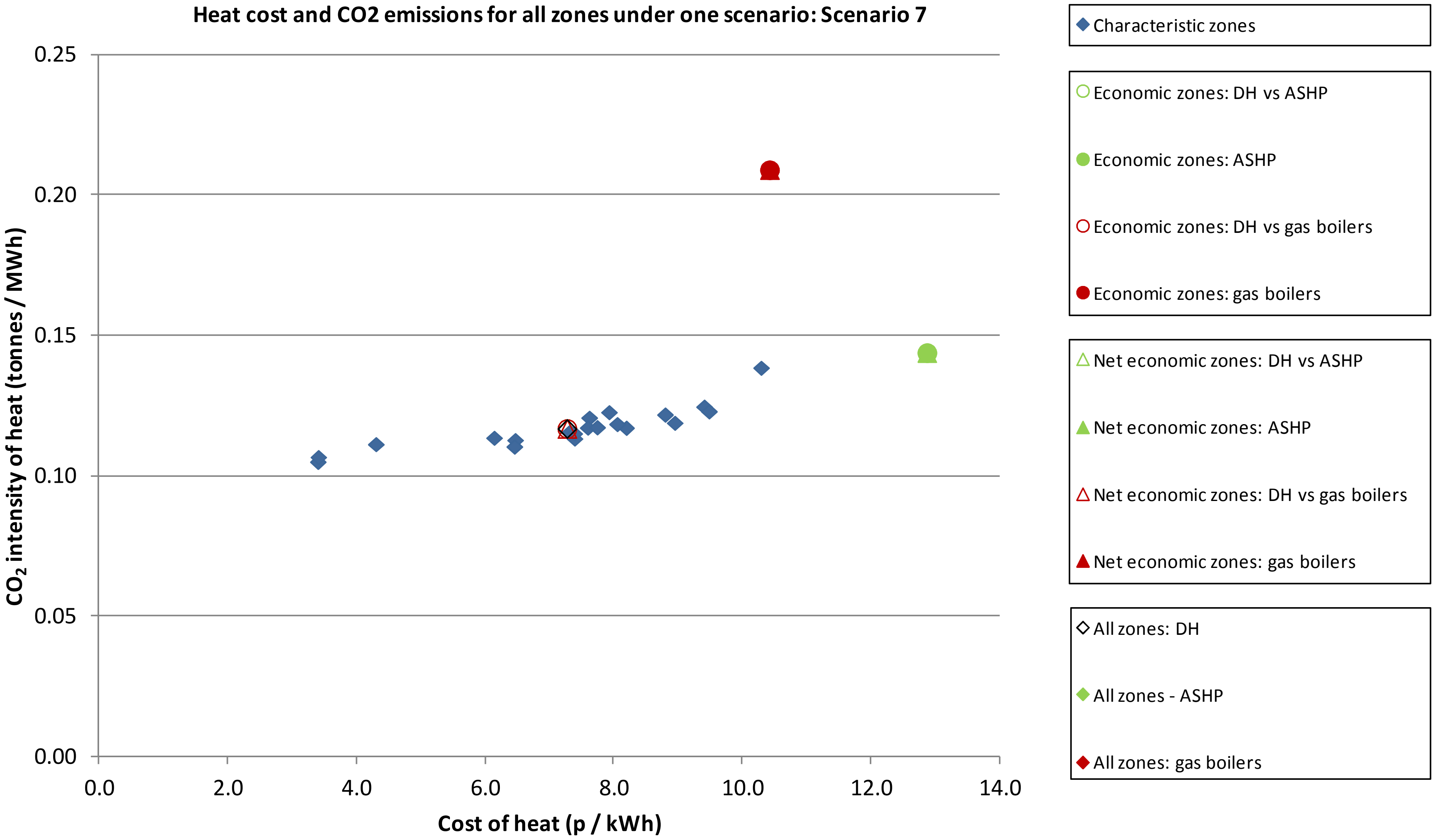
Heat cost and CO2 emissions for all zones under one scenario: Scenario 2

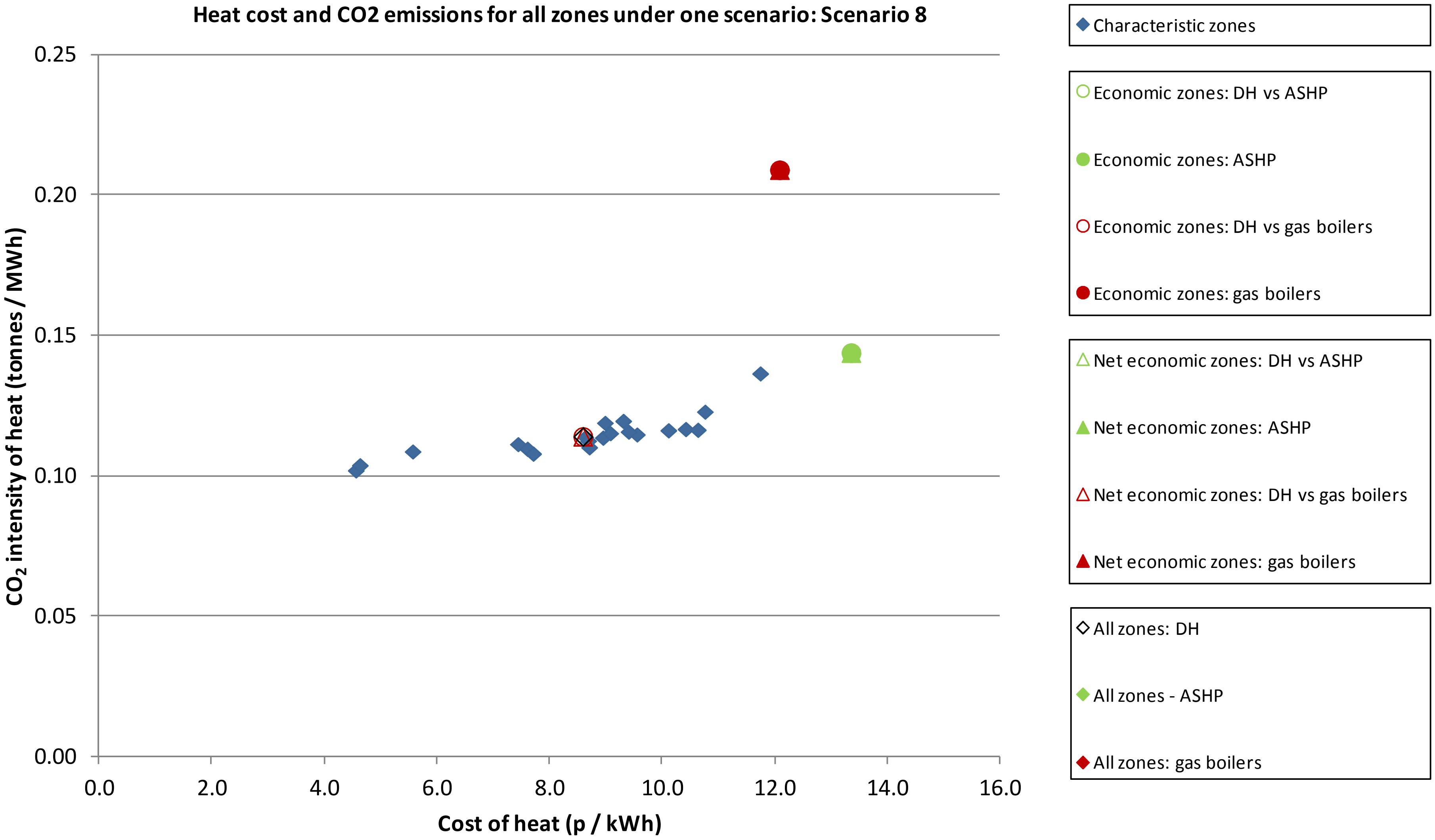

Heat cost and CO2 emissions for all zones under one scenario: Scenario 3
0.25
0.20
0.15
0.10
0.05
0.00
CO$_2$ intensity of heat (tonnes / MWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Cost of heat (p / kWh)
◆ Characteristic zones
○ Economic zones: DH vs ASHP
● Economic zones: ASHP
○ Economic zones: DH vs gas boilers
● Economic zones: gas boilers
△ Net economic zones: DH vs ASHP
▲ Net economic zones: ASHP
△ Net economic zones: DH vs gas boilers
▲ Net economic zones: gas boilers
◇ All zones: DH
◆ All zones - ASHP
◆ All zones: gas boilers

