Programme Area: Distributed Energy

Project: Macro DE

Title: Application of Energy Centre Design Tool to Characteristic Zones

Abstract:

This deliverable is number 2 of 3 in Work Package 4. This report presents a summary of the results of the application of the tool and design methodology developed in D4.1 to the 20 characteristic zones of demand created in work package 2 (see deliverable D2.3). The evaluation is carried out for all 20 characteristic zones in terms of economic performance, carbon emission, efficiency in the use of fuel and also energy security

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.

Energy Technologies Institute – Macro Distributed Energy Project

Deliverable 4.2

Macro DE Project:

Application of Energy Centre Design Tool to Characteristic Zones

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Executive Summary

The ETI Macro DE design tool is applied to the characteristic zones defined in Work Package 2 of the Macro DE project. The design tool generates the design for an energy centre and estimates costs for DE solutions (where a DE solution is an optimised energy centre and the associated district heating network, DHN) to meet the heat requirements of each characteristic zone. The purpose of the characteristic zones is to facilitate understanding of the potential for Macro DE in Great Britain by evaluating only a limited number of characteristic zones, each representing a class of demand zones. The model inputs, such as fuel prices and electricity emissions factor (0.485 kg/kWh), and the design results, pertain to a 2010 scenario.

Optimised design results for all characteristic zones are presented, based on the cost of delivering heat to meet the demand of the characteristic zone. In all cases, combined heat and power generation in the energy centre is selected by the design tool; the selected technology is gas engines with natural gas. A high proportion of the heat (> 85%) is generated by the engines. These design results are evaluated in terms of annualised cost, carbon dioxide emissions, DE centre energy efficiency and energy security.

In the characteristic zones, the thermal demand ranges from 23 GWh to 480 GWh. The costs of energy production, energy delivery and the total cost (comprising production and delivery) range from £0.024 to 0.030/kWh, £0.039 to £0.064/kWh and £0.065 to £0.092/kWh, respectively.

'Global' carbon dioxide emissions are calculated by subtracting 'CO_2 emissions claimed from electricity sold' from 'CO_2 emissions from fuel combustion' (see Deliverable 4.1[1]). Per unit of heat delivered, the emissions are 0.002 to 0.040 tCO2/MWh. These results compare very favourably with the reference 'baseline' case, in which heating is provided by individual boilers and no electricity is generated – the reduction in carbon emissions is around 90%.

The contribution of DE solutions to energy security is considered briefly. In the 2010 scenario being considered, the only fuel selected is natural gas.

Chapter 1: Introduction to the Macro DE Design Tool

1.1. *Introduction*

The ETI Macro DE project aims to evaluate future opportunities for application of macro-scale distributed energy for district heating, with electricity generation in the range 100 kW_e to 50 MW_e. To this end, the Macro DE project characterises energy consumption in Great Britain (GB) using the concept of characteristic zones. The DE design tool developed within the project has been used to design the energy centre and cost the DE solution (i.e. the energy centre and district heating network) to meet the heat requirements of each characteristic zone. In Work Package 2 of the project, the suitability of the characteristic zones to truly represent classes of zones was investigated in detail (*See Deliverable 2.3 Energy Demand Analysis in GB*[2]*)*. The design results for each characteristic zone will be used in Work Package 5 of the project to evaluate the performance of all zones in a class. This means that a limited number of zones – only the characteristic zones – need to be assessed to build an understanding of the potential for DE in GB.

In Work Package 4 (WP4), the University of Manchester has developed a methodology for the design of energy centres and has implemented this methodology in a software tool. Deliverable 4.1 (February 2011) describes the modelling and optimisation approach and the assumptions applied in the modelling; the deliverable demonstrates that the designs generated by the tool are well aligned with industrial practice and with important economic and performance trends. Chapter 5 ("Application of DE design tool to evaluate characterisation of zones") of Deliverable 2.3 provides design results for the characteristic zones.

This report presents a summary of the application of the design methodology to characteristic zones. The evaluation is carried out for all 20 characteristic zones in terms of economic performance, carbon emissions both from fuel and 'avoided' emissions, efficiency in the use of fuel, and energy security.

1.2. DE design methodology – summary

The objective of the design methodology is to optimise the energy centre within the DE solution for a given zone with a known heat demand. This means selecting a suite of DE systems (e.g. engines and boilers of given capacities, and thermal storage units) and their operating schedule to meet the heat demand with the minimum operating and capital costs. The cost of the associated district heating network (DHN) is accounted for using a simple cost algorithm, although the heat network itself is not designed or optimised; a more detailed algorithm is currently being developed within the project and will be included in WP5. The CO_2 emissions generated by the energy centre are computed, taking into account fuel combustion and avoided emissions associated with electricity generated. The heat demand is expected to vary with the season and time of day according to the demand methodology developed within WP2 2.0; 'time bands' are defined to represent typical, constant use on a given type of day (weekday or weekend), season (summer, winter or 'transition'), and time of day, as shown in Figure 1.1.

	Weekdays (WD)	**Hours**	**Winter (W)**	**Summer (S)**	**Transition (T)**
Thermal, MW	0:00 - 04:59	5	53	10.6	30.5
	5:00 - 6:59	2	105.8	35.4	71
	7:00 - 9:59	3	104.6	32.8	69.1
	10:00 - 16:59	7	89.3	22.7	54.5
	17:00 - 18:59	2	98.7	23.8	61.3
	19:00 - 21:59	3	94.2	25.8	60.9
	22:00 - 23:59	2	56.3	13.6	33.8
	Baseload		12.8	11.2	4.1
	Peak		167.7	124.2	65.8
	Days		87	86	88
	Weekends (WE)	**Hours**			
	0:00 - 04:59	5	54	30	9
	5:00 - 6:59	2	107.9	70.9	32.3
	7:00 - 9:59	3	105.8	68.7	29.7
	10:00 - 16:59	7	91.2	54.3	20.3
	17:00 - 21:59	5	99.4	61.9	22.4
	22:00 - 23:59	2	58.9	34.7	12.4
	Days		34	36	34

Figure 1.1 Example of heat demand of a zone by time band

The design objective is to minimise the cost of meeting the heat demand of a zone by the DE solution (energy centre, optimised, and district heating network). The costs include capital costs and operating costs – *i.e.* fuel costs, electricity costs for pumping and maintenance costs; electricity exported to the grid generates revenue. Maintenance costs include variable maintenance costs that depend on the output of the unit (e.g. MWh of heat produced) and fixed maintenance costs, to allow the asset to operate for its full lifetime, e.g. including replacement of parts.

Important trade-offs in the design problem relate to:

i) the number, type and size of DE systems – where larger units benefit from economies of scale and improved efficiencies, but have higher capital costs;
ii) the operating schedule of the centre – as revenue from electricity generation depends in principle on the season and time of day;
iii) the type of primary energy sources – fossil fuels cost less than biofuels, but have higher CO_2 emissions.

The design methodology applies optimisation techniques to account for these trade-offs while taking into account relevant constraints.

The design problem – the choice of DE systems and their operating schedules – is formulated using integer variables and linear relationships to represent the number and type of DE systems and their performance, e.g. fuel consumption, electricity generation, thermal storage requirements, as well as relevant constraints. Such a formulation (a mixed-integer linear program or MILP) facilitates optimisation, in spite of the relatively large number of variables and relationships involved. Details are presented in Deliverable 4.1.

Constraints applied in the design pertain to practical limitations, such as the minimum part-load of combined heat and power (CHP) units, suitable redundancy in the design and the daily energy balance. Design assumptions are summarised in Table 1.1. Deliverable 4.1 presents the design assumptions in more detail; some additional assumptions have been introduced to provide more practical designs and address more realistic scenarios.

Table 1.1 Design assumptions for analysis of characteristic zones

Heat and electrical power demand	The energy centre must be able to deliver heat to satisfy maximum peak thermal demand. Heat demand is characterised using time bands during which the demand is assumed constant. Only new DE solutions (energy centres, optimised, and district heating networks) are assessed.
District Heating Network (DHN)	All heat demand in a zone is produced by the energy centre and delivered via the district heating network (DHN). To cover thermal losses from the district heating network, heat **production** exceeds heat **delivered** by 10% of the annual thermal **demand** in each time band[3]. The temperature difference between supply and return is assumed to be 40°C[4]. The methodology costs, but does not design, the district heating network. Costs cover the piping network from the energy centre to dwellings and heat interface units (HIU) in dwellings. The cost model used for the district heating network will be reported in a separate deliverable. A summary is presented in Table 1.2. The general formula is: DHN capital cost (£, 2010) **=** Heat Demand (GWh/y) · [Length of transmission pipe (m/GWh) · Cost of transmission pipe (£/m) **+** Length of distribution pipe (m/GWh) · Cost of distribution pipe (£/m)] **+** Cost of domestic heat interface units **+** Cost of tertiary* heat interface units **'tertiary' = commercial and industrial users* Electricity required for pumping (kWh) is 2%[5] of the heat demand (in kWh) in each time band; the electricity will be supplied by the national grid. Refurbishing of houses and buildings is out of scope.
Revenue and expenditure	The basis for design cost calculations is 2009/2010. User inputs related to some other scenarios can be accommodated. The cost of generating heat will be determined (income from heat generation will not be included). **All** electricity generated will be sold to the grid. Electricity sales prices and costs are based on an average value of 6.36 p/kWh[6]: • The peak rate (07:00 -24:00) is taken to be 7.0 p/kWh (avg. +10%) • The off-peak rate (00:00 – 07:00) is taken to be 4.8 kWh/p (avg. –25%). For purchased electricity, the same costs are applied *i.e.* the electricity used in the energy centre reduces the net revenue from electricity sold. The gas price is assumed to be 2.64 p/kWh[7] (DECC IAG retail: industrial

	price for 2010, gross calorific value basis *i.e.* higher heating value basis). Any capital items with a lifespan of less than the project life will need to be replaced; replacement costs will be incurred at the project outset. If more than one unit of a supply technology is required during the project lifetime, the capital cost of replacement units is reduced by 30% (assuming new foundations, piping, instrumentation, etc. would not be required)[8]. The cost of housing the energy centre and service facilities will account for 25% of the total fixed investment (capital expenditure) and engineering and contingency costs will account for 20% of the total fixed investment (capital expenditure)[8]. Annualised capital investment is spread over the project life, by applying an annual capital charge ratio based on an interest rate of **8%** and project life of **25 years** for both the energy centre and the DHN (although typically a DHN will last for 40 years).
Supply technologies	To provide a practical level of redundancy in the energy centre: i) The maximum peak thermal demand must be met by boilers alone – *i.e.* without relying on CHP units, thermal storage units or solar heaters. ii) The maximum capacity of any single boiler should be less than 50% of the maximum peak thermal demand. The minimum load of DE systems is accounted for: engines: 50%; turbines: 50%; fuel cells: 50 %; boilers: 5% Fuel (natural gas) consumption, reported in terms of net calorific value (lower heating value) in the models, is converted to the gross CV / higher HV using a factor of 1.109[9]. The annual amount of electricity generated is not limited. Table 1.3 summarises the DE systems applied for evaluating characteristic zones.
Thermal storage	Heat can be stored as hot water at the supply temperature (90°C); the energy balance is closed for each 24 hour period. Longer term storage solutions and other storage technologies are not considered. Thermal storage units are sized by assuming that 10% of the total volume of the tank is not available for heat supply. Thermal losses per day are assumed to be 2% of the total energy content of the storage unit[10, 11]. The default is to include thermal storage units in the design.
CO_2 emissions	CO_2 generated and emitted includes: • CO_2 generated through fuel combustion (WP3 data) • CO_2 associated with generation of imported electricity (0.485 kg/kWh) For exported electricity, equivalent credit (0.485 kg/kWh)[12] is given to account for emissions avoided by reducing centralised power production.

	'Embodied' carbon, *i.e.* CO_2 emissions associated with the manufacture of DE systems as given in WP3 data, is *not* included in the overall emissions (to allow like-for-like comparisons to be made with the baseline). CO_2 emissions from the energy centre (emissions from fuel combustion less avoided emissions claimed for exported power) are compared with the baseline CO_2 emissions from fuel burnt in individual boilers.

Table 1.2 Simple algorithm for estimating capital cost of district heating network

Zone type	Annual heat demand (£, 2010)
Low density (LD) < 0.35 GWh/hectare	HeatDemand (GWh/y) x (**725.3** m/GWh x 512.5 £/m + **556.6** m/GWh x 132 £/m) + NumberHH x 1,750 £/meter + NumberTertiary x 4,800 £/meter
High density (HD) > 0.35 GWh/hectare, < 0.04 GWh/meter	HeatDemand (GWh/y) x (**543.8** m/GWh x 512.5 £/m + **360.9** m/GWh x 132 £/m) + NumberHH x 1,750 £/meter + NumberTertiary x 4,800 £/meter
High density, high intensity (HD/HI) > 0.35 GWh/hectare, > 0.04 GWh/meter	HeatDemand (GWh/y) x (**482.2** m/GWh x 512.5 £/m + **381.3** m/GWh x 132 £/m) + NumberHH x 1,750 £/meter + NumberTertiary x 4,800 £/meter

NumberHH: number of households; meter: gas meter; NumberTertiary: number of tertiary meters

Table 1.3 Summary of DE systems included in superstructure[13]

Technology		Available sizes (thermal capacity, MWh_{th})					
1	Gas engine	0.47	1.62	2.29	4.42	5.24	7.00
2	Gas turbine	8.38	15.23	18.39			
3	Gas boiler	0.25	1.40	3.50	7.00	10.00	20.00
4	Diesel engine	0.52	1.39	5.15			
5	Biodiesel engine	0.52	1.39	5.15			
6	Landfill gas engine	0.47	1.39	2.74			
7	Fuel cell (natural gas)	0.50					
8	Solar heater	0.1					
9	Heat pump (waste heat)	3.17	4.15				

1.3. Energy centre design model

Two of the main constraints of the problem are the system energy balances for power and heat. The total heat that can be produced within the energy centre must be at least equal to total heat to be delivered. Producing more heat than that required is undesirable because fuel consumption and CO_2 emissions will increase, but can bring benefits in terms of increased revenue from exported electricity. The design model allows the option of 'dumping' excess heat, but in the results presented in this analysis, no heat dumping is allowed.

A thermal storage tank can be included by the user in order to allow CHP units to keep working when thermal demand falls but electricity generation is profitable. A thermal storage tank is a heat accumulator used for storage of water-based energy. The difference between the total heat produced by the energy centre and the heat to be delivered in each time band defines the amount of water (heat) being diverted to the thermal storage or extracted from it. To avoid computational complexity, the heat accumulation cycle is taken to be 24 hours. The maximum heat storage capacity of the tank is computed by the design tool to minimise operating costs.

Figure 1.2 provides an example of an optimised energy centre to satisfy the demand presented in Figure 1.1. It may be seen that heat generated in a time band sometimes exceeds demand, and sometimes does not meet demand: the thermal storage unit is used to transfer heat between time bands. It may be noted that electricity production is lowest in time bands 1 and 2 (between midnight and 07:00) when the sales prices of electricity is lowest and heat demand is also relatively low.

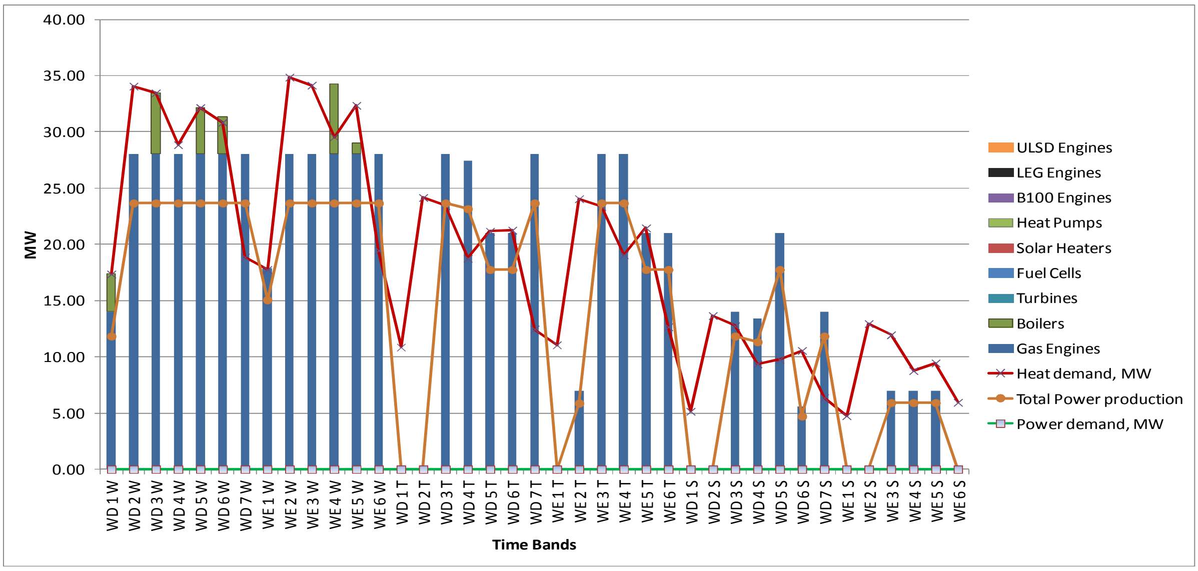

Figure 1.2 Optimised energy centre design, showing DE systems and operating schedule by time band

To provide redundancy to allow the heat demand of a zone to be satisfied, the sum of the total thermal capacity of the DE systems, excluding solar heaters and the thermal storage unit, must be at least larger than the peak heat demand of the zone. Furthermore, it must be possible to satisfy the peak heat demand by boilers alone (rather than CHP units), none of which should provide more than 50% of the peak heat demand.