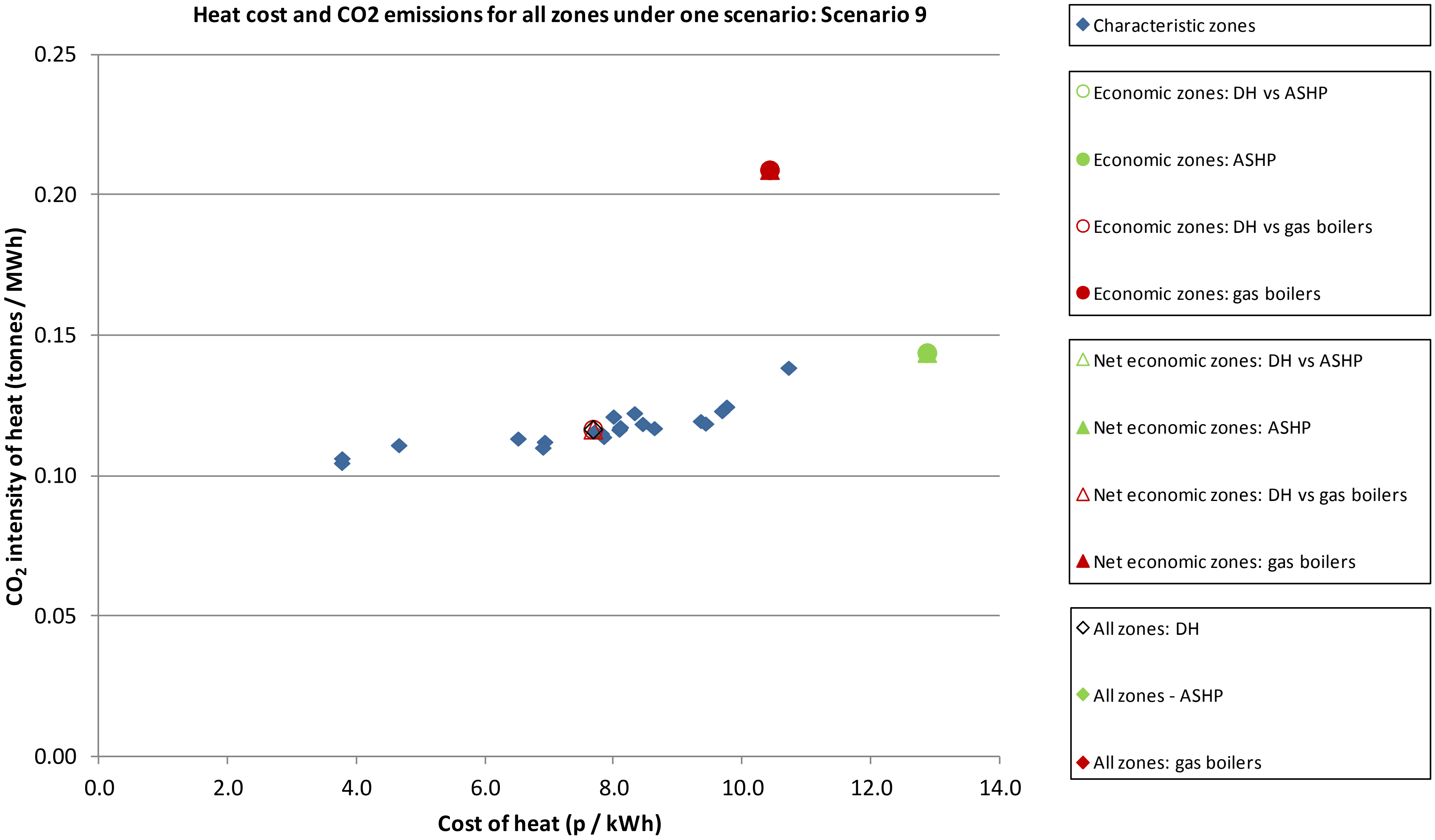

Heat cost and CO2 emissions for all zones under one scenario: Scenario 4
0.25
0.20
0.15
0.10
0.05
0.00
CO_2 intensity of heat (tonnes / MWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Cost of heat (p / kWh)
Characteristic zones
Economic zones: DH vs ASHP
Economic zones: ASHP
Economic zones: DH vs gas boilers
Economic zones: gas boilers
Net economic zones: DH vs ASHP
Net economic zones: ASHP
Net economic zones: DH vs gas boilers
Net economic zones: gas boilers
All zones: DH
All zones - ASHP
All zones: gas boilers

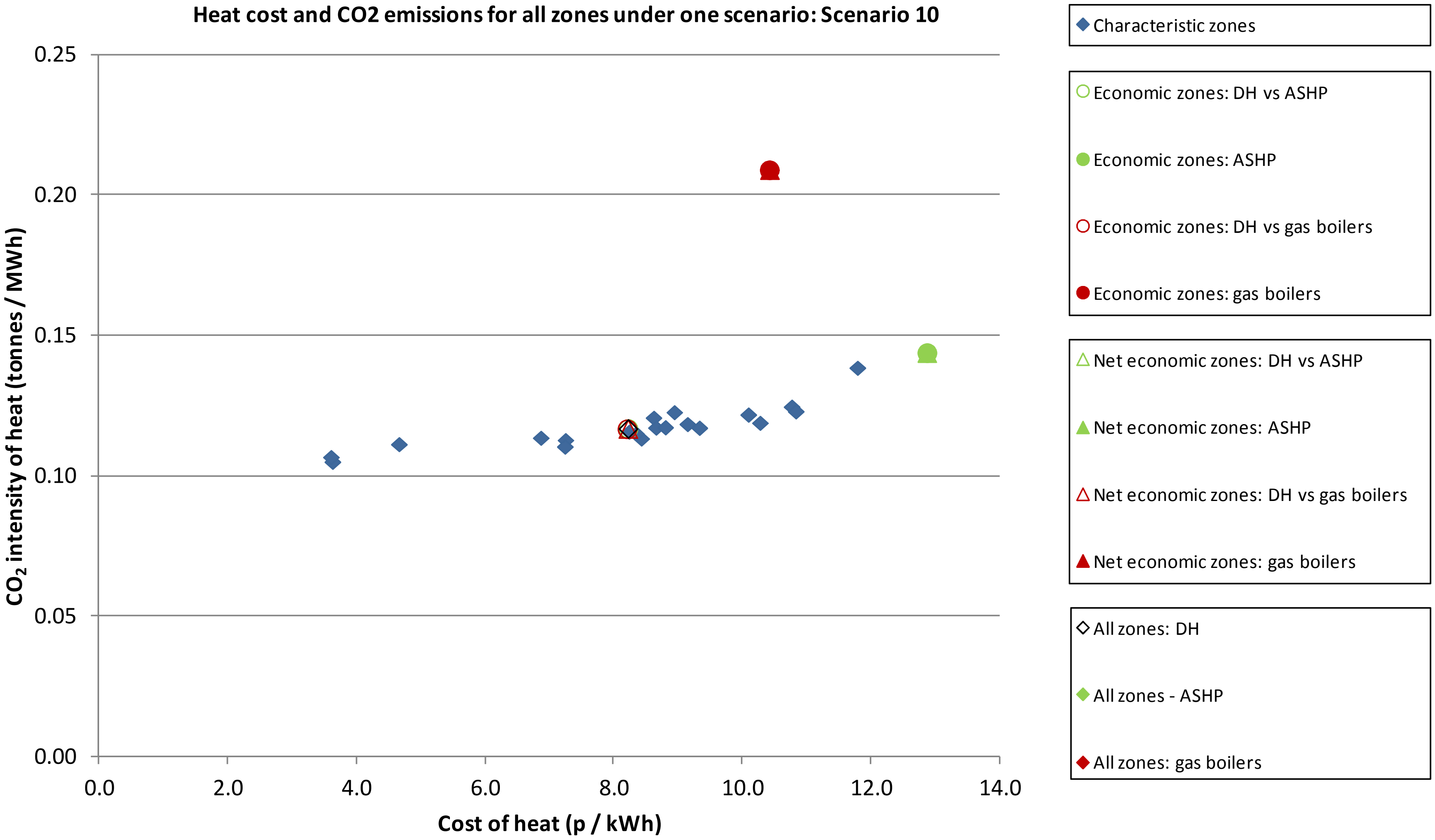

Heat cost and CO2 emissions for all zones under one scenario: Scenario 5
CO_2 intensity of heat (tonnes / MWh)
0.25
0.20
0.15
0.10
0.05
0.00
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Cost of heat (p / kWh)
◆ Characteristic zones
○ Economic zones: DH vs ASHP
● Economic zones: ASHP
○ Economic zones: DH vs gas boilers
● Economic zones: gas boilers
△ Net economic zones: DH vs ASHP
▲ Net economic zones: ASHP
△ Net economic zones: DH vs gas boilers
▲ Net economic zones: gas boilers
◇ All zones: DH
◆ All zones - ASHP
◆ All zones: gas boilers

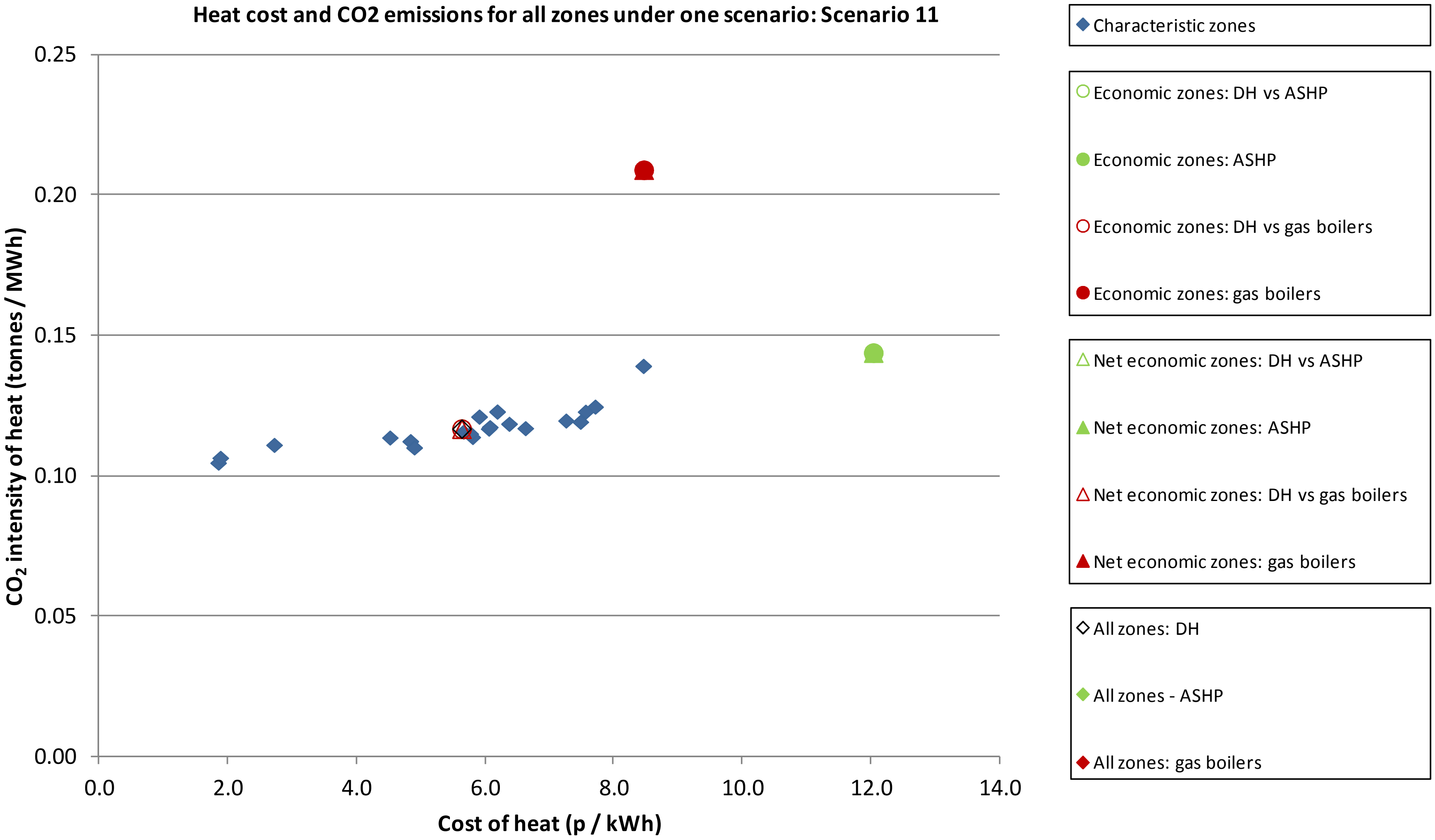

Heat cost and CO2 emissions for all zones under one scenario: Scenario 6
CO₂ intensity of heat (tonnes / MWh)
0.25
0.20
0.15
0.10
0.05
0.00
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Cost of heat (p / kWh)
Characteristic zones
Economic zones: DH vs ASHP
Economic zones: ASHP
Economic zones: DH vs gas boilers
Economic zones: gas boilers
Net economic zones: DH vs ASHP
Net economic zones: ASHP
Net economic zones: DH vs gas boilers
Net economic zones: gas boilers
All zones: DH
All zones - ASHP
All zones: gas boilers