The ‘baseline’ for performance analysis is that all electricity is supplied by the main power grid and the heat demand is met by gas boilers (80% efficient, 8 year life span, as defined in Deliverable 1.1). The design tool compares the performance of optimised DE centres to this baseline in terms of operating cost and CO_2 emissions (capital cost will be compared in WP5).

1.4. Evaluating energy centre designs

The energy centre performance will be evaluated in terms of its economic performance, CO_2 emissions; including CO_2 emissions associated with the energy centre and those associated with imported and exported electricity (emissions or avoided emissions from centrally generated electricity), efficiency in the use of fuel to satisfy the thermal demand of the zones and energy security.

1.5. Software Tool Application

The design methodology has been implemented in Microsoft Excel, with the add-in WhatsBest! for optimisation. The optimiser minimises the total annualised cost of the energy centre and calculates the CO_2 emissions associated with operating the energy centre and heat network. Constraints may be imposed by the user, e.g. to select or deselect certain DE systems, to achieve a given level of CO_2 emissions less than a specified limit, etc. To optimise the design and operation of the energy centre to satisfy the thermal demand of a zone takes around 5 minutes computing time on a desktop PC.

The tool has been applied to 100 different designs in the classification and clustering process of WP 2, confirming a level of robustness of the tool. In this report, results for the 20 characteristic zones are presented.

This deliverable comprises four main sections. Section 2 provides insights into the characteristic zones. Section 3 presents the energy centre design results for characteristic zones, considering cost, CO_2 emissions, energy security, and energy efficiencies of the energy centres. Finally, Section 4 presents conclusions and outlines future work.

Appendix A presents the thermal demand of all characteristic zones in 39 time bands; Appendix B summarises the energy centre designs for the characteristic zones, and Appendix C presents the operating schedule for the characteristic zones.

Chapter 2: DE centre designs for characteristic zones

2.1 Designing for Characteristic Zones

The concept of a 'characteristic zone' in principle allows the potential for macro-scale DE in GB to be evaluated in terms of cost and CO_2 emissions. For demand zones generated and classified (see Deliverable 2.3), the centroid within each class was defined by the mean value of the total heat demand and total heat density; the zone with the shortest Euclidean distance to those mean values was selected and called the 'characteristic zone' for the class. Energy centre designs are generated for each of this limited number of characteristic zones and the performance of the DE solutions is evaluated; this performance is then ascribed to all zones in that class, allowing all classified zones to be evaluated. (Only zones deemed to have the potential to be viable, i.e. with a total heat density of above 200,000 kWh/ha, were included in the classification processes.) Deliverable 2.3 presents the clustering and classification process that allows around 48% of the GB thermal demand to be represented by 20 classes with 20 characteristic zones.

2.2 Description of Characteristic Zones

Table 2.1 presents general attributes for all characteristic zones and Table 2.2 presents the associated annual demand and heat density data determined in Work Package 2 of the Macro DE Project. It may be seen that Characteristic Zone 127, representing Class 7, has the highest population and the most domestic metres. Zone 154, representing Class 1, has the lowest area, which makes it attractive for district heating due to the low cost of piping. The characteristic zones also differ with respect to the number of domestic vs. tertiary heat users and in the population and number of households.

Table 2.1 Attributes of Characteristic Zones (Deliverable 2.3 – Table 4.27)

Class no.	Zone no.	Zone population	Zone area (ha)	No. households	No. tertiary meters	No. MLSOAs
1	154	15089	81	8361	3206	2
2	711	42350	976	18551	892	6
3	239	28259	1027	11605	2052	4
4	619	36680	1749	14890	3848	5
5	70	37325	821	15296	8388	6
6	509	45254	1478	18787	1842	6
7	127	64948	2097	27243	5657	9
8	145	41887	467	18779	2999	6
9	29	47184	533	21924	15295	7
10	138	67152	1051	28590	2981	9
11	566	15128	455	6461	476	2
12	313	49510	1993	19912	3807	7
13	686	21070	806	8768	323	3
14	535	5510	149	2312	158	1
15	734	7724	255	3150	563	1
16	148	22075	256	10586	12227	3
17	23	36020	1063	15063	3551	5
18	547	23745	964	10543	2154	3
19	701	41394	1757	18045	1968	5
20	909	3222	108	1576	70	1

2.3 *Energy Centre Design Inputs*

Design inputs include the energy demand of the zones, the peak thermal demand, thermal density, primary energy costs, supply units and CO_2 associated with centrally generated power. The energy centre design depends on energy demand, peak thermal demand and heat density. The simple DHN model takes into account heat density and intensity of heat use (average demand per heat user), as described in Table 1.2.

The annual thermal demand is represented using 39 time bands (see Figure 1.1); annual thermal demand data for the characteristic zones are represented in Appendix A. The thermal demand of a zone affects the energy centre performance in terms of both cost and CO_2 emissions. Electrical demand, while estimated in WP2, is not taken into account, as it is assumed that all electricity produced in the energy centre is sold (see assumptions in Table 1.1).

Table 2.2 Annual heat demand and heat density data for characteristic zones (Deliverable 2.3 – Table 4.27)

Class No.	**Zone No.**	**Annual thermal demand (GWh)**	**Annual electrical demand (GWh)**	**Peak thermal demand (MWh)**	**Thermal density (GWh/ha)**	**Thermal density type** (See Table 1.2)
1	154	349	242	142	4.31	HD/LI
2	711	310	90	108	0.32	LD
3	239	230	74	77	0.22	LD
4	619	400	237	140	0.23	LD
5	70	270	193	104	0.33	LD
6	509	328	102	113	0.22	LD
7	127	480	1355	190	0.23	LD
8	145	281	112	107	0.60	HD/LI
9	29	452	437	160	0.85	HD/LI
10	138	364	136	134	0.35	LD
11	566	113	28	38	0.25	LD
12	313	444	183	153	0.22	LD
13	686	181	56	60	0.22	LD
14	535	38	12	14	0.25	LD
15	734	57	20	20	0.22	LD
16	148	374	502	145	1.46	HD/LI
17	23	297	99	119	0.28	LD
18	547	268	90	89	0.28	LD
19	701	364	123	121	0.21	LD
20	909	23	7	7	0.21	LD

A user input into the design is primary energy cost; within the library of DE systems, various fuels are needed, including natural gas, biodiesel, diesel and landfill gas. The fuel prices assumed in this work are presented in Table 2.3. The emissions associated with electricity generated centrally are given in Table 1.3.

The energy supply units (DE systems) used in the superstructure are shown in Table 1.3. For each DE system, a performance model is provided in Work Package 3 of the project in the format shown in Table 2.4. The design tool selects the number of each DE system needed to meet the heat demand most cost effectively. The DE system selections are represented in Appendix B. Constraints, as presented in Table 1.2, are imposed on the solution to facilitate development of practical, robust designs: a constraint is added to ensure that no single boiler in the energy centre can provide more than 50% of the peak heat to be delivered. This constraint ensures that the DE centre would be able to deliver at least 50% of the heat demand even if all the CHP units and the largest boiler were unavailable.

The annual thermal demand of the characteristic zones varies widely – from 23 GWh to 480 GWh. The characteristic zone for Class 7 (Zone 127), which has the highest population, also has the highest annual thermal demand; the characteristic zone for Class 20 (Zone 909), with the lowest population, has the lowest thermal demand.

Table 2.3 Primary energy costs[13]

Fuel	Fuel heat value	Unit	Price per unit	Unit	Price (£/kWh)
Natural Gas	35.4	MJ/Nm^3	0.29	£/Nm3	0.029
Diesel	35.9	MJ/L	0.59	£/L	0.059
Biodiesel (B100)	32.3	MJ/L	0.67	£/L	0.075
Landfill gas (LEG)	22.4	MJ/Nm^3	0.20	£/Nm3	0.032

Table 2.4 Format for DE system models – Example: 375 kW gas engine (Deliverable 3.2)

General	Model	4006-23TRS2		
	Total kW	375		
	Fuel Type	Natural Gas		
	Fuel heat value, MJ/Nm^3	35.4		
	Cost of energy input, $£/Nm^3$	0.288		
	Fuel CO_2 generation, kg/Nm^3	1.96		
Capital Costs	Capex (Installed Cost), £/kW	1248		
	Expected lifespan, h (average)	131400		
	Footprint (Package), m x m	2.2	1.6	
	Availability of the Technology , %	95		
Operating Costs	Fixed Maintenance Cost, £/y	0		
	Variable Maintenance Cost, £/kWh	0.0125		
Performance	CO_2 manufacture, g/kW	39800		
	Load, %	Fuel consumption, Nm^3/h	Electrical output, kW_e	Thermal output at 99℃, kW_{th}
	100	94	375	473
	75	74	281	383
	50	52	187.5	282.4

Chapter 3: Evaluation of DE Solutions for Characteristic Zones

In Work Package 5, the performance of zones in which DE is adopted will be compared to the ‘baseline’ performance, when heat is supplied by individual gas boilers and all electricity is imported from the national grid. This chapter provides performance results for the DE solutions for each of the characteristic zones to allow such a comparison to be carried out. Performance in terms of the cost of delivering heat, the CO_2 emissions and the energy security will be discussed. WP5 will also use the design tool to assess the performance of other scenarios, present and future.

3.1 Economic performance of DE solutions for characteristic zones

The objective of the energy centre design is to minimize the total cost of heat production, i.e. the sum of capital, fuel and maintenance costs less revenue from electricity sold:

$$\min\{C_{total} = C_{total\ capital} + C_{operating} - C_{electricity\ sold}\} \quad (1)$$

The capital cost is annualised using an annualisation factor with a fixed interest rate for the project life time. The investment in DE systems for heat supply and thermal storage, as selected by the design tool, consider the project life time, replacements costs and cost of housing are well accounted for (see Table 1.2). Operating costs are the cost of fuel consumed to deliver heat to satisfy the thermal demand of the zone and variable maintenance costs. As all electricity produced is sold to the grid, revenue from exported electricity is included in the optimisation. The cost of electricity imported to run the pumps for heat distribution is added to the costs after the optimised solution has been determined. The cost breakdown for the characteristic zones is presented in Figure 3.1 and Table 3.1.

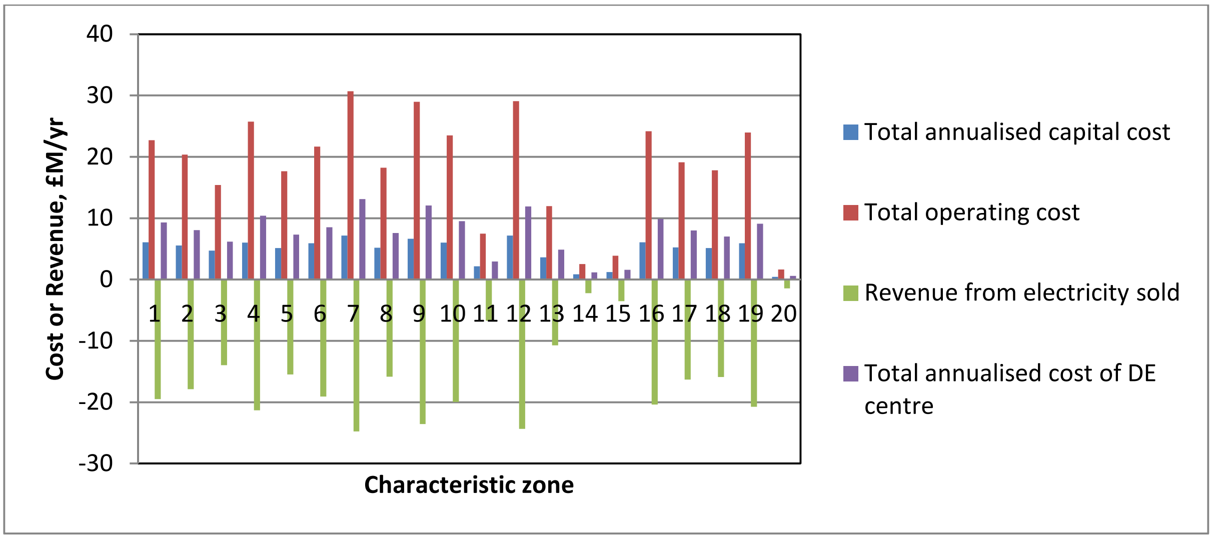

Figure 3.1 Energy centre cost breakdown for characteristic zones

Table 3.1 DE solution economic performance

Class No.	Electricity generated (GWh)	DE centre: Cap. cost (£M/yr)	DE centre: Tot. ann. cost (£M/yr)	DHN: Ann. capital cost (£M/yr)	Total ann. cost £M/yr	Revenue: electricity sold (£M/yr)	Piping : fraction of DHN cost
1	286	6.1	9.3	13.5	22.8	19.5	0.79
2	259	5.5	8.0	16.4	24.4	17.9	0.79
3	202	4.7	6.2	12.4	18.6	13.9	0.77
4	315	6.0	10.4	20.8	31.3	21.3	0.80
5	225	5.1	7.3	17.5	24.9	15.5	0.64
6	277	5.9	8.5	17.6	26.1	19.1	0.78
7	366	7.2	13.1	27.0	40.1	24.8	0.74
8	230	5.2	7.6	13.0	20.6	15.8	0.66
9	349	6.7	12.1	24.3	36.3	23.6	0.57
10	291	6.0	9.5	21.2	30.7	20.0	0.72
11	97	2.2	2.9	6.0	8.9	6.7	0.79
12	357	7.2	11.9	23.5	35.4	24.3	0.79
13	155	3.6	4.9	9.1	14.0	10.7	0.83
14	32	0.8	1.2	2.0	3.2	2.2	0.78
15	51	1.2	1.6	3.1	4.7	3.5	0.75
16	300	6.1	9.9	18.7	28.5	20.4	0.61
17	237	5.2	8.0	16.5	24.5	16.3	0.75
18	230	5.1	7.0	13.9	20.9	15.9	0.81
19	302	5.9	9.1	19.0	28.1	20.8	0.80
20	21	0.4	0.6	1.3	1.8	1.5	0.77

Figure 3.1 and Table 3.1 present annualised costs for the energy centres designed for each characteristic zone. These costs correspond to the DE centres and operating schedules presented in Appendices B and C, respectively. Figure 3.2 presents the costs against the annual thermal demand of the characteristic zones. As expected, the costs increase with the annual heat demand. For example, the characteristic zone for Class 20 has the lowest annual thermal demand and lowest cost of heat production; the characteristic zone for Class 7 has the highest demand and highest costs.

In Figure 3.1, it can be seen that the operating cost has a similar magnitude as the revenue from electricity sold. Revenue from electricity sold clearly has a very significant impact on the energy centre economics, as it offsets the operating costs significantly. These results also imply that the electricity tariff and tariff structure will have a significant effect on the energy centre economics.

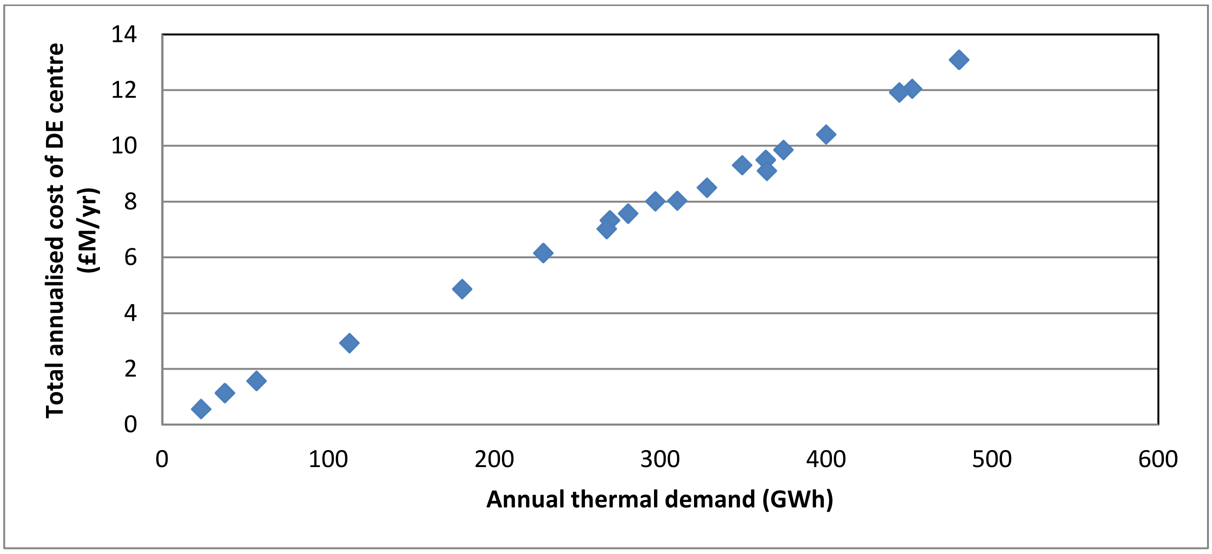

Figure 3.2 Total annualised cost of energy centre for characteristic zones

The cost of distributing heat is presented in Figure 3.3 and Table 3.1. As expected, the cost of heat delivery also increases with thermal demand, which affects the pipe diameter (especially for transmission pipes) which in turn dominates the DHN cost. Other components of the DHN cost include the cost for domestic and industrial Heat Interface Units (HIU). Annualised heat network costs range from £M1.26/yr to £M27.03/yr; they account for 60 to 70% of the total annualised cost of the energy centre. Note that the cost of heat delivery is not an integral part of the design optimisation.

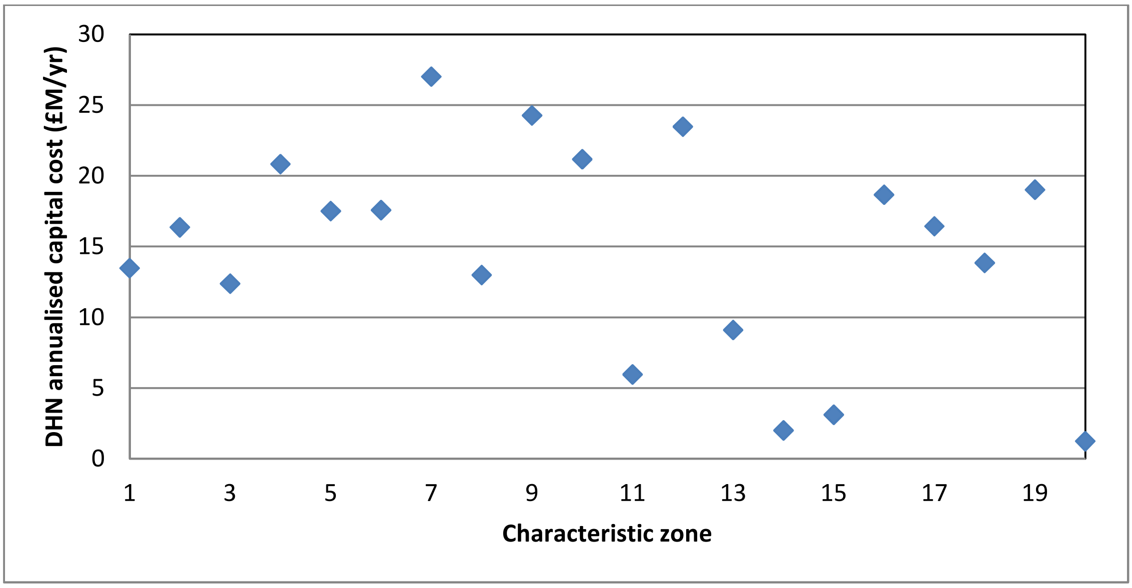

Figure 3.3 Annualised capital cost of DHN for characteristic zones

The total annualised cost of the DE solution is the sum of annual costs of heat production and heat delivery. Table 3.1 and Figure 3.4 present total annualised costs; in Figure 3.5 the breakdown of costs is plotted against thermal demand.

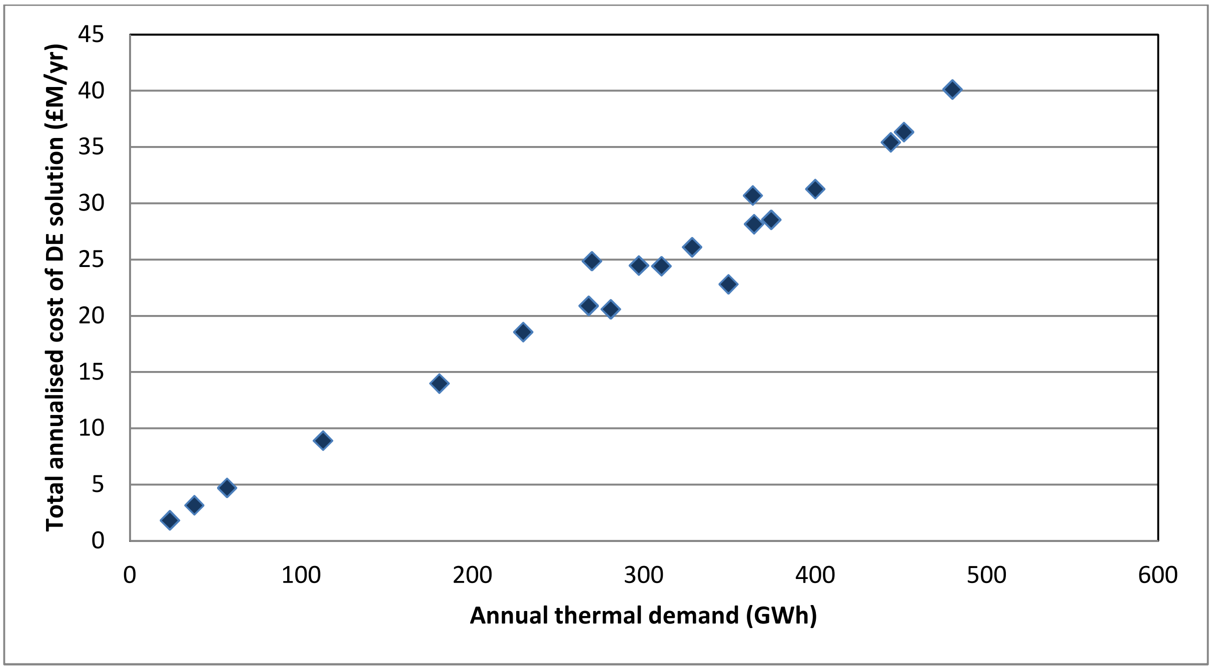

Figure 3.4 Total annualised cost of DE solution vs. annual thermal demand

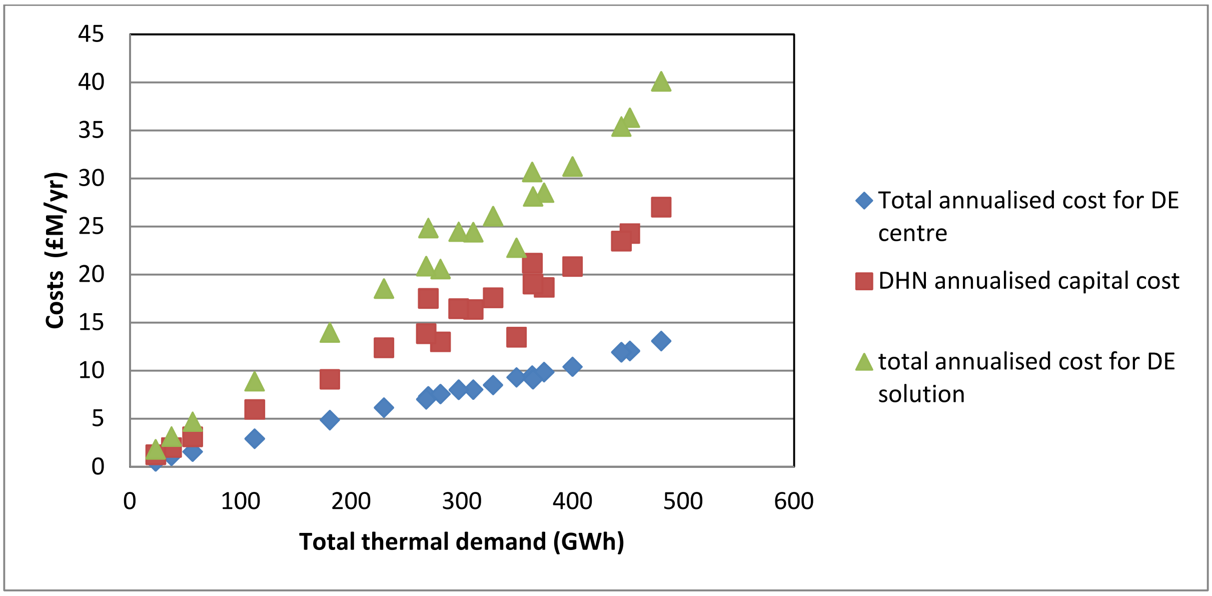

Figure 3.5 Breakdown of DE solution costs vs. annual thermal demand

The cost of producing heat (per unit of heat delivered), represented in Figure 3.6, ranges from 2 to 3 p/kWh. The costs of producing heat are relatively similar in all characteristic zones. This is expected, as the effects of scale have largely been removed. Furthermore, all the energy centres designed use the same DE systems (gas engines of various sizes and boilers, as shown in Appendix B).

Taking into account the costs of distributing heat (ranging from 3.9 to 6.5 p/kWh), the total annualised cost of delivering heat is between 6.5 and 9 p/kWh. The cost of heat delivery per unit of heat delivered is rather variable, even when the simple cost model for the DHN is applied. In the simple cost model, heat distribution costs depend not only on the annual thermal demand, but also on the number of heat interface units (both domestic and tertiary), as shown in Table 1.2. Table 2.1 shows that there is wide variation in the number of households and number of tertiary heat users (i.e. gas meters) in the characteristic zones. The contribution of piping to the total distribution costs is shown in Table 3.1 to vary widely, between 57 % and 83% – the remainder of the costs are attributable to costs of heat interface units.

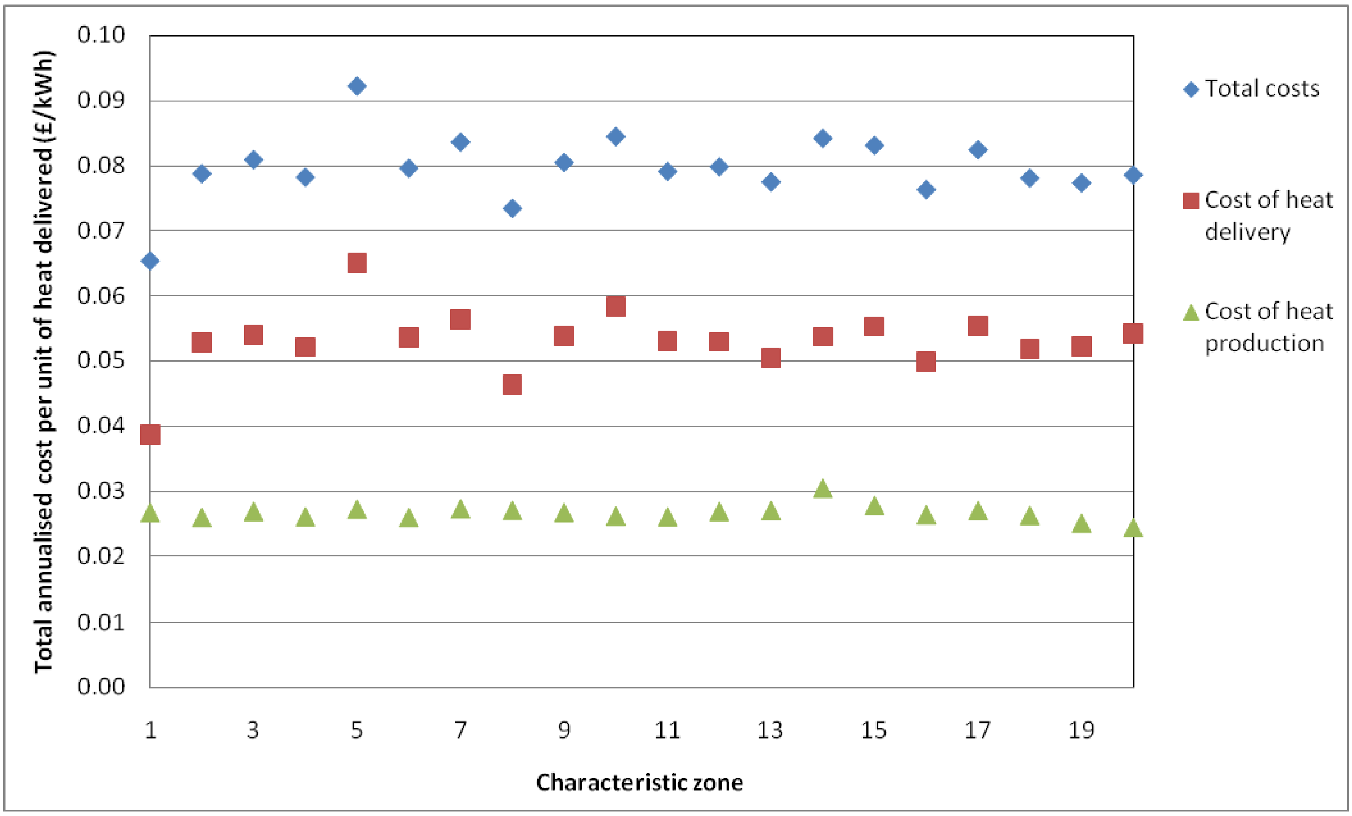

Figure 3.6 Total annualised cost of DE solutions per unit of heat delivered (£/kWh)

3.2 Economic performance compared to baseline

The baseline for performance analysis is that all electricity is centrally generated and that each gas user satisfies the average heat demand with a stand-alone boiler. Natural gas-fired boilers are assumed to be 80% efficient and to meet 100% of the annual thermal demand of the characteristic zone. The boiler life is taken to be 8 years. The baseline fuel costs are calculated by the design tool to allow their comparison with the DE solutions obtained, as shown in Figure 3.7.

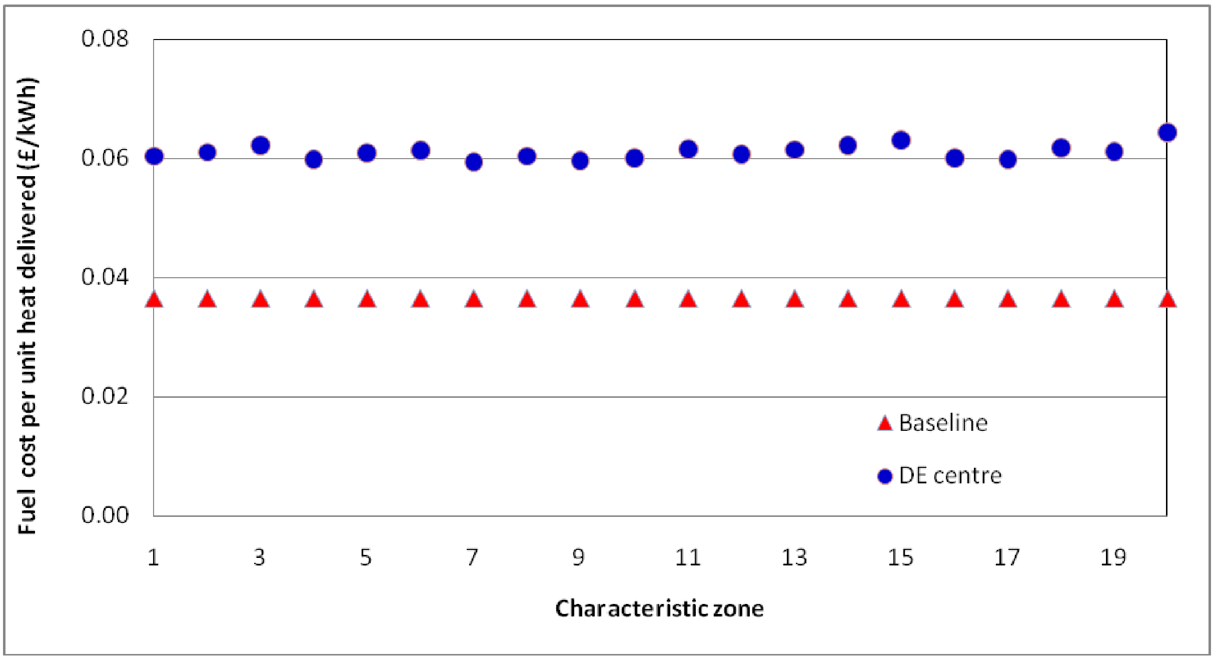

Figure 3.7 Fuel cost per unit of heat delivered for baseline case and energy centre

While in the baseline case, boilers use fuel only for heat generation, in energy centres both heat and power are generated. There are considerable heat losses from the heat distribution network (around 10%), which further increases the consumption of fuel in an energy centre, relative to that in a stand-alone boiler. Per unit of heat delivered, therefore, the gas-fired boilers have significantly lower fuel costs. In the energy centres, the revenue from electricity generation offsets the fuel costs significantly. The baseline case will be compared more fully with DE solutions in Work Package 5, taking into account the value of electricity generated, the cost of heat delivery and capital investment.

In summary, the design tool has been applied to design energy centres for 20 characteristic zones; their designs and operating schedules are summarised in Appendices B and C and their costs have been presented.

3.3 Carbon dioxide emissions from characteristic zones

One of the major drivers for distributed energy is the reduction in carbon dioxide emissions that can be achieved, compared to conventional energy systems. By generating both heat and electricity, distributed energy centres generate less CO_2 emissions: fuel is used very efficiently by cogeneration systems. In addition, low-carbon energy sources, such as biofuels and solar heating, can be used. Emissions from the energy centre comprise CO_2 emissions from fuel combustion and CO_2 embodied in the DE systems making up the energy centre. When electricity is generated in the energy centre, it allows higher-carbon electricity generation (e.g. in a coal- or gas-fired power station) to be avoided; by this reasoning, CO_2 emissions credits are claimed for any electricity generated for export to the national grid. Together, the CO_2 emissions from fuel combustion and embodied carbon associated with equipment manufacture, plus the CO_2 associated with electricity required for pumping heat through the heat network, less the amount of CO_2 avoided by generating electricity in the energy centre, are termed 'global CO_2 emissions'. In this report, the embodied carbon is not reported; its contribution to the overall CO_2 emissions is expected to be low. For example, the annual CO_2 emissions from a 5 MW diesel engine, a 6 MW gas engine and a 20 MW gas boiler are expected to be less than 10 t/y over a 25 year life.

Table 3.2 summarises the calculated CO_2 emissions. Figure 3.8 presents the CO_2 emissions from fuel combustion plotted against annual thermal demand and Figure 3.9 shows the fuel CO_2 emissions per unit of heat delivered. Characteristic zones with high thermal demand emit the most CO_2 from fuel combustion, as shown in Figure 3.8. It can be seen in Figure 3.9 that the CO_2 emitted per unit of heat is similar for all characteristic zones because only natural gas is selected as fuel.