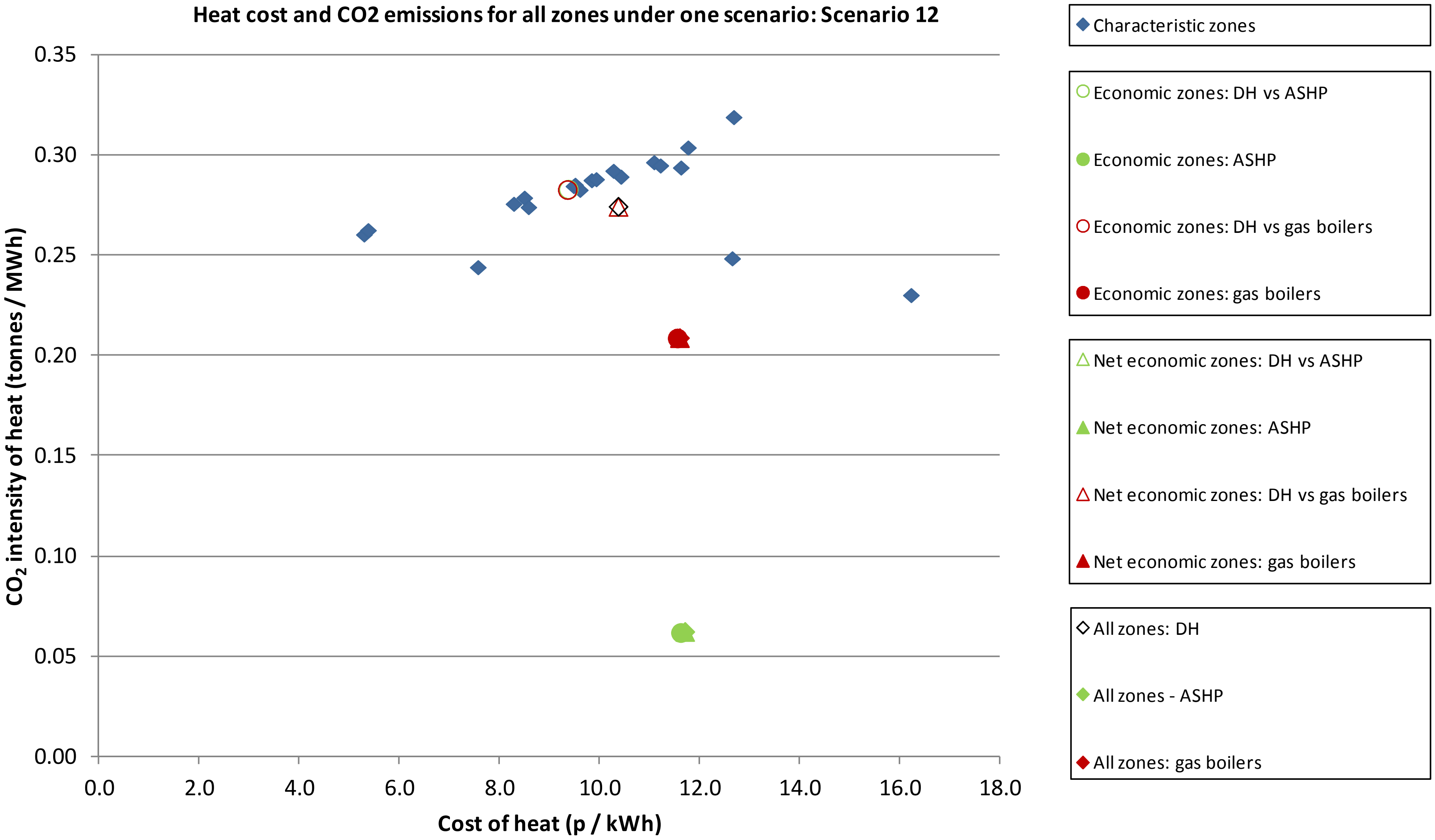
Heat cost and CO2 emissions for all zones under one scenario: Scenario 7
CO₂ intensity of heat (tonnes / MWh)
0.25
0.20
0.15
0.10
0.05
0.00
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Cost of heat (p / kWh)
◆ Characteristic zones
○ Economic zones: DH vs ASHP
● Economic zones: ASHP
○ Economic zones: DH vs gas boilers
● Economic zones: gas boilers
△ Net economic zones: DH vs ASHP
▲ Net economic zones: ASHP
△ Net economic zones: DH vs gas boilers
▲ Net economic zones: gas boilers
◇ All zones: DH
◆ All zones - ASHP
◆ All zones: gas boilers

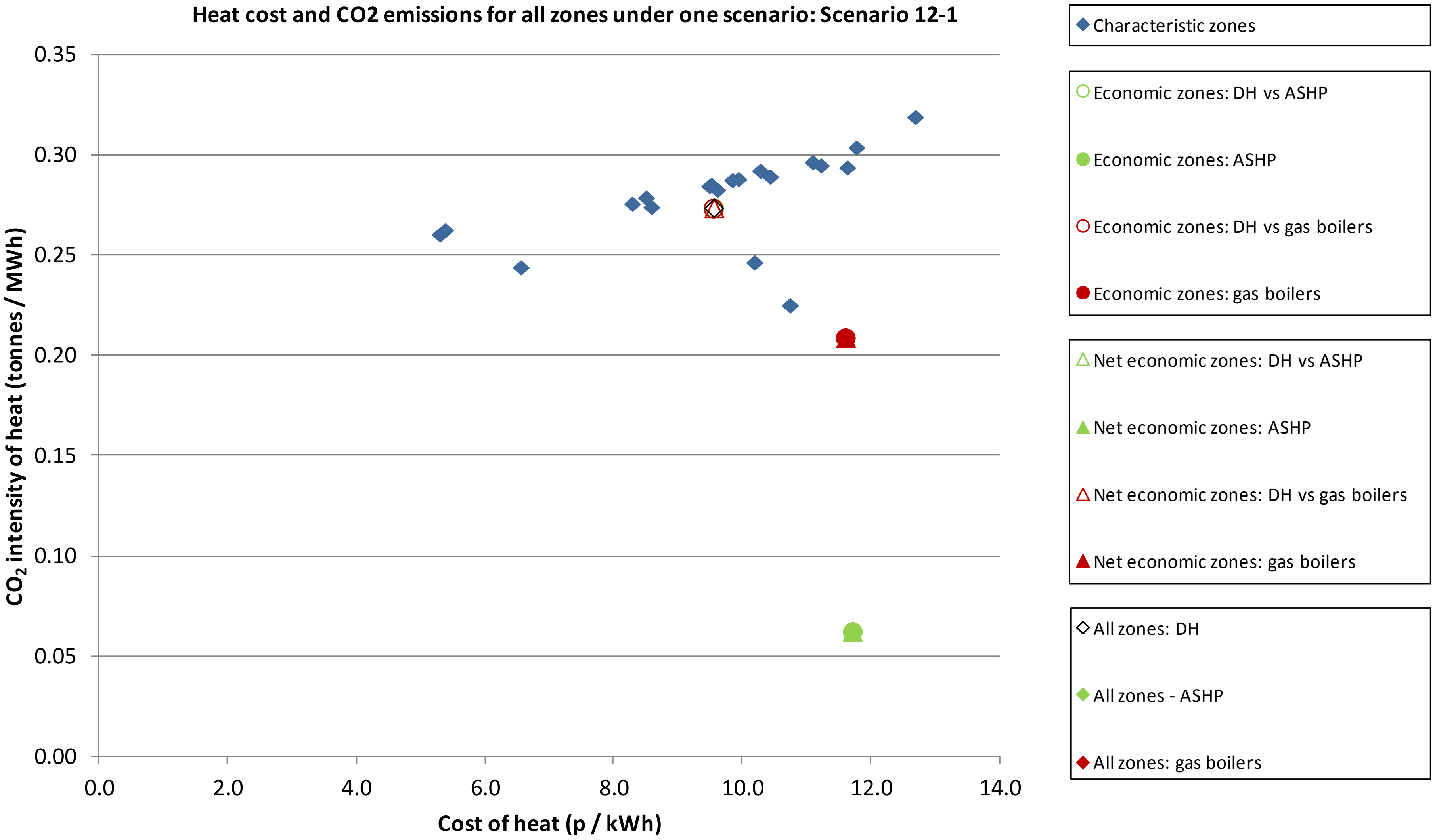

Heat cost and CO2 emissions for all zones under one scenario: Scenario 8
0.25
0.20
0.15
0.10
0.05
0.00
CO$_2$ intensity of heat (tonnes / MWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Cost of heat (p / kWh)
Characteristic zones
Economic zones: DH vs ASHP
Economic zones: ASHP
Economic zones: DH vs gas boilers
Economic zones: gas boilers
Net economic zones: DH vs ASHP
Net economic zones: ASHP
Net economic zones: DH vs gas boilers
Net economic zones: gas boilers
All zones: DH
All zones - ASHP
All zones: gas boilers