Table 3.2 CO_2 emissions of characteristic zones

Class No.	Annual thermal demand (GWh)	Fuel CO_2 t/y	CO_2 avoided t/y	Global CO_2 t/y	Baseline CO_2 t/y
1	349	142,000	139,000	7,000	87,000
2	310	127,000	126,000	5,000	77,000
3	230	96,000	98,000	1,000	57,000
4	400	162,000	153,000	14,000	99,000
5	270	111,000	109,000	4,000	67,000
6	328	136,000	134,000	5,000	82,000
7	480	194,000	177,000	21,000	119,000
8	281	114,000	112,000	5,000	70,000
9	452	184,000	169,000	19,000	112,000
10	364	148,000	141,000	11,000	90,000
11	113	47,000	47,000	1,000	28,000
12	444	183,000	173,000	14,000	110,000
13	181	75,000	75,000	1,000	45,000
14	38	16,000	16,000	1,000	9,000
15	57	24,000	25,000	100	14,000
16	374	155,000	145,000	13,000	93,000
17	297	120,000	115,000	8,000	74,000
18	268	111,000	112,000	2,000	67,000
19	364	153,000	146,000	10,000	90,000
20	23	10,000	10,000	300	6,000

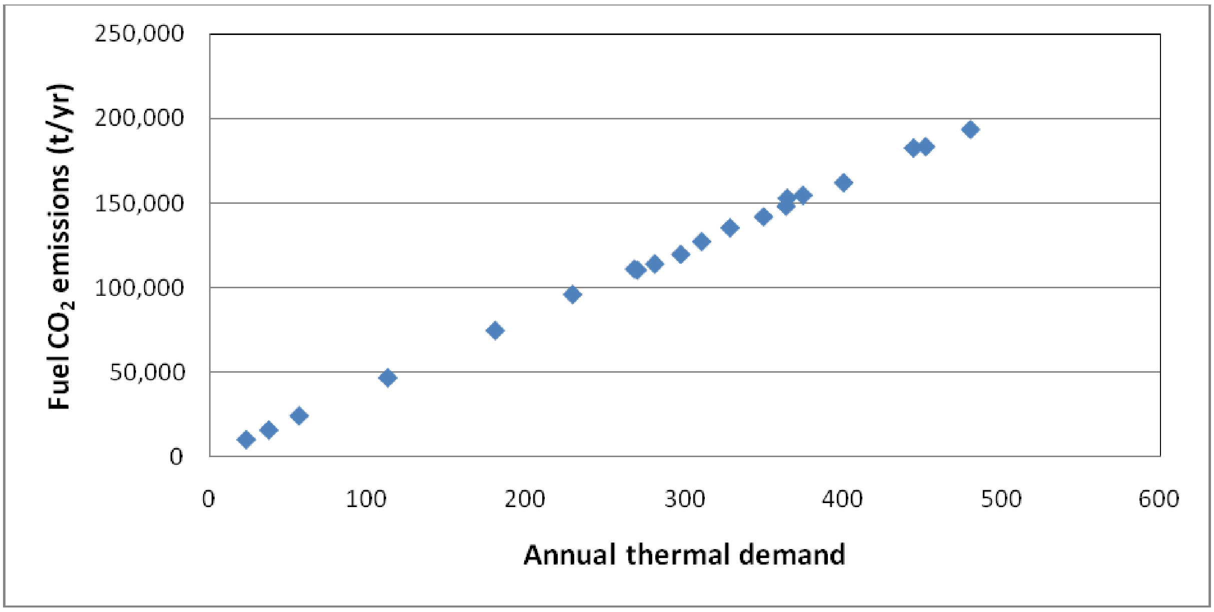

Figure 3.8 Fuel CO_2 emissions plotted against annual thermal demand

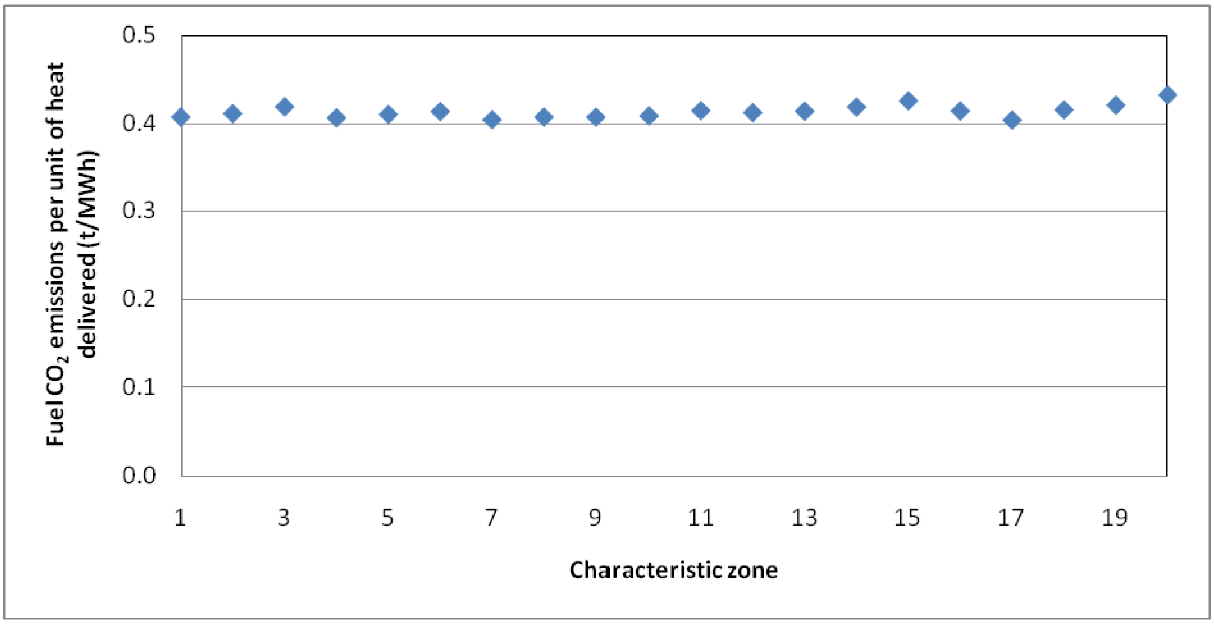

Figure 3.9 Fuel CO_2 emissions per unit of heat delivered in characteristic zones

Under the design assumptions, all electricity produced from the energy centre is sold to the grid which results in revenue for the centre and allows CO_2 emissions from central electricity generation to be avoided. The carbon emissions avoided per unit of heat delivered are represented in Figure 3.9. It may be seen that the emissions from fuel and the emissions avoided are very similar. The difference between the fuel CO_2 emissions and CO_2 credits for electricity sold to the grid are the global CO_2 emissions. Figure 3.11 (CO_2 emissions vs. annual thermal demand) and Figure 3.12 (CO_2 emissions per unit of heat delivered) present the global CO_2 emissions. It may be seen than the global CO_2 emissions are very low, in the region of 0.02 to 0.04 t/MWh, especially for zones with lower annual demand (less than 250 GWh), as in these zones more electricity is produced per unit of heat than in the zones with larger demand (see Table 3.3).

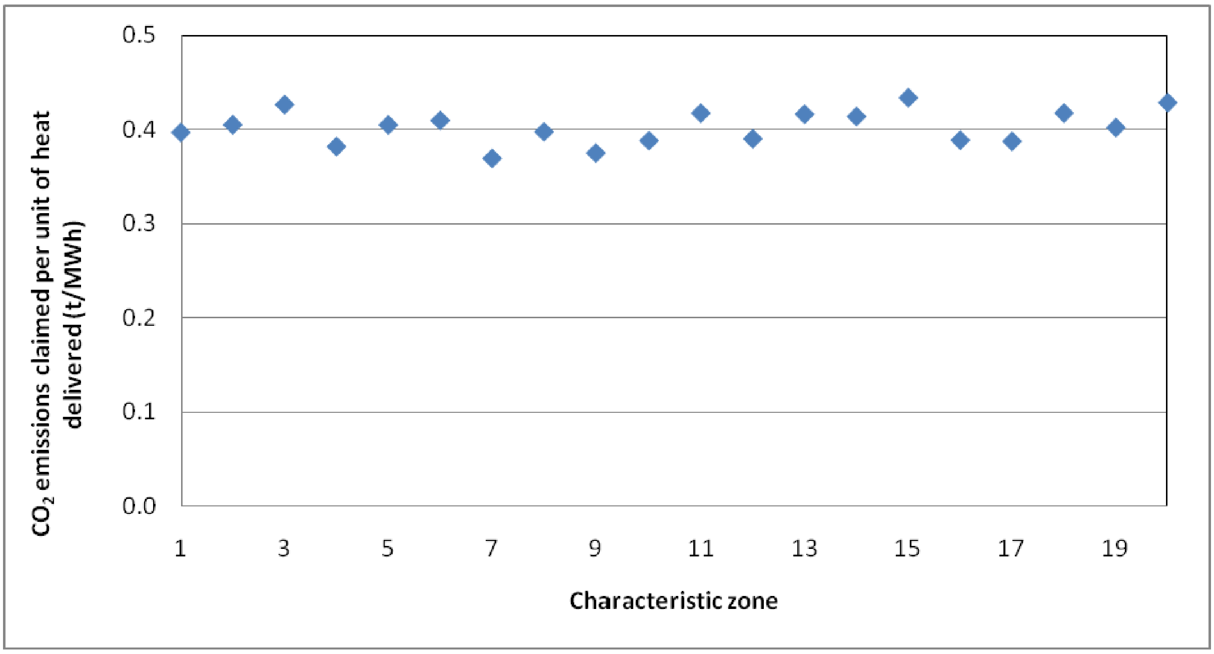

Figure 3.10 CO_2 emissions credits claimed per unit of heat delivered

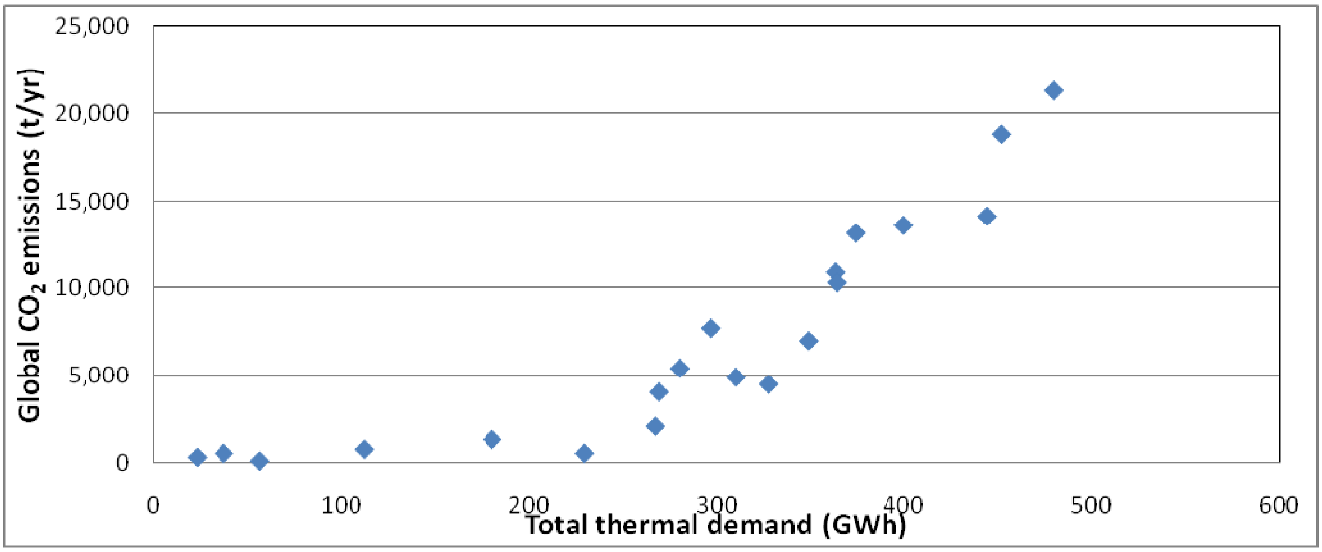

Figure 3.11 Annual global CO_2 emissions plotted against annual thermal demand

CO_2 emitted in the baseline case is that associated with natural gas consumed to satisfy the thermal demand. Global CO_2 emissions from the energy centre are compared with the baseline case in Figure 3.13. As can be seen in Figure 3.13, this level of emissions of the DE solution is an order of magnitude less than that in the base line case, where heat is provided by individual boilers. On average DE solution emissions are 91% less than in the baseline case, which implies that DE can facilitate significant reductions in carbon emissions.

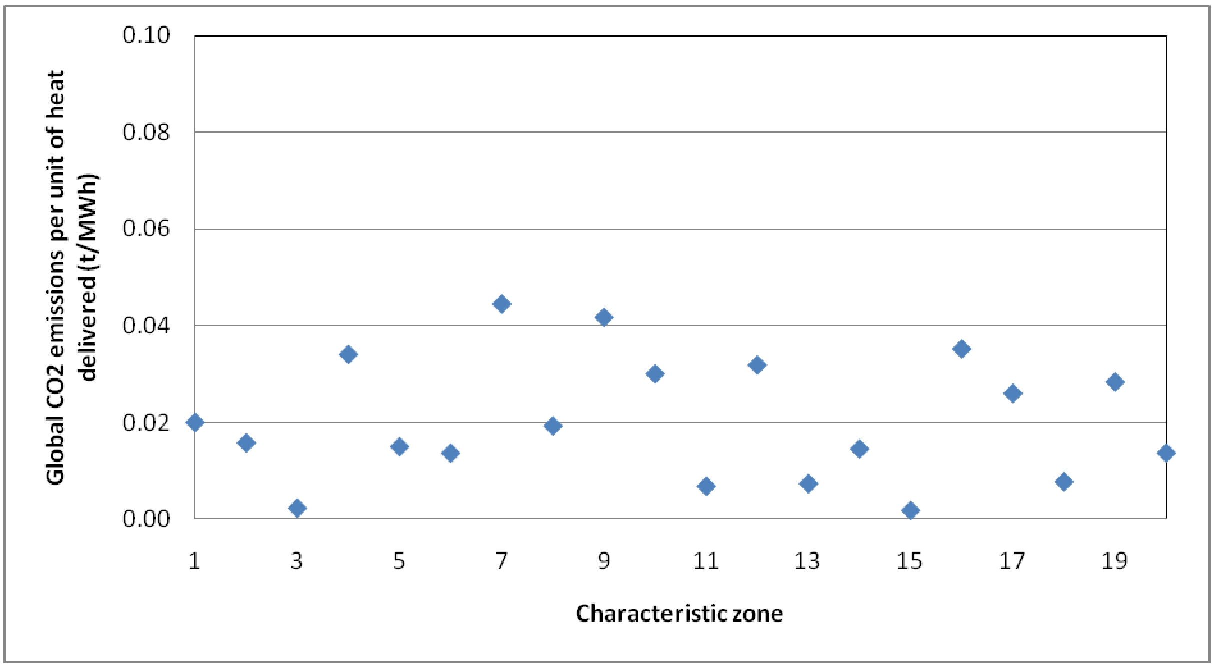

Figure 3.12 Global CO_2 emissions per unit of heat delivered

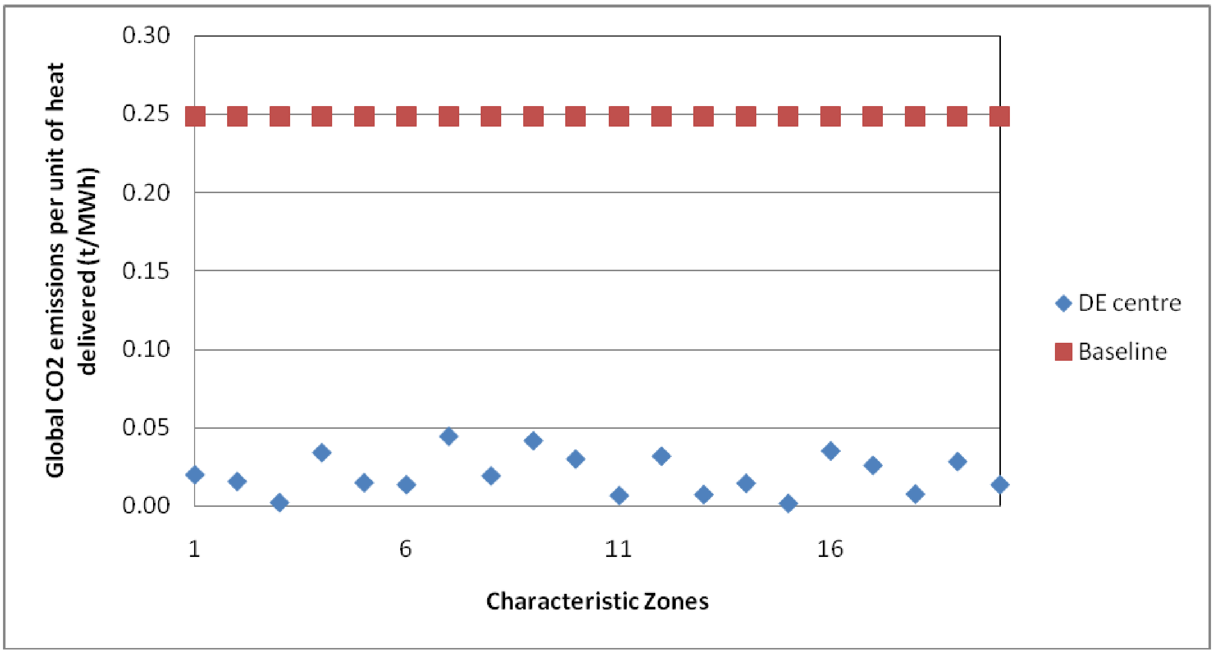

Figure 3.13 Comparing CO_2 emissions from DE solution and baseline

3.4 Energy Efficiency

Overall energy flows for the 20 characteristic zones are summarised in Table 3.3. Energy efficiency may be defined as the fraction of the energy of a fuel that is converted to useful energy, e.g. heat and power[14, 15]. By this definition, the energy efficiency of energy centres is greater than 90%, as shown in Table 3.3. This high efficiency is attributable to the extensive use of combined heat and power (CHP) devices, because of the economic benefits they bring. Figure 3.14 illustrates the high contribution of CHP to heat provision in the characteristic zones.