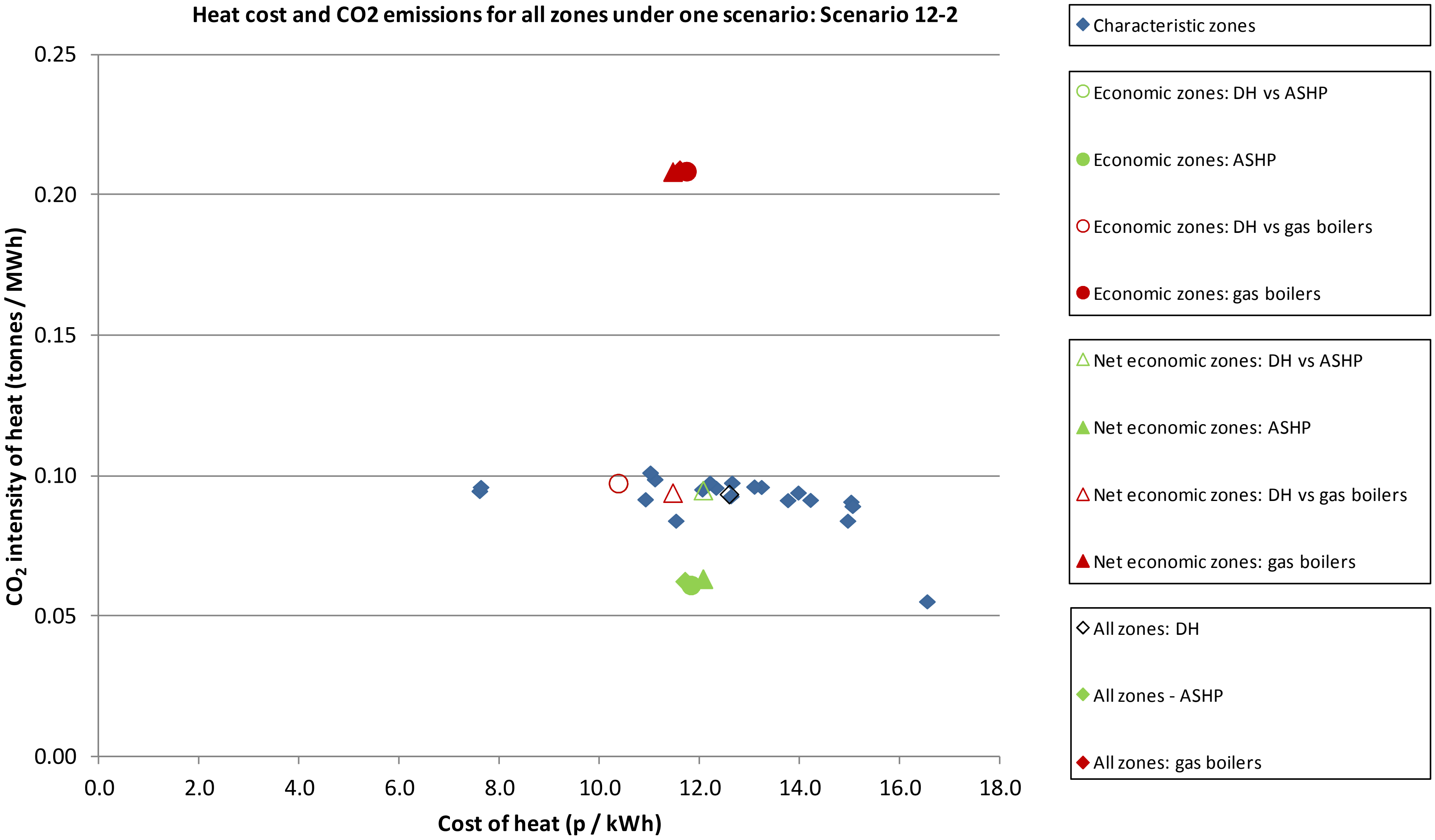

Heat cost and CO2 emissions for all zones under one scenario: Scenario 9
0.25
0.20
0.15
0.10
0.05
0.00
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Cost of heat (p / kWh)
CO2 intensity of heat (tonnes / MWh)
◆ Characteristic zones
○ Economic zones: DH vs ASHP
● Economic zones: ASHP
○ Economic zones: DH vs gas boilers
● Economic zones: gas boilers
△ Net economic zones: DH vs ASHP
▲ Net economic zones: ASHP
△ Net economic zones: DH vs gas boilers
▲ Net economic zones: gas boilers
◇ All zones: DH
◆ All zones - ASHP
◆ All zones: gas boilers


Heat cost and CO2 emissions for all zones under one scenario: Scenario 10
0.25
0.20
0.15
0.10
0.05
0.00
CO2 intensity of heat (tonnes / MWh)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Cost of heat (p / kWh)
◆ Characteristic zones
○ Economic zones: DH vs ASHP
● Economic zones: ASHP
○ Economic zones: DH vs gas boilers
● Economic zones: gas boilers
△ Net economic zones: DH vs ASHP
▲ Net economic zones: ASHP
△ Net economic zones: DH vs gas boilers
▲ Net economic zones: gas boilers
◇ All zones: DH
◆ All zones - ASHP
◆ All zones: gas boilers


Heat cost and CO2 emissions for all zones under one scenario: Scenario 11
CO_2 intensity of heat (tonnes / MWh)
0.25
0.20
0.15
0.10
0.05
0.00
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Cost of heat (p / kWh)
◆ Characteristic zones
○ Economic zones: DH vs ASHP
● Economic zones: ASHP
○ Economic zones: DH vs gas boilers
● Economic zones: gas boilers
△ Net economic zones: DH vs ASHP
▲ Net economic zones: ASHP
△ Net economic zones: DH vs gas boilers
▲ Net economic zones: gas boilers
◇ All zones: DH
◆ All zones - ASHP
◆ All zones: gas boilers


Heat cost and CO2 emissions for all zones under one scenario: Scenario 12
CO2 intensity of heat (tonnes / MWh)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
Cost of heat (p / kWh)
Characteristic zones
Economic zones: DH vs ASHP
Economic zones: ASHP
Economic zones: DH vs gas boilers
Economic zones: gas boilers
Net economic zones: DH vs ASHP
Net economic zones: ASHP
Net economic zones: DH vs gas boilers
Net economic zones: gas boilers
All zones: DH
All zones - ASHP
All zones: gas boilers


Heat cost and CO2 emissions for all zones under one scenario: Scenario 12-1
CO_2 intensity of heat (tonnes / MWh)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Cost of heat (p / kWh)
Characteristic zones
Economic zones: DH vs ASHP
Economic zones: ASHP
Economic zones: DH vs gas boilers
Economic zones: gas boilers
Net economic zones: DH vs ASHP
Net economic zones: ASHP
Net economic zones: DH vs gas boilers
Net economic zones: gas boilers
All zones: DH
All zones - ASHP
All zones: gas boilers



Heat cost and CO2 emissions for all zones under one scenario: Scenario 12-2

Appendix 3 – Input assumptions to scenarios

The modelling in work package 5.1 is based around twelve assessment scenarios. These scenarios are used to define the input assumptions used in the optimisation model, and allow the assessment of sensitivities which may impact the potential for DE across GB.

The scenarios are illustrated in Figure A3.1 below.

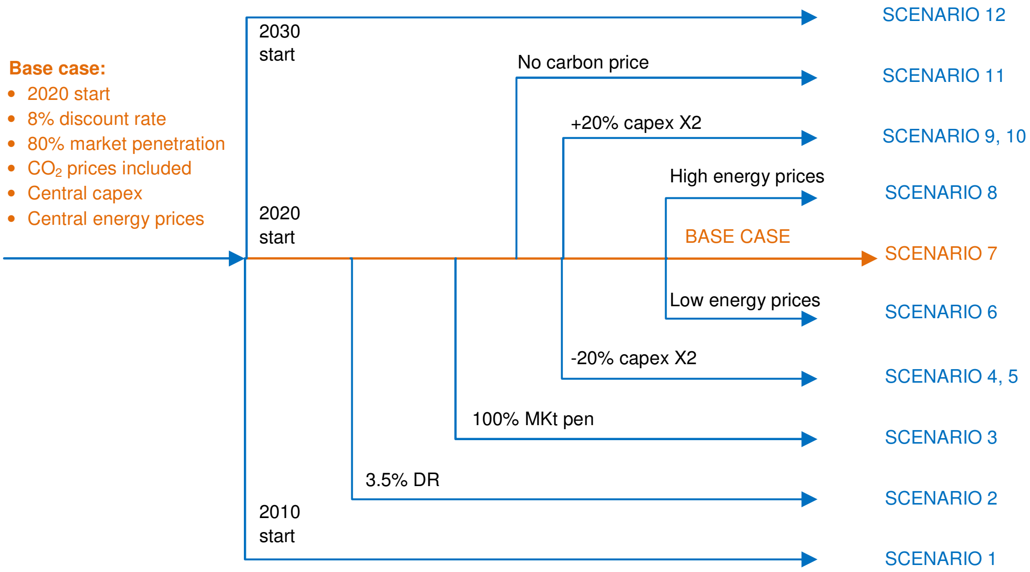


Figure A3.1: Schematic showing the various assessment scenarios.

The following sections provide further information on the inputs used to form the scenarios.

Decadal analysis

A number of the input parameters change over time, in particular the projected costs and revenues from energy, and the CO_2 intensity of grid electricity. The CO_2 benefit of gas-engine CHP will reduce over time as the grid is decarbonised. It is therefore important to reflect this in the analysis of the CO_2 emissions. The modelling uses a 25 year period of operation (to reflect the design life of the DH network) for the lifecycle costing analysis. Three scenarios are formed with starting years of 2010, 2020, and 2030. The 2010 case represents a project that might be initiated now, demonstrating how macro DE schemes may perform in the earlier stages of mass deployment. The 2020 period represents schemes that are implemented in the peak deployment period envisaged by ETI. After 2030 some predictions (Climate Change Committee) indicate that the grid will be fully decarbonised by this time and so the position would be similar in any year after this date.

Market penetration

The model as constructed assumes that 80% of the heat market in any one zone will be supplied from start-up and that this is reflected in: the energy data, the Energy Centre design optimisation and the heat network. This provides a realistic approach where the possibility of no regulation requiring connection, and acceptance that some buildings may find it difficult to connect even in the presence of regulation, limits the maximum penetration. The outcome of this reduction in penetration is:

- The energy centre and transmission network are sized for 100% penetration
- The distribution and connections are sized / costed for 80% penetration.

The ongoing costs and revenues from the generation and sale of energy are reduced in line with the reduced heat demand. However the excess capital cost associated with the energy centre and transmission being sized for 100% results in a higher overall levelised cost.

The 80% market penetration case is a central assumption and used in the majority of the scenarios. A sensitivity scenario is also modelled where penetration achieves 100% (for example through regulation and mandatory connection) and the levelised costs are reduced.

The market penetration defined here is within the zone and should not be confused with the overall national penetration of DE which could vary from 0% to 45% approximately depending on the cost-effectiveness calculated for each CZ.

Financing costs

As a Macro-DE project is capital intensive, the cost of financing is crucial in the analysis. This is modelled by selecting a discount rate and period of economic analysis when calculating the annualised cost of heat supply. The selection of discount rate is partly a function of whether the project is expected to be developed within the private sector or the public sector and if in the private sector the degree of risk associated with the business opportunity. If the project is de-risked through regulation for example guarantee of the heat market then the private sector would be able to raise capital at lower rates of return as typically seen for other utility services.

It is also important to consider the cost of finance for the comparator heat supply options to ensure that the Macro-DE project is not unduly favoured. Whilst the electricity and gas sectors are privatised the distribution businesses are regulated as natural monopolies and thus have relatively low financing costs.

To examine the impact of financing costs the assessment assumes a base case of an 8% discount rate (in real terms) to represent a typical private sector return and, as an alternative scenario, a 3.5% discount rate to represent a public sector project. These same discount rates are used throughout for the comparator heat supply options. An 8% return has been adopted for other ETI projects and is therefore consistent with these other studies.

The economic calculations derive annualised costs for the Energy Centre equipment and DHN based on its typical economic life. The lifetimes vary depending on the technology with the DH network assumed to have a 25 year life for the economic assessment. In reality, the life is likely to be longer and therefore replacement generation technologies after this period will have a more attractive rate of return.

Capital costs

This study uses a sensitivity test of +/-20 % on the costs of the district heating network and separately +/-20% on the cost of the Energy Centre. There are a number of uncertainties around capital costs, from the cost of the actual equipment, to site specific factors such as connection costs and construction requirements. Rather than examine each in detail, the simpler percentage adjustment route allows investigation of the potential outcomes.

Energy prices

Macro DE schemes are an example of a capital investment resulting in an energy saving. Hence when energy prices are high, there will generally be a greater rate of return from macro DE schemes. The modelling is based around mid energy price projections for the central case, with high and low sensitivity cases. All three sets of projections are based around the price *scenarios* published by DECC in the IAG guidance. Although the economics of CHP is influenced both by electricity and gas prices these are not independent parameters as part of our electricity is produced from gas. It is also important that any future price scenarios used are also consistent with the CO_2 emission factors that are assumed for the electricity supply, and the use of IAG marginal electricity emission factors ensures this consistency.

These future price scenarios or sensitivities are applied to both the macro-DE cases and the counterfactual options.

Carbon Prices

The central case will assume that carbon emissions have an associated cost at the non-traded level in the IAG guidance. This reflects the fact that some sectors currently are liable for carbon costs through the CRC and EU-ETS, and that this situation is likely to continue with an expansion. The Carbon Price floor proposed in the electricity market reform is one sign that carbon prices will become more widespread and affect more sectors.

As a sensitivity, a scenario is presented without the carbon prices applied to examine the impact of carbon pricing on technology selection.

CO_2 emissions

The calculation of CO_2 emissions can be complex, especially in relation to offsetting grid electricity. Whilst the grid has an ‘average’ emissions factor over a year based on the amount of electricity generation, and different fuels used, reducing or increasing demand on the grid will require a decrease or increase in certain generation types, which has an associated emissions factor called the ‘marginal’ factor. Thus the assessment effectively needs to be made against the marginal factor because it is the marginal plant which will be affected.

The marginal factor will change over time and depends on the market conditions and type of generation. Intermittent renewable technologies such as wind will not be marginal because they cannot be simply turned on and off. Low carbon nuclear will also not be marginal due to the low emissions and base load characteristics. Therefore the marginal factor is likely to be influenced by fossil (CCS and non CCS) for the foreseeable future.

There are also two aspects to marginal generation – ‘operational marginal’ which reflects the operation of existing power stations on the system and ‘build marginal’ which considers which types of plant would be built or not built as demand changes.

This study uses marginal emissions factors from the latest (October 2011) DECC IAG guidance. This means that the CO_2 projections are consistent with the future energy price assumptions also used in this modelling. This marginal factor represents ‘build marginal’ and therefore suited to large scale displacement of grid generation through significant uptakes of macro DE.

It is important to note that the grid electricity CO_2 emission factors are independent of the level of macro DE uptake, and further work should examine the impact that large scale macro DE may have on the grid generation mix.

Table A3.1 show the CO_2 emissions factors assumed for grid electricity and other fuels included in the work package 5.1 technology library.

Table A3.1: Summary of CO_2 emissions factors used in the WP 5.1 modelling.