Table 3.3 Summary of energy centre energy flows

Class Number	Fuel consumed (GWh)	Heat produced (GWh)	Electricity produced (GWh)	Energy centre energy efficiency*	Fraction of heat demand met by CHP
1	713	384	286	94%	92%
2	640	341	259	94%	93%
3	482	252	202	94%	99%
4	808	440	315	93%	88%
5	555	297	225	94%	93%
6	680	361	277	94%	94%
7	964	528	366	93%	84%
8	573	309	230	94%	92%
9	909	497	349	93%	86%
10	737	400	291	94%	89%
11	234	124	97	94%	96%
12	911	488	357	93%	89%
13	375	199	155	94%	96%
14	79	41	32	93%	95%
15	121	62	51	93%	99%
16	759	411	300	94%	90%
17	601	327	237	94%	89%
18	558	294	230	94%	97%
19	751	401	302	94%	93%
20	51	26	21	91%	98%

* Efficiency = useful energy / energy in fuel consumed

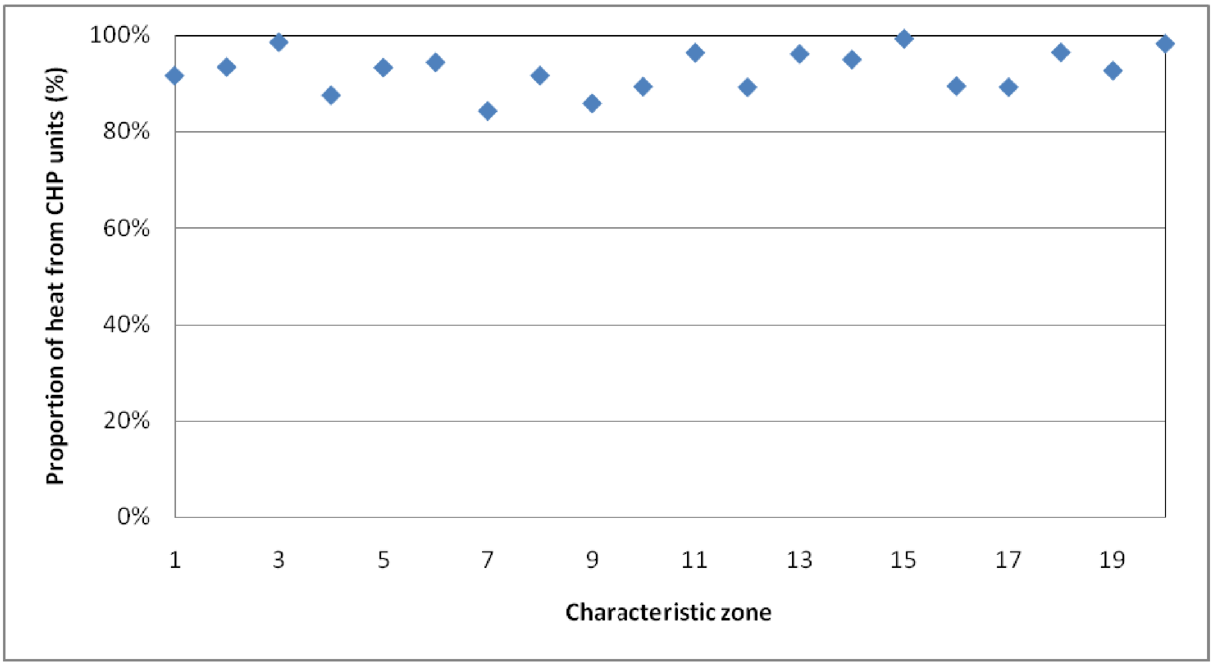

Figure 3.14 Proportion of heat demand provided CHP units in energy centre designs

3.5 Energy security

Three issues related to energy security are important in the United Kingdom[16]:

- *Physical security:* relates to continuous provision of energy;
- *Price security*: relates to avoiding price increases because of imbalances between supply and demand;
- *Geopolitical security*: relates to the UK being relatively independent of specific external suppliers of energy.

Here, the DE designs generated by the design tool are analysed for their potential contributions to energy security.

Firstly, the energy centres have been designed with a degree of redundancy, which means that heat supply to the zone would not be significantly compromised by unexpected shutdowns of some DE systems in the energy centre. Table 3.4 summarises the redundancy in the energy centres designed for the characteristic zones. From Table 3.4 it can be seen that if the CHP units all failed, boilers alone can meet the peak thermal demand; even if the largest boiler also fails, over 60% of the peak heat demand can still be satisfied, which minimises interruptions to the heat supply. However, as the designs select the energy centre designs that have the lowest cost, all the DE systems selected use natural gas. There is an associated reliance on natural gas; if gas supplies were interrupted, it is likely that heat provision would also be interrupted.

Table 3.4 Redundancy in energy centre designs

		CHP and Boilers		Boilers only		Largest boiler fails	
Class Number	Peak demand, MW	Installed thermal capacity MW	% of peak heat demand	Installed thermal capacity MW	% of peak heat demand	Installed heat capacity MW	% of peak heat demand
1	142	223	157%	142	100%	122	86%
2	108	185	172%	108	100%	88	82%
3	77	148	192%	80	104%	60	78%
4	140	221	158%	140	100%	120	86%
5	104	176	170%	104	100%	84	81%
6	113	195	173%	114	101%	94	83%
7	190	283	149%	190	100%	170	90%
8	107	179	168%	107	100%	87	81%
9	160	249	156%	160	100%	140	88%
10	134	216	161%	135	100%	115	86%
11	38	68	178%	38	101%	28	74%
12	153	251	164%	154	100%	134	87%
13	60	113	189%	60	100%	40	67%
14	14	26	190%	14	103%	11	77%
15	20	37	185%	20	103%	13	67%
16	145	226	156%	145	100%	125	86%
17	119	192	162%	120	101%	100	84%
18	89	162	183%	90	102%	70	79%
19	121	203	167%	121	100%	101	84%
20	7	12	166%	8	105%	4	58%

The energy centres, as designed, have some capacity for resilience to changes in fuel prices. The boiler capacity that is available to address resilience also provides flexibility to deliver heat. This flexibility allows operation to be optimised according to changes in fuel prices and electricity tariffs. Macro-scale DE can thus contribute to price security for heat provision in the UK.

The energy centres designed to minimise the cost of heat delivered only use natural gas to provide heat (and power). As such, the energy centre designs do not help to provide energy security with respect to reliance on supplies of gas. Macro-scale DE can potentially use a mix of fuels and technologies, including fossil fuels and renewable sources of energy such as biofuels and solar heating, which would improve energy security in the UK. However, energy economics in the current timeframes favour the use of natural gas. The extent to which macro-scale DE could address geopolitical energy security depends on how fuel prices change in future and on any mechanisms in place to encourage the use of a more diverse mix of fuels.

Chapter 4: Conclusions

The design tool developed at the University of Manchester in the ETI Macro DE project has been applied to the characteristic zones identified in the project. The DE solutions obtained using the tool have been discussed in terms of their economic performance, their CO_2 emissions and their role in improving energy security in the UK.

The designs obtained are summarised – these include gas-fired engines for heat and power generation, where the proportion of the heat provided by the CHP units is very high. The predominant use of CHP units for heat provision has significant benefits in terms of revenue from electricity sales and reductions in CO_2 emissions, by allowing CO_2 emissions from inefficient central power stations to be substituted by electricity generated in energy centres. Some practical considerations in the energy centre design, including sufficient provision of back-up heat generation capacity, in case CHP units fail, are demonstrated.

The design methodology, and the pre-prototype software tool in which it has been implemented, will be used in Work Package 5 of the Macro DE project to allow quantitative assessment of the potential for DE in GB with respect to affordability, impact on CO_2 emissions and energy security.

In Work Package 5, the same characteristic zones will be analysed for a range of scenarios, and a range of technologies will be introduced to the 'library' of technologies. The associated design results will allow the case for macro-scale distributed energy in GB to be developed and for opportunities of future technology development to be identified.

An enhanced, validated model for the DHN cost will be applied to each characteristic zone, based on work currently being undertaken by Mooney Kelly Niras. The assumptions to be applied for the base case, as well as in future scenarios will be revised, e.g. to consider changing fuels prices and emissions from electricity distributed via the national grid over the project life. The revised base case analysis will be presented in WP5 deliverables.

In Work Package 5, the baseline (effectively a 'business as usual' reference point, where heat is provided by individual boilers to all households and tertiary heat users) will receive significant attention. In particular, the capital investment associated with the baseline, the cost of heat delivery, and the CO_2 emissions will be compared to the corresponding values for characteristic zones and for the corresponding classes of zones.

The DE solution performances will be extrapolated to consider application of DE to all zones in each class in order to assess the overall effect on GB. The results will be compared with the baseline performance to provide insights into the difference in costs and in CO_2 emissions, relative to business as usual.

Appendix A: Demand data for all characteristic zones (in MW)

Table A.1 Demand data for CZ 154 (Class 1)

	Weeekdays (WD)	Hours	Winter	Summer	Transition
Thermal MW	0:00 - 04:59	5	57	12	32
	5:00 - 6:59	2	90	24	56
	7:00 - 9:59	3	90	21	53
	10:00 - 16:59	7	71	16	40
	17:00 - 18:59	2	66	14	36
	19:00 - 21:59	3	63	14	35
	22:00 - 23:59	2	50	11	28
	Baseload		13	6	11
	Peak		142	52	112
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	53	10	28
	5:00 - 6:59	2	77	17	45
	7:00 - 9:59	3	74	16	42
	10:00 - 16:59	7	64	12	34
	17:00 - 21:59	5	66	12	35
	22:00 - 23:59	2	55	11	30
	Days		34	36	34

Table A.2 Demand data for CZ 711 (Class 2)

	Weeekdays (WD)	Hours	Winter	Summer	Transition
Thermal MW	0:00 - 04:59	5	35	7	20
	5:00 - 6:59	2	70	24	48
	7:00 - 9:59	3	69	23	47
	10:00 - 16:59	7	60	16	37
	17:00 - 18:59	2	67	17	42
	19:00 - 21:59	3	64	18	42
	22:00 - 23:59	2	37	9	23
	Baseload		8	3	7
	Peak Days		108	47	81
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	36	6	20
	5:00 - 6:59	2	72	23	48
	7:00 - 9:59	3	71	21	46
	10:00 - 16:59	7	62	14	37
	17:00 - 21:59	5	67	16	42
	22:00 - 23:59	2	39	8	23
	Days		34	36	34

Table A.3 Demand data for CZ 239 (Class 3)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	27	7	17
	5:00 - 6:59	2	51	19	36
	7:00 - 9:59	3	50	18	35
	10:00 - 16:59	7	43	13	28
	17:00 - 18:59	2	46	13	30
	19:00 - 21:59	3	44	14	30
	22:00 - 23:59	2	28	8	18
	Baseload		8	3	6
	Peak Days		77	39	58
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	27	6	16
	5:00 - 6:59	2	50	17	34
	7:00 - 9:59	3	49	16	33
	10:00 - 16:59	7	43	11	27
	17:00 - 21:59	5	46	13	30
	22:00 - 23:59	2	29	7	18
	Days		34	36	34

Table A.4 Demand data for CZ 619 (Class 4)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	55	12	32
	5:00 - 6:59	2	95	30	63
	7:00 - 9:59	3	95	27	61
	10:00 - 16:59	7	80	19	47
	17:00 - 18:59	2	81	19	48
	19:00 - 21:59	3	76	19	47
	22:00 - 23:59	2	53	12	30
	Baseload		14	5	11
	Peak Days		140	57	109
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	53	10	29
	5:00 - 6:59	2	89	24	55
	7:00 - 9:59	3	87	22	53
	10:00 - 16:59	7	76	16	43
	17:00 - 21:59	5	81	17	47
	22:00 - 23:59	2	56	11	31
	Days		34	36	34

Table A.5 Demand data for CZ 70 (Class 5)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	33	7	18
	5:00 - 6:59	2	65	19	41
	7:00 - 9:59	3	63	18	40
	10:00 - 16:59	7	53	12	31
	17:00 - 18:59	2	58	13	33
	19:00 - 21:59	3	57	14	34
	22:00 - 23:59	2	36	8	21
	Baseload		7	3	6
	Peak Days		104	35	78
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	34	6	18
	5:00 - 6:59	2	65	17	40
	7:00 - 9:59	3	64	16	39
	10:00 - 16:59	7	55	11	30
	17:00 - 21:59	5	60	12	34
	22:00 - 23:59	2	38	8	21
	Days		34	36	34

Table A.6 Demand data for CZ 509 (Class 6)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	39	8	22
	5:00 - 6:59	2	75	25	50
	7:00 - 9:59	3	74	23	49
	10:00 - 16:59	7	64	16	39
	17:00 - 18:59	2	70	17	43
	19:00 - 21:59	3	67	19	43
	22:00 - 23:59	2	41	10	25
	Baseload		10	3	8
	Peak Days		113	45	85
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	39	7	21
	5:00 - 6:59	2	76	23	49
	7:00 - 9:59	3	75	21	47
	10:00 - 16:59	7	65	15	38
	17:00 - 21:59	5	71	16	43
	22:00 - 23:59	2	43	9	25
	Days		34	36	34

Table A.7 Demand data for CZ 127 (Class 7)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	56	10	30
	5:00 - 6:59	2	116	35	74
	7:00 - 9:59	3	113	32	71
	10:00 - 16:59	7	95	22	55
	17:00 - 18:59	2	106	23	61
	19:00 - 21:59	3	103	25	62
	22:00 - 23:59	2	62	14	35
	Baseload		10	4	9
	Peak Days		190	63	142
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	58	9	30
	5:00 - 6:59	2	118	32	73
	7:00 - 9:59	3	115	29	70
	10:00 - 16:59	7	99	20	54
	17:00 - 21:59	5	108	22	62
	22:00 - 23:59	2	65	13	36
	Days		34	36	34

Table A.8 Demand data for CZ 145 (Class 8)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	34	7	18
	5:00 - 6:59	2	67	20	43
	7:00 - 9:59	3	65	18	41
	10:00 - 16:59	7	55	13	32
	17:00 - 18:59	2	61	13	35
	19:00 - 21:59	3	59	14	36
	22:00 - 23:59	2	38	9	22
	Baseload		7	3	6
	Peak Days		107	36	80
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	35	6	18
	5:00 - 6:59	2	68	18	42
	7:00 - 9:59	3	66	16	40
	10:00 - 16:59	7	57	12	32
	17:00 - 21:59	5	62	13	36
	22:00 - 23:59	2	40	8	23
	Days		34	36	34

Table A.9 Demand data for CZ 29 (Class 9)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	63	15	37
	5:00 - 6:59	2	106	31	67
	7:00 - 9:59	3	105	29	65
	10:00 - 16:59	7	88	22	51
	17:00 - 18:59	2	89	21	52
	19:00 - 21:59	3	88	23	53
	22:00 - 23:59	2	65	17	39
	Baseload		16	8	15
	Peak Days		160	58	117
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	61	13	34
	5:00 - 6:59	2	101	25	61
	7:00 - 9:59	3	98	25	60
	10:00 - 16:59	7	86	19	49
	17:00 - 21:59	5	91	20	52
	22:00 - 23:59	2	70	16	41
	Days		34	36	34

Table A.10 Demand data for CZ 138 (Class 10)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	42	9	23
	5:00 - 6:59	2	86	25	55
	7:00 - 9:59	3	83	23	52
	10:00 - 16:59	7	71	17	42
	17:00 - 18:59	2	79	17	46
	19:00 - 21:59	3	78	19	48
	22:00 - 23:59	2	49	12	29
	Baseload		10	4	8
	Peak Days		134	47	102
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	44	8	23
	5:00 - 6:59	2	88	23	55
	7:00 - 9:59	3	85	21	52
	10:00 - 16:59	7	74	16	42
	17:00 - 21:59	5	82	17	47
	22:00 - 23:59	2	52	11	30
	Days		34	36	34

Table A.11 Demand data for CZ 566 (Class 11)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	12	3	7
	5:00 - 6:59	2	25	10	18
	7:00 - 9:59	3	24	9	17
	10:00 - 16:59	7	21	6	14
	17:00 - 18:59	2	23	7	15
	19:00 - 21:59	3	22	7	15
	22:00 - 23:59	2	13	4	8
	Baseload		3	1	3
	Peak Days		38	19	29
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	13	3	7
	5:00 - 6:59	2	25	9	17
	7:00 - 9:59	3	25	8	17
	10:00 - 16:59	7	21	6	13
	17:00 - 21:59	5	23	7	15
	22:00 - 23:59	2	14	4	8
	Days		34	36	34

Table A.12 Demand data for CZ 313 (Class 12)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	53	11	31
	5:00 - 6:59	2	100	35	70
	7:00 - 9:59	3	100	32	68
	10:00 - 16:59	7	85	22	53
	17:00 - 18:59	2	92	23	59
	19:00 - 21:59	3	88	25	58
	22:00 - 23:59	2	54	14	34
	Baseload		13	5	12
	Peak Days		153	65	119
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	53	10	31
	5:00 - 6:59	2	100	31	67
	7:00 - 9:59	3	99	29	65
	10:00 - 16:59	7	85	20	52
	17:00 - 21:59	5	92	22	59
	22:00 - 23:59	2	57	13	34
	Days		34	36	34

Table A.13 Demand data for CZ 686 (Class 13)

	Weeekdays (WD)	Hours	Winter	Summer	Transition
Thermal MW	0:00 - 04:59	5	21	5	12
	5:00 - 6:59	2	40	15	27
	7:00 - 9:59	3	40	14	27
	10:00 - 16:59	7	34	9	21
	17:00 - 18:59	2	38	10	24
	19:00 - 21:59	3	37	11	24
	22:00 - 23:59	2	23	6	14
	Baseload		6	2	5
	Peak Days		60	26	46
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	22	4	12
	5:00 - 6:59	2	41	13	27
	7:00 - 9:59	3	41	13	26
	10:00 - 16:59	7	35	9	21
	17:00 - 21:59	5	38	10	24
	22:00 - 23:59	2	23	6	14
	Days		34	36	34