Fuel type	Year	Emissions factor (10 year average)
Natural gas	na	0.199
Landfill gas	na	0.000
Grid electricity	2010	0.485
	2020	0.351
	2030	0.160

Scenario inputs

Full details of the inputs used for the scenario modelling are shown on in table A3.2. All time variable factors such as energy costs and carbon costs are shown as an annualised figure over the 25 year economic assessment period.

Table A3.2: Summary of inputs used in the scenario modelling.

Scenario Number	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10	SC11	SC12
Year	2010	2020										2030
Macro DE inputs												
1. Discount rate	8%	3.5%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
2. Fuel prices, p/kWh												
a. Natural gas	4.76	5.61	5.42	5.42	5.42	4.35	5.42	6.53	5.42	5.42	3.74	6.45
b. Diesel	10.93	12.38	12.09	12.09	12.09	9.24	12.09	15.06	12.09	12.09	9.93	13.56
c. Biodiesel	12.71	14.03	13.82	13.82	13.82	10.22	13.82	17.55	13.82	13.82	12.53	14.87
d. Landfill gas	5.06	5.43	5.39	5.39	5.39	3.84	5.39	7.00	5.39	5.39	5.39	5.54
3. Electricity tariff, p/kWh	11.90	12.97	12.91	12.91	12.91	10.76	12.91	14.11	12.91	12.91	10.88	13.07
4. Grid emission factor, kg/kWh	0.485	0.351	0.351	0.351	0.351	0.351	0.351	0.351	0.351	0.351	0.351	0.160
5. Market penetration	80%	80%	100%	80%	80%	80%	80%	80%	80%	80%	80%	80%
6. DHN capex	-		-	-	-20%	-	-	-	-	20%	-	-
7. CHP capex	-		-	-20%	-	-	-	-	20%	-	-	-
Counterfactual inputs												
Domestic												
Natural gas price p/kWh	6.93	7.81	7.62	7.62	7.62	6.18	7.62	9.11	7.62	7.62	5.94	3.91
Electricity tariff p/kWh	20.77	23.30	23.24	23.24	23.24	19.42	23.24	24.45	23.24	23.24	21.21	13.05
Commercial												
Natural gas price p/kWh	5.34	6.21	6.02	6.02	6.02	4.81	6.02	7.27	6.02	6.02	4.33	7.05
Electricity tariff p/kWh	17.05	19.06	19.04	19.04	19.04	15.55	19.04	20.19	19.04	19.04	17.00	19.03

Appendix 4 – Counterfactual assumptions

The following tables provide a summary of the inputs used for the counterfactual calculations

Table A4.1: Counterfactual inputs for gas boilers

Gas boilers					
	Units	**Value**			**Reference and notes**
Domestic		**2010**	**2020**	**2030**	
Capital cost	£ / dwelling	£2,500	£2,500	£2,500	ETI
Annual Maintenance	£ / dwelling	£200	£200	£200	Typical annual contract (note 3)
Efficiency	%	85%	85%	85%	C
Lifetime	years	15	15	15	A
Fuel input	type	Gas	Gas	Gas	D
Fuel cost	IAG rate	Retail domestic	Retail domestic	Retail domestic	D
Commercial					
Capital cost	£ / kW	79	79	79	A (see note 1)
Annual Maintenance	£ / kW.yr	£2	£2	£2	A (see note 1 and 3)
Efficiency	%	90%	90%	90%	B
Lifetime	years	15	15	15	A
Fuel input	type	Gas	Gas	Gas	D
Fuel cost	IAG rate	Retail commercial	Retail commercial	Retail commercial	D

Table A4.1: Counterfactual inputs for air source heat pumps.

Air source heat pumps					
	Units	**Value**			**Reference and notes**
Domestic		**2010**	**2020**	**2030**	
Capital cost	£ / dwelling	£7,500	£4,500	£3,500	ETI - central. Assume nominal 10 kW
Annual Maintenance	£ / dwelling	£100	£100	£100	ETI (note 3)
Efficiency	%	208%	219%	229%	ETI (note 5)
Lifetime	years	15	15	15	ETI
Fuel input	type	Electricity	Electricity	Electricity	D
Fuel cost	IAG rate	Retail domestic	Retail domestic	Retail domestic	D
Commercial					
Capital cost	£ / kW	£449	£269	£210	B (see note 1 and 2)

Annual Maintenance	£ / kW.yr	£7.30	£7.30	£7.30	B (see note 1 and 3)
Efficiency	%	375%	394%	413%	B (see note 1 and 4)
Lifetime	years	20	20	20	A
Fuel input	type	Electricity	Electricity	Electricity	D
Fuel cost	IAG rate	Retail commercial	Retail commercial	Retail commercial	D

References

A NERA / AEA. UK Supply curve for Renewable Heat. 2009. DECC.

B AEA review of technical information on renewable heat technologies. 2010. DECC

C Getting warmer: A field trial of heat pumps. 2010. Energy Saving Trust.

D Valuation of Energy Use and Greenhouse Gas Emissions for Appraisal and Evaluation. 2011. DECC and HM Treasury.

Notes

1 Values are provided for large and small installations for commercial/public. A mid range value is selected to represent medium installations.

2 The learning rates for commercial ASHP are assumed to be similar to the ETI figures for domestic.

3 Assumes that maintenance is labour dominated and therefore unlikely to change.

4 Efficiencies assumed to increase in line with ETI assumptions.

5 Based on ESME values of 208% for 2010 and 250% in 2050. Linear interpolation gives 218.5% for 2020 and 229% for 2030.

Appendix 5: Additional analysis of scenarios

This appendix includes some additional analysis on certain scenarios.

Scenarios 4 and 9

Whilst the overall levelised cost changes slightly for scenarios 4 and 9, the cost adjustment does not directly reflect the energy centre cost range. If the capital expenditure requirements for the CHP plant alter from the central cost, these changes are included in the scheme design and optimisation. At a simplistic level, there may be no alteration to the existing plant or operation, and the capital expenditure reduction or increase simply results in a higher or lower rate of return. However in practice a change in CHP cost allows some complex decisions to be made as illustrated in Figure A5.1. The data demonstrates that only CZs 14, and 20 do not change the CHP capacity as a result of changes in capital cost – these are the two smallest zones with only a single large gas engine, leaving little scope for optimisation. All of the other CZs change their thermal CHP capacity for either or both an increase or reduction in capital cost.

With an increase in cost, a decision may be taken to reduce the CHP plant requirements, and put in either smaller or fewer engines. This can result in a lower carbon reduction with a smaller fraction of heat provided by the CHP units, and more extensive use of the remaining CHP units to meet the shortfall. It the latter occurs, the CHP engines may need replacing earlier, therefore increasing capital expenditure. Thus there is a trade off between operation and capital requirements for replacement.

With a reduction in cost, a decision may be made to increase the number of CHP units, allowing for greater modularisation and an increase in electricity revenues. Similarly, lower costs may also allow higher use of the engines and more frequent replacement. However an alternative output is that the reduced capital cost lessens the need for generating a larger revenue, permitting lower use of the engines resulting in a lower replacement rate.

The results showing plant schedules for each CZ illustrate the complexity of the optimisation and the range of outcomes described above. They highlight the need for careful optimisation of each scheme, and consideration of other factors such as space availability (which may also influence the number of engines) alongside the purely economic considerations.

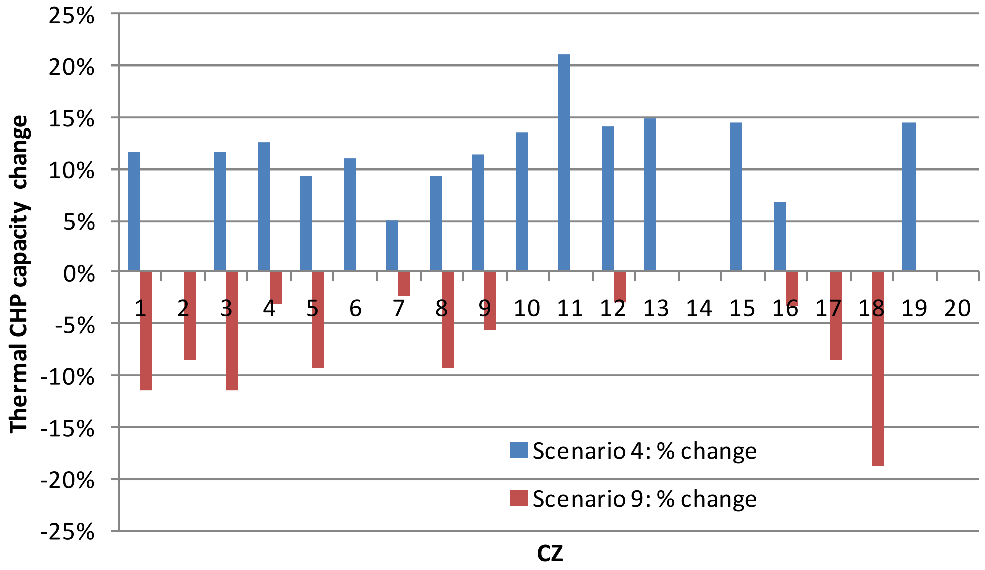


Figure A5.1: Impact of energy centre cost on the installed capacity of CHP units for each CZ.

Scenarios 6 and 8

If changes to energy prices result in a less economic operation, then it is possible that a smaller CHP capacity will be installed, whilst improving economics may result in a greater CHP capacity. The results presented in Figure A5.2 show these general relations where there is a change in capacity, although there are many CZs which do not exhibit a change under either or both the low and high scenarios.

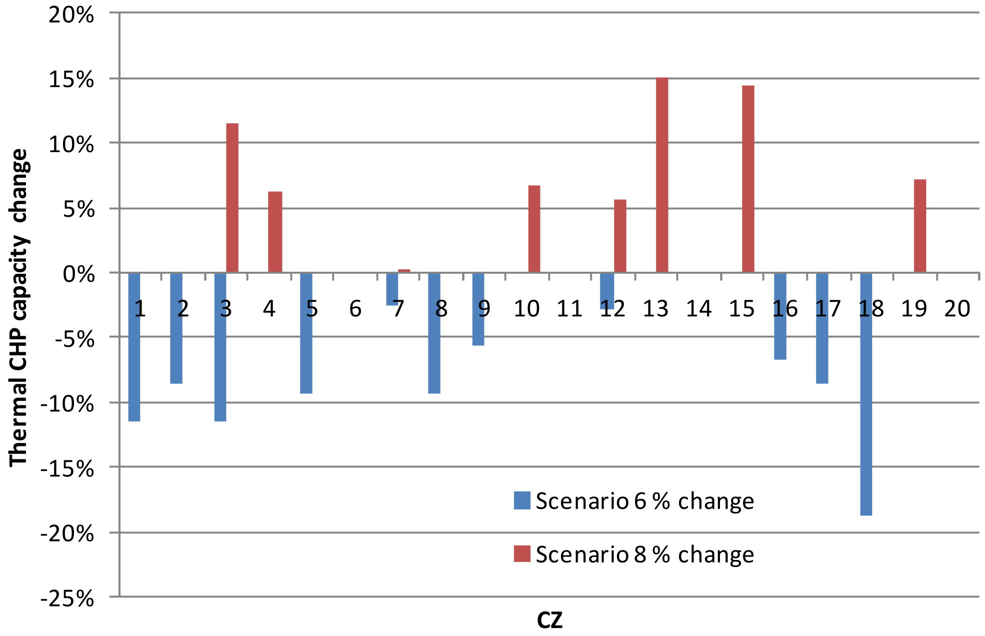


Figure A5.2: Change in thermal capacity of CHP installations compared with the central case with changes to future energy prices.

Scenario 11

The results presented in Figure 25 are based on the 10 year CO_2 calculation for the heat CO_2 intensity and demonstrate the ability of macro DE to save CO_2 against both the ASHP and gas boiler counterfactuals. However (as can be seen in Scenario 12), changes to the grid CO_2 emissions factor, may reduce the CO_2 savings from gas CHP schemes in future years. If the savings are removed, then the economic assessment with carbon pricing will reflect this period.

With a gas boiler counterfactual, the net effect is a reduction in cost effectiveness of circa 0.3 p / kWh, resulting in a reduction in the GB economic benefit of £0.7 billion[14]. This is to be expected as a scheme which saves CO_2 will see a reduction in incentives with no carbon pricing.

But when compared with the ASHP counterfactual, the GB economic benefit actually increases from £11.1 billion to £12.7 billion despite a CO_2 reduction being maintained, suggesting that the carbon price is acting as a disincentive .This occurs because despite the CO_2 reduction in the 10 year CO_2 calculation period, there is expected to be a net CO_2 increase from gas CHP over the 25 year economic assessment period, and the carbon costs applied reflect this.

Whilst this anomaly can be easily explained here, it presents a problem for the assessment of macro DE schemes. The investment in DHNs is significant and the pay-back period long. The payback will be determined by the choice of energy generation technology, and the ability of this technology to provide heat at a lower cost than the counterfactual. However at the outset of a scheme, future technologies which are likely to be connected to the DHN are unknown and their selection will depend on a wide range of criteria. Therefore the initial technology is often assumed to perform for the economic assessment period as in this study. Work package 5.3 examines the potential of new and developing technologies for providing heat in macro DE schemes. With an understanding of these, it is possible to identify potential transition technologies which may assist with the later stages of payback on the DHN, and provide confidence in the widespread adoption of macro DE.

---

[14] This assumes that the CO_2 payments are not included in this GB economic benefit calculation and we are considering the heat market economy only. If the payments resulting from CO_2 pricing are retained within the overall GB economy, then the net effect of scenario 10 would be no change from scenario 7.

Glossary

Base Case: :This is the central scenario used for all modelling, around which sensitivities are investigated.

Baseline: The baseline is a scheme where DH is not adopted and alternative individual dwelling technologies are used. For the 2010 case, the baseline is conventional individual gas boilers. In future years, the baseline includes the use of heat pumps.

Benefits Cases: Three benefits cases are considered for GB, covering commercial potential (only economic schemes), economic potential (allowing more economic schemes to subsidise un-economic schemes with a neutral cost impact on GB), and maximum CO_2 savings (all schemes).

Characteristic Zone (CZ): This is the “central” zone within a Class selected for use in modelling the DE schemes and representative of all of the zones with the Class.

Class: A class is a collection of zones that has been shown to be distinct from other Classes and where the zones are sufficiently similar to other zones in the Class.

Market Penetration: The uptake of customers and connections on a DH network is termed market penetration. The best case is that 100% market penetration is achieved with all potential customers connected. In reality, the value will be lower with uptake happening over a number of years to the maximum level.

National Penetration: The uptake of DE across the GB expressed as a percentage of heat provided by heat networks, or the percentage of non domestic and domestic customers.

Scenario: A set of conditions under which the schemes are modelled for each CZ. A total of 11 scenarios are proposed.

Zone – A group of MLSOAs ....

Acronyms

ASHP: Air source heat pump

CHP: Combined heat and power

CoP: Coefficient of performance .

CZ: Characteristic zone. A zone which represents all other zones in a class and is statistically selected based on a number of criteria describing energy consumption of the zones.

DE: Distributed Energy

DHN: District heating network

GSHP: Ground source heat pump

IAG: Interdepartmental Analysts Group

MLSOA: Middle Layer Super Output Area.

NPV: Net present value of a discounted cashflow.

WP: Work package.