Table A.14 Demand data for CZ 535 (Class 14)

	Weeekdays (WD)	Hours	Winter	Summer	Transition
Thermal MW	0:00 - 04:59	5	4	1	2
	5:00 - 6:59	2	9	3	6
	7:00 - 9:59	3	8	3	6
	10:00 - 16:59	7	7	2	4
	17:00 - 18:59	2	8	2	5
	19:00 - 21:59	3	8	2	5
	22:00 - 23:59	2	5	1	3
	Baseload		1	0	1
	Peak Days		14	5	10
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	4	1	3
	5:00 - 6:59	2	9	3	6
	7:00 - 9:59	3	8	3	6
	10:00 - 16:59	7	7	2	5
	17:00 - 21:59	5	8	2	5
	22:00 - 23:59	2	5	1	3
	Days		34	36	34

Table A.15 Demand data for CZ 734 (Class 15)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	6	1	4
	5:00 - 6:59	2	13	4	9
	7:00 - 9:59	3	13	4	9
	10:00 - 16:59	7	11	3	7
	17:00 - 18:59	2	12	3	8
	19:00 - 21:59	3	12	3	8
	22:00 - 23:59	2	7	2	4
	Baseload		2	1	1
	Peak Days		20	8	15
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	7	1	4
	5:00 - 6:59	2	13	4	9
	7:00 - 9:59	3	13	4	9
	10:00 - 16:59	7	11	3	7
	17:00 - 21:59	5	12	3	8
	22:00 - 23:59	2	7	2	4
	Days		34	36	34

Table A.16 Demand data for CZ 148 (Class 16)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	57	13	32
	5:00 - 6:59	2	94	26	59
	7:00 - 9:59	3	93	23	55
	10:00 - 16:59	7	75	17	42
	17:00 - 18:59	2	72	16	41
	19:00 - 21:59	3	69	17	40
	22:00 - 23:59	2	54	13	31
	Baseload		14	7	12
	Peak Days		145	53	112
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	54	11	29
	5:00 - 6:59	2	83	19	49
	7:00 - 9:59	3	80	18	47
	10:00 - 16:59	7	70	14	38
	17:00 - 21:59	5	73	14	40
	22:00 - 23:59	2	58	12	32
	Days		34	36	34

Table A.17 Demand data for CZ 23 (Class 17)

	Weeekdays (WD)	Hours	Winter	Summer	Transition
Thermal MW	0:00 - 04:59	5	35	6	19
	5:00 - 6:59	2	72	22	46
	7:00 - 9:59	3	71	20	44
	10:00 - 16:59	7	59	14	34
	17:00 - 18:59	2	66	14	37
	19:00 - 21:59	3	63	15	38
	22:00 - 23:59	2	38	8	21
	Baseload		6	2	5
	Peak Days		119	39	89
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	36	5	18
	5:00 - 6:59	2	73	20	45
	7:00 - 9:59	3	72	18	43
	10:00 - 16:59	7	61	12	34
	17:00 - 21:59	5	67	13	38
	22:00 - 23:59	2	40	8	22
	Days		34	36	34

Table A.18 Demand data for CZ 547 (Class 18)

	Weeekdays (WD)	Hours	Winter	Summer	Transition
Thermal MW	0:00 - 04:59	5	33	8	20
	5:00 - 6:59	2	59	21	41
	7:00 - 9:59	3	59	20	40
	10:00 - 16:59	7	50	14	32
	17:00 - 18:59	2	55	15	35
	19:00 - 21:59	3	53	16	35
	22:00 - 23:59	2	34	9	21
	Baseload		9	3	8
	Peak Days		89	41	67
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	32	7	19
	5:00 - 6:59	2	59	19	39
	7:00 - 9:59	3	59	19	39
	10:00 - 16:59	7	51	13	31
	17:00 - 21:59	5	55	14	35
	22:00 - 23:59	2	35	9	22
	Days		34	36	34

Table A.19 Demand data for CZ 701 (Class 19)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	42	11	26
	5:00 - 6:59	2	79	31	56
	7:00 - 9:59	3	79	29	55
	10:00 - 16:59	7	67	20	43
	17:00 - 18:59	2	74	22	49
	19:00 - 21:59	3	71	23	48
	22:00 - 23:59	2	44	13	28
	Baseload		12	4	9
	Peak Days		121	61	91
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	42	10	25
	5:00 - 6:59	2	79	27	54
	7:00 - 9:59	3	79	26	53
	10:00 - 16:59	7	68	18	43
	17:00 - 21:59	5	74	21	48
	22:00 - 23:59	2	45	12	28
	Days		34	36	34

Table A.20 Demand data for CZ 909 (Class 20)

Thermal MW	Weeekdays (WD)	Hours	Winter	Summer	Transition
	0:00 - 04:59	5	3	1	2
	5:00 - 6:59	2	5	2	4
	7:00 - 9:59	3	5	2	4
	10:00 - 16:59	7	4	1	3
	17:00 - 18:59	2	5	1	3
	19:00 - 21:59	3	5	2	3
	22:00 - 23:59	2	3	1	2
	Baseload		1	0	1
	Peak Days		7	4	6
	Days		87	86	88
	Weekends (WE)				
	0:00 - 04:59	5	3	1	2
	5:00 - 6:59	2	5	2	4
	7:00 - 9:59	3	5	2	3
	10:00 - 16:59	7	4	1	3
	17:00 - 21:59	5	5	1	3
	22:00 - 23:59	2	3	1	2
	Days		34	36	34

APPENDIX B: Summary of DE centre designs

Table B.1 DE centre design: technology type, size and number of units selected for characteristic zones

Technology	Size (MW)	1	2	3	4	5	6	7	8	9	10
Gas Engines	3.86							2			
	4.44	5	4	2	5	3	5	6	3	6	5
	5.917	10	10	10	10	10	10	10	10	10	10
Boilers	0.25	2				1					
	1.4	1	1					1		2	1
	3.5					1	1	1			1
	7		1					5	1	1	
	10	4			4		1	5	0	5	3
	20	5	5	4	5	5	5	5	5	5	5

Table B.1 (continued) DE centre design: technology type, size and number of units selected for characteristic zones

Technology	Size (MW)	11	12	13	14	15	16	17	18	19	20
Gas Engines	3.86		2								
	4.44		7			1	5	3	3	5	1
	5.917	5	10	9	2	2	10	10	10	10	0
Boilers	0.25										
	1.4	1				2	1			1	3
	3.5		1		4	1	1				1
	7	1				2					
	10	3	5				4	2	1	2	
	20		5	3			5	5	4	5	

Appendix C: Operating schedules for DE centres designed for characteristic zones

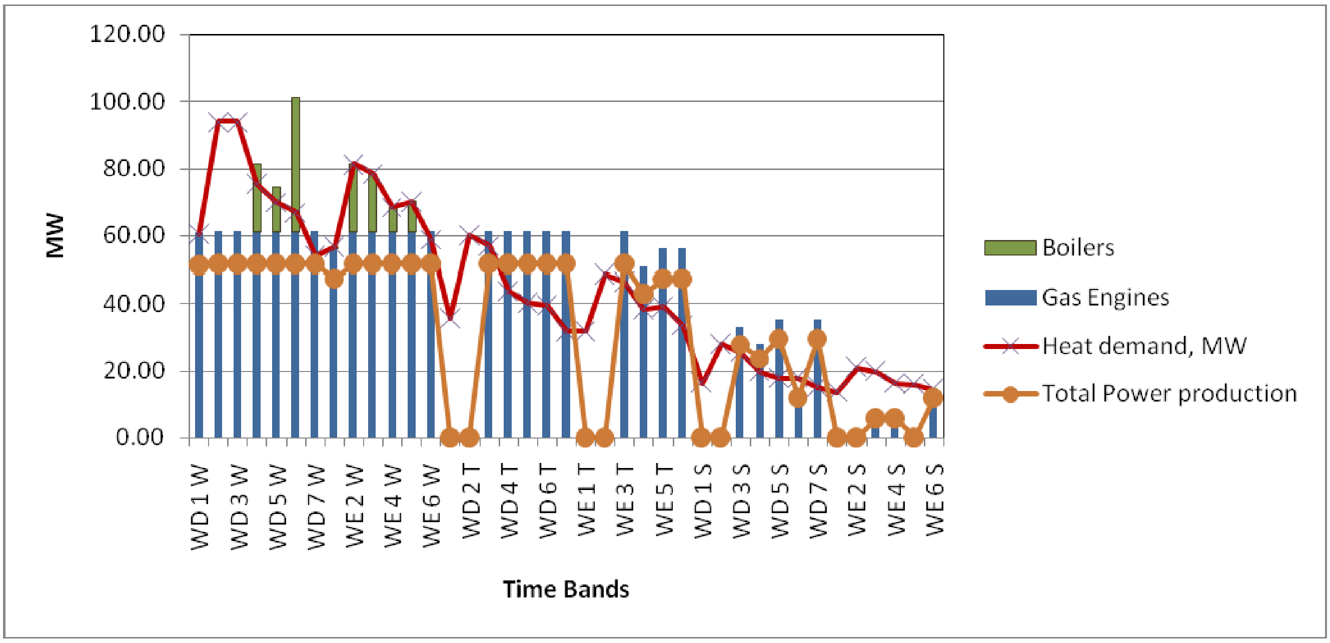

Figure C.1 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 154 (Class 1)

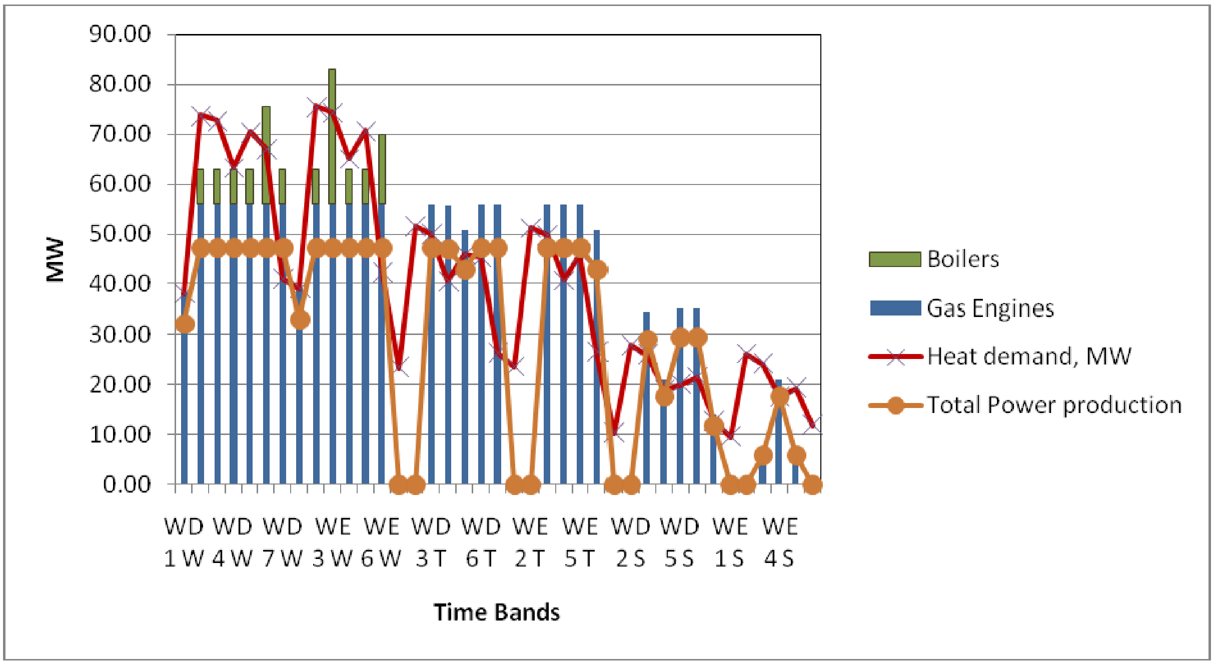

Figure C.2 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 711 (Class 2)

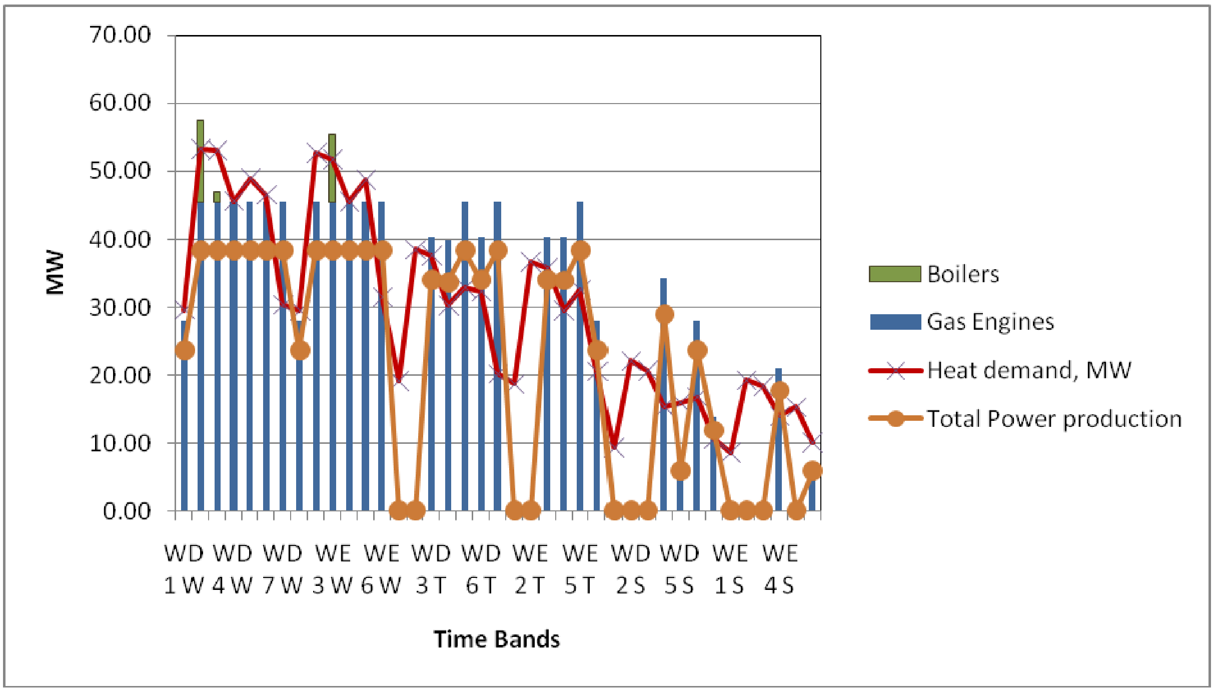

Figure C.3 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 239 (Class 3)

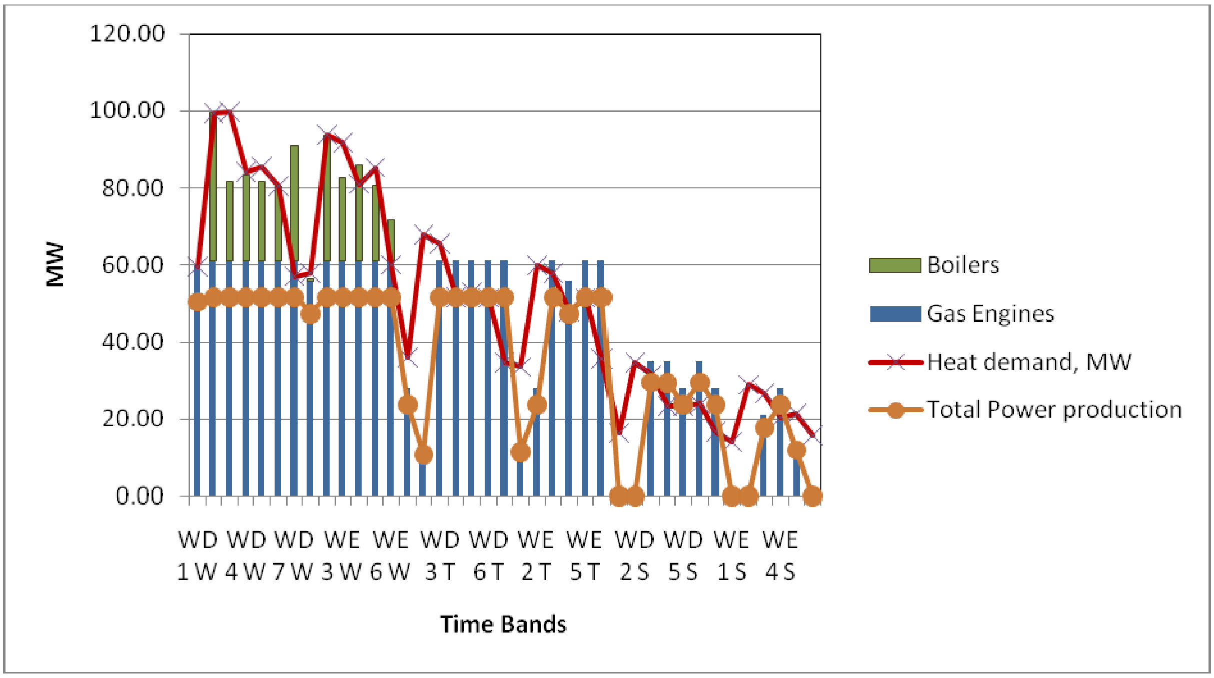

Figure C.4 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 619 (Class 4)

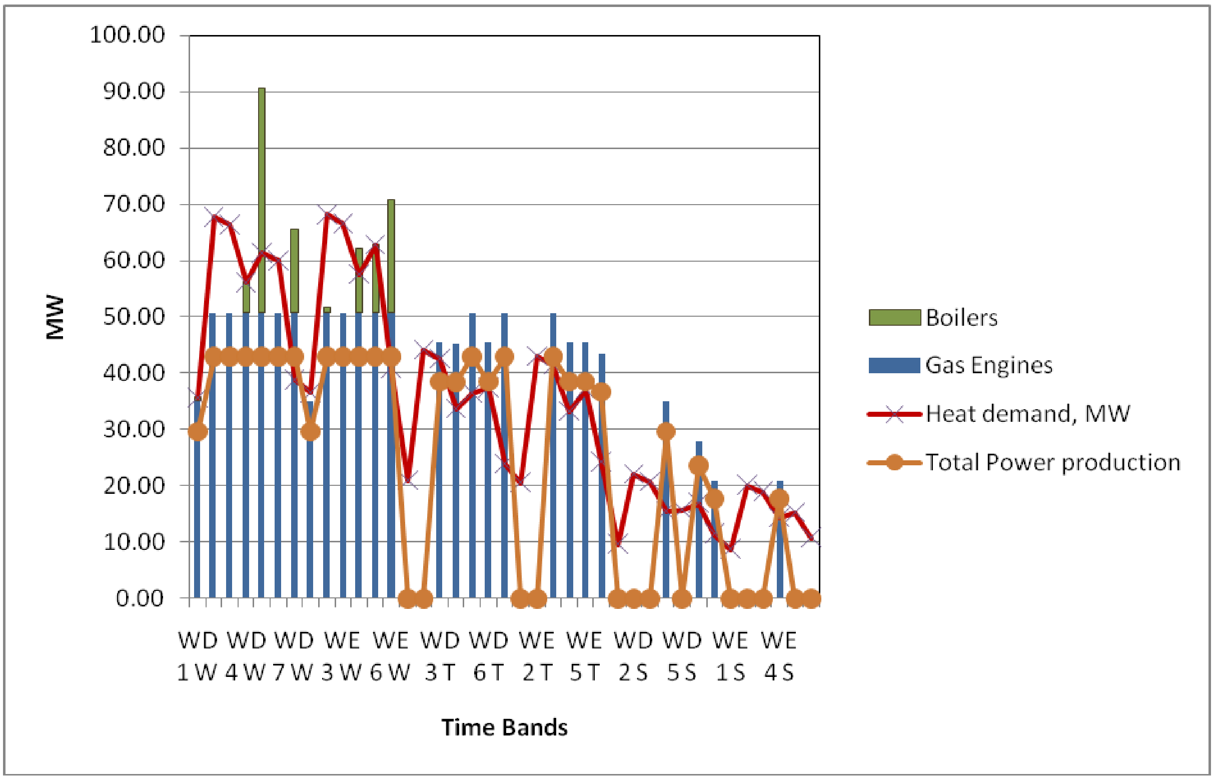

Figure C.5 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 70 (Class 5)

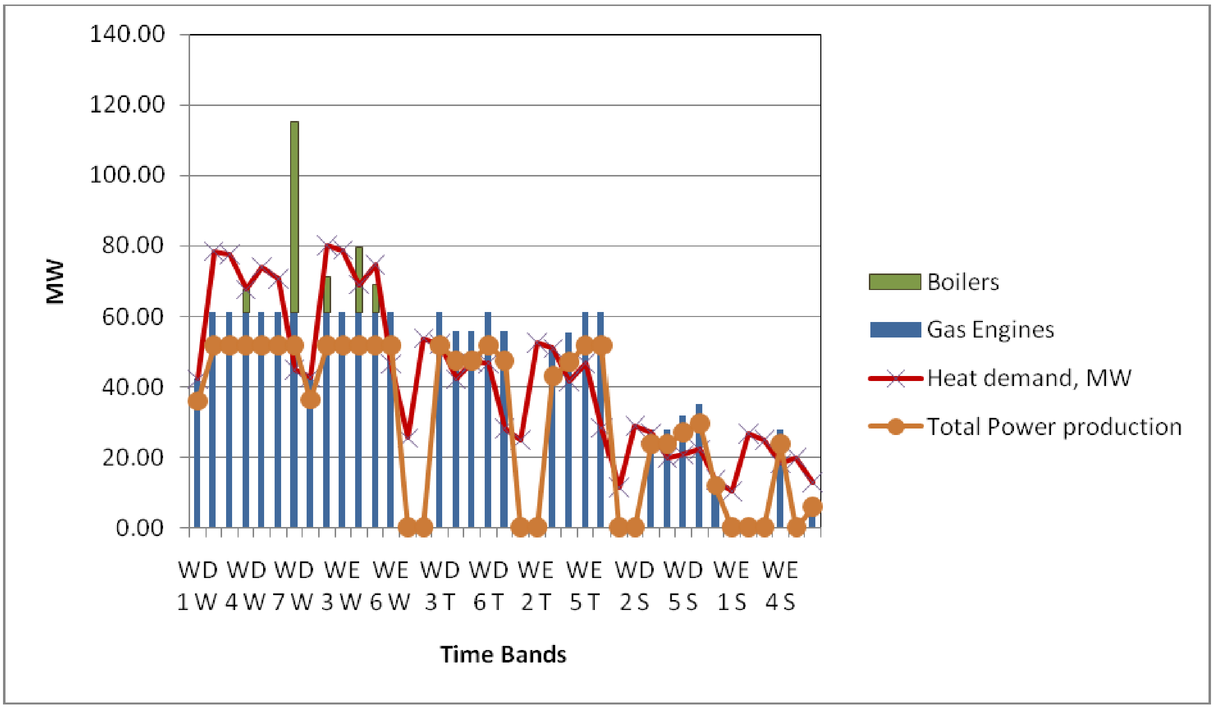

Figure C.6 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 509 (Class 6)

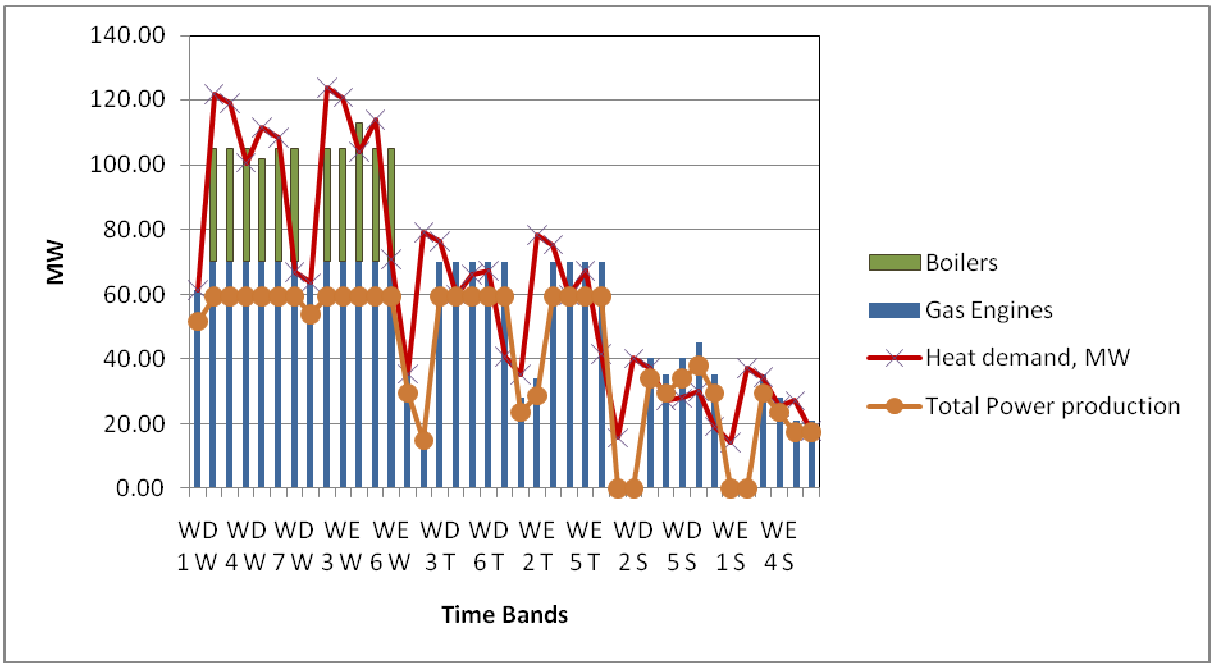

Figure C.7 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 127 (Class 7)

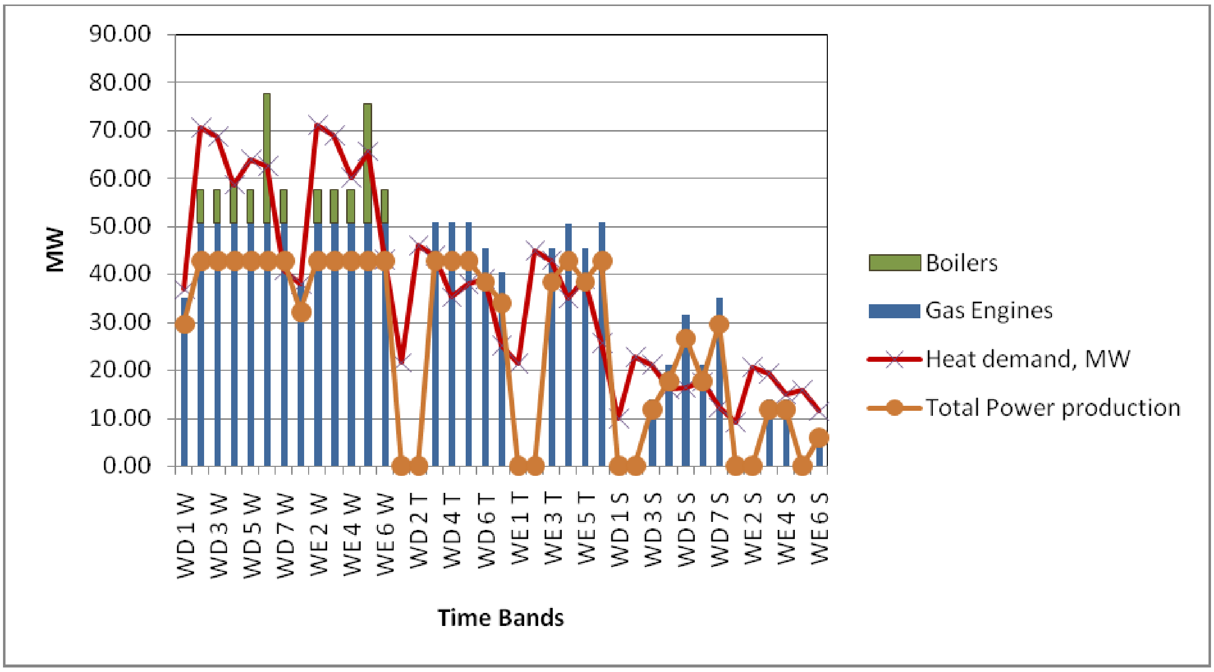

Figure C.8 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 145 (Class 8)

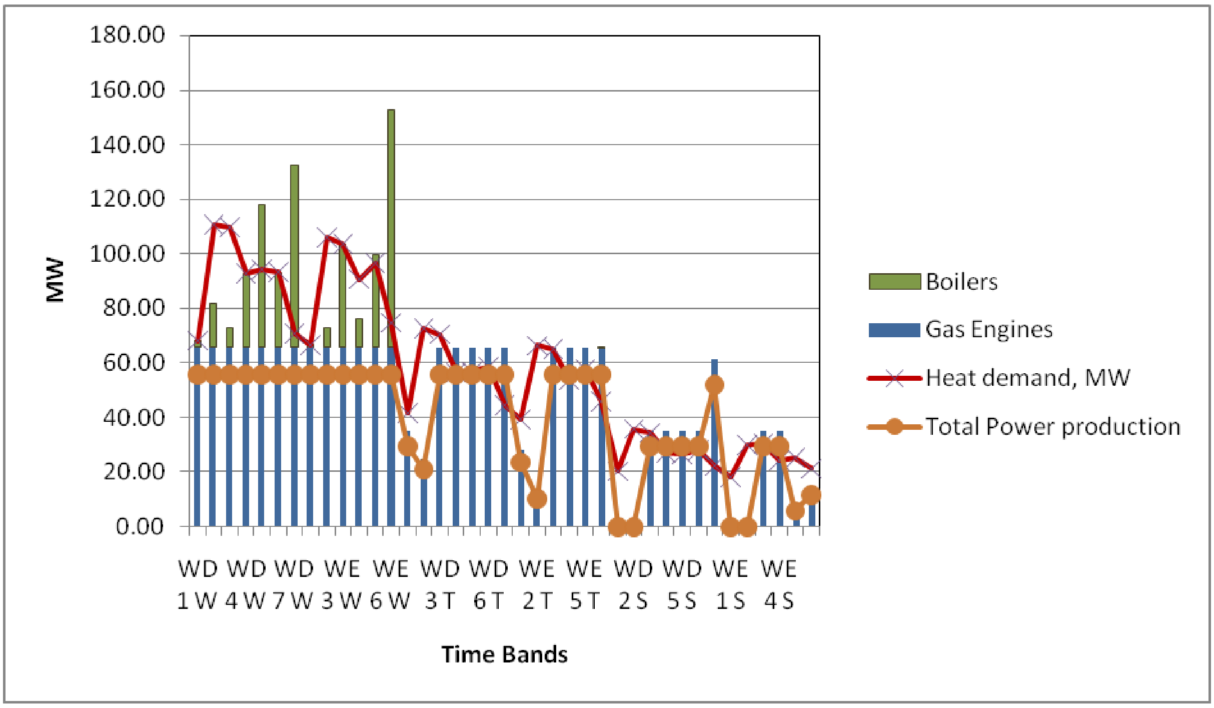

Figure C.9 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 29 (Class 9)

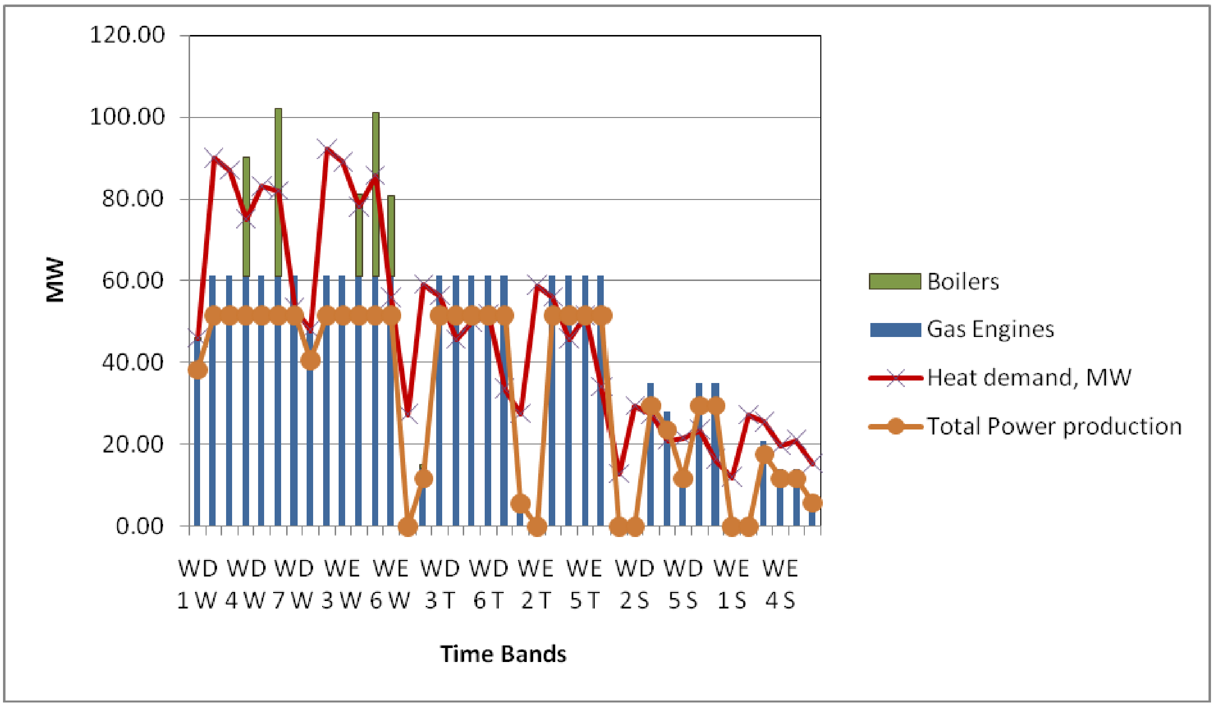

Figure C.10 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 138 (Class 10)

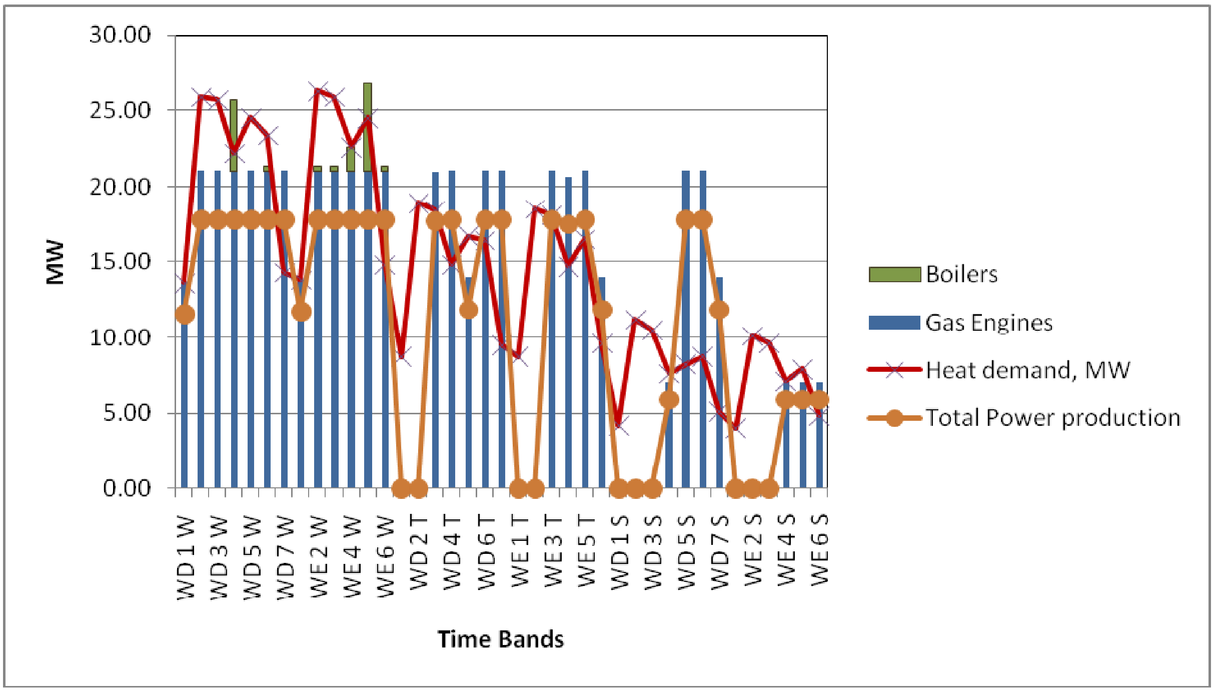

Figure C.11 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 566 (Class 11)

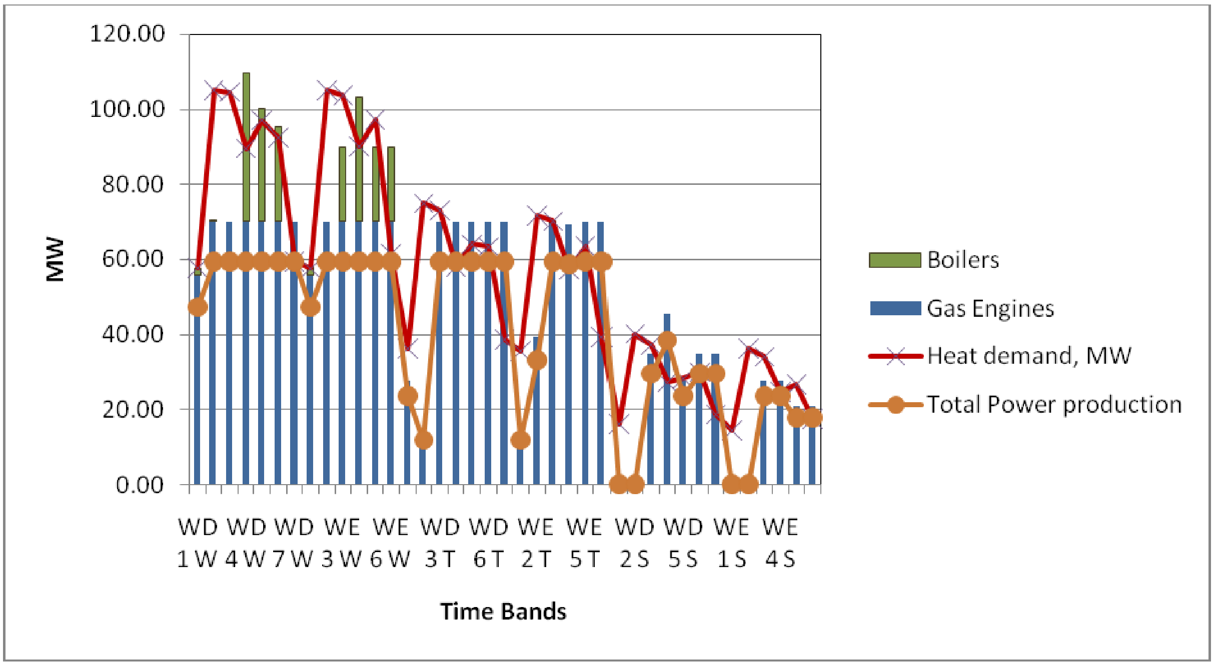

Figure C.12 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 313 (Class 12)

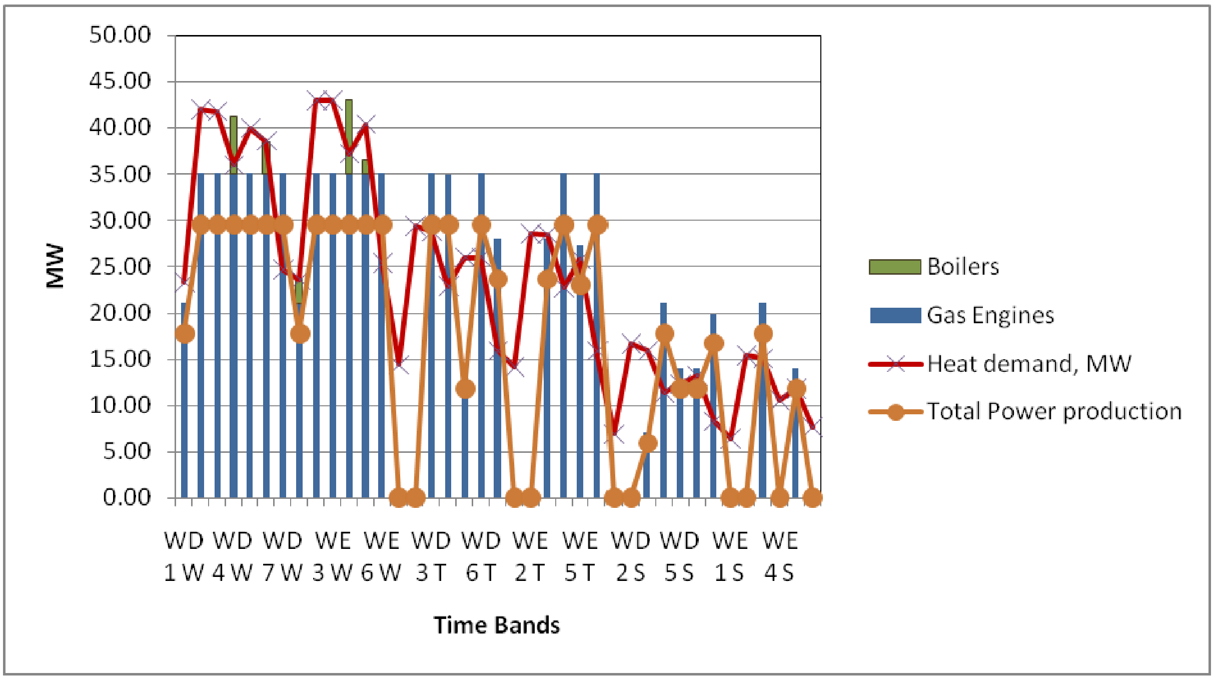

Figure C.13 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 686 (Class 13)

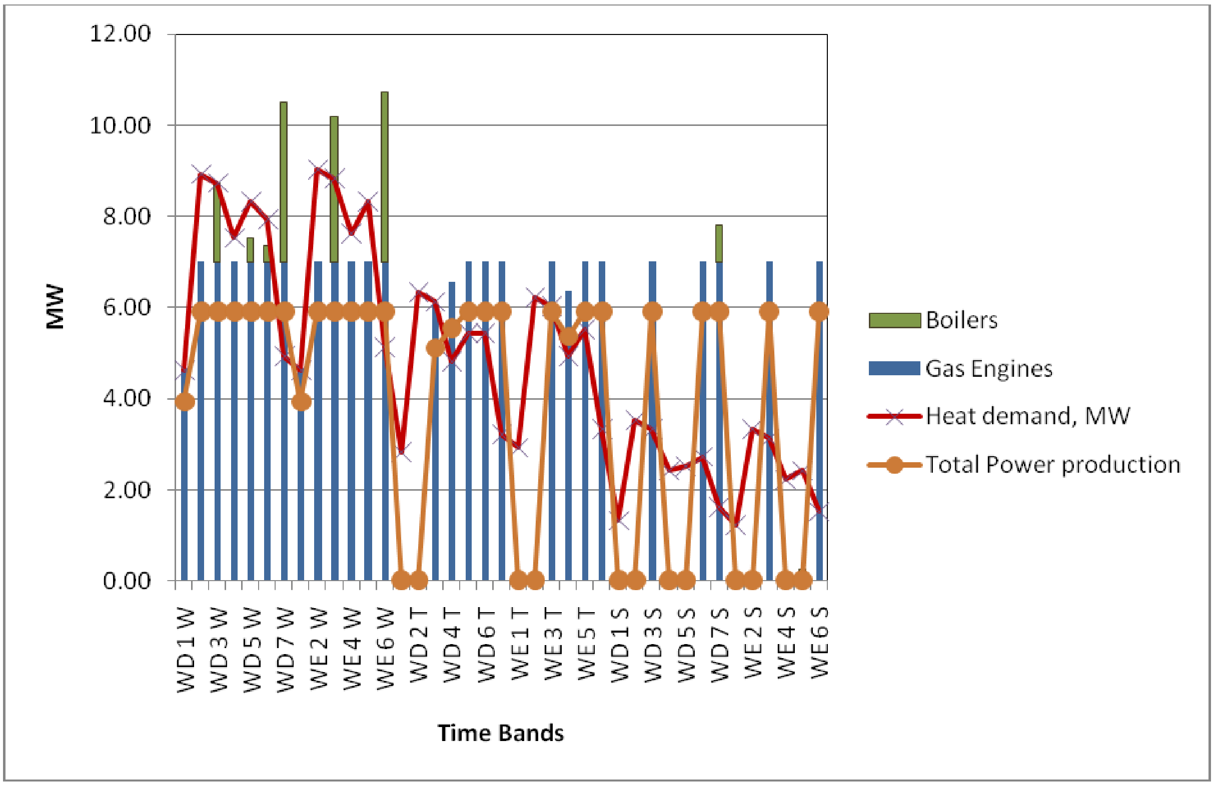

Figure C.14 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 535 (Class 14)

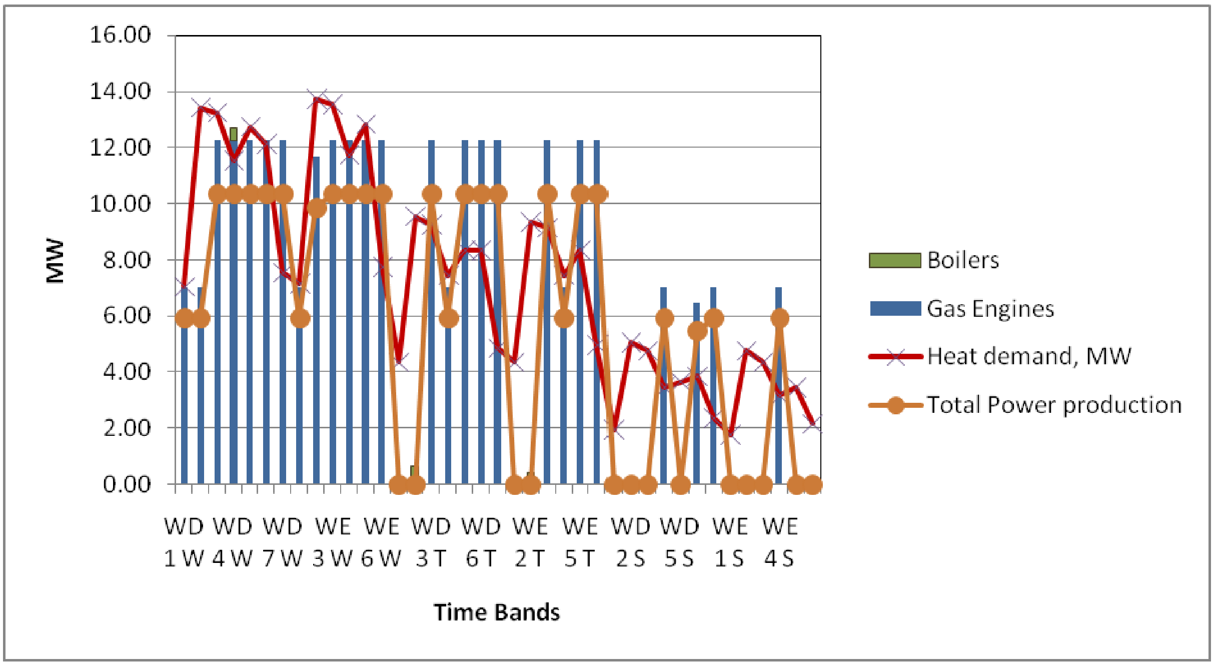

Figure C.15 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 734 (Class 15)

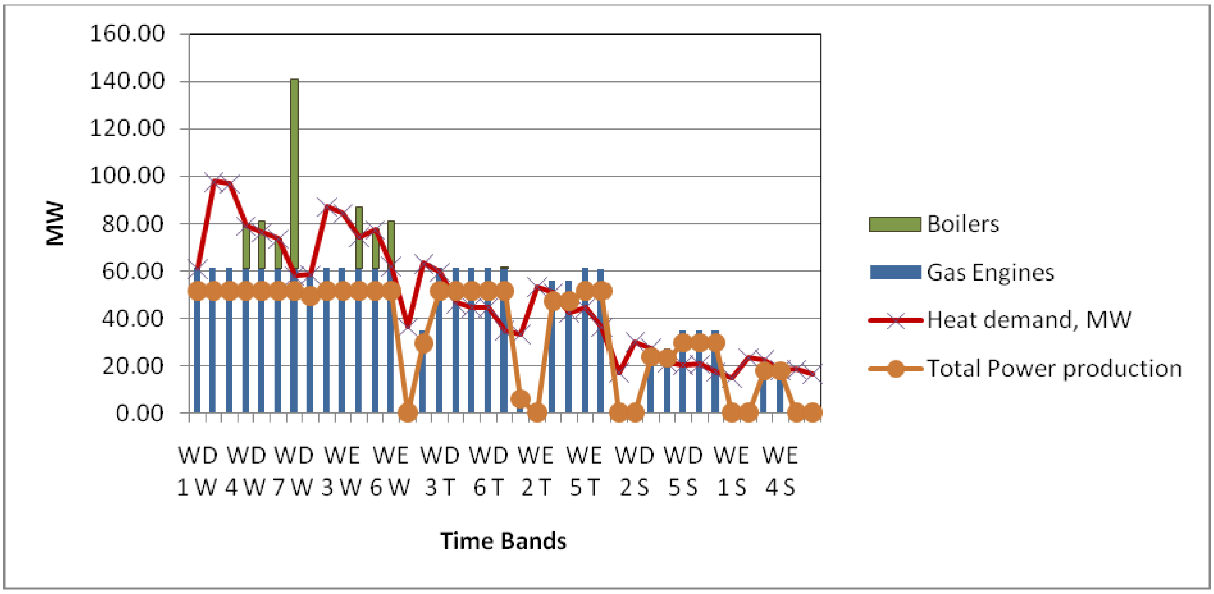

Figure C.16 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 148 (Class 16)

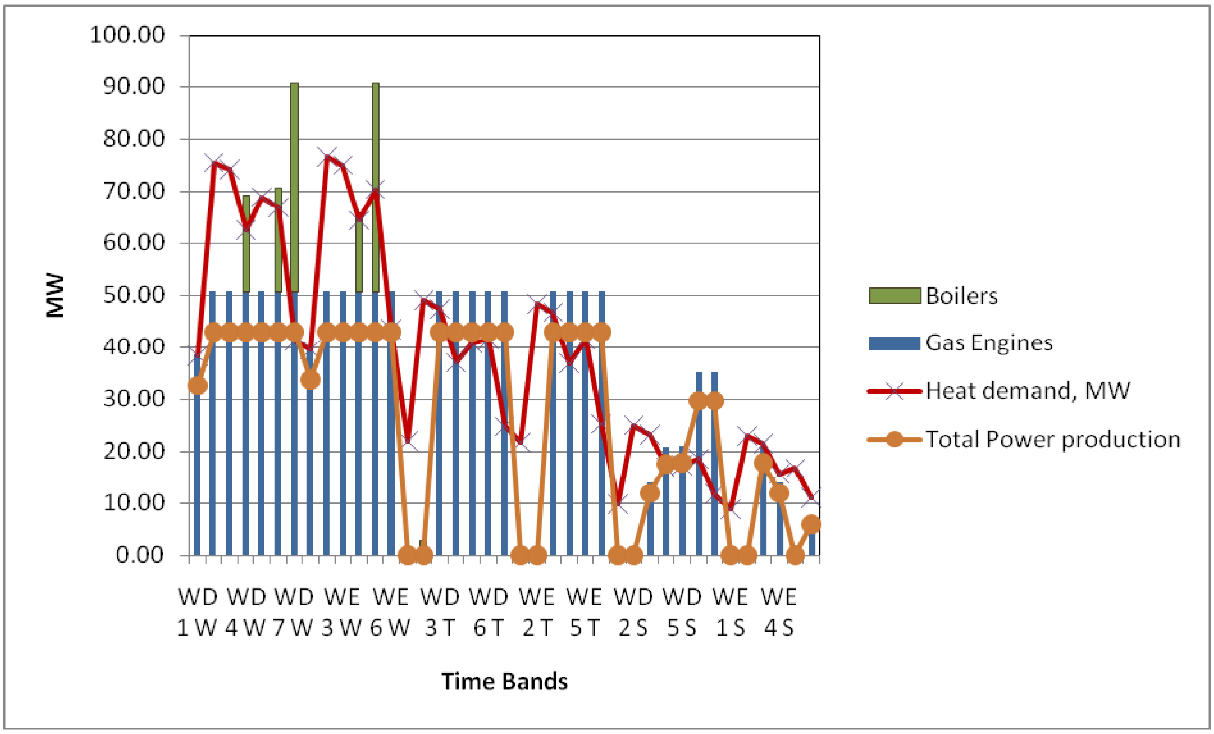

Figure C.17 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 23 (Class 17)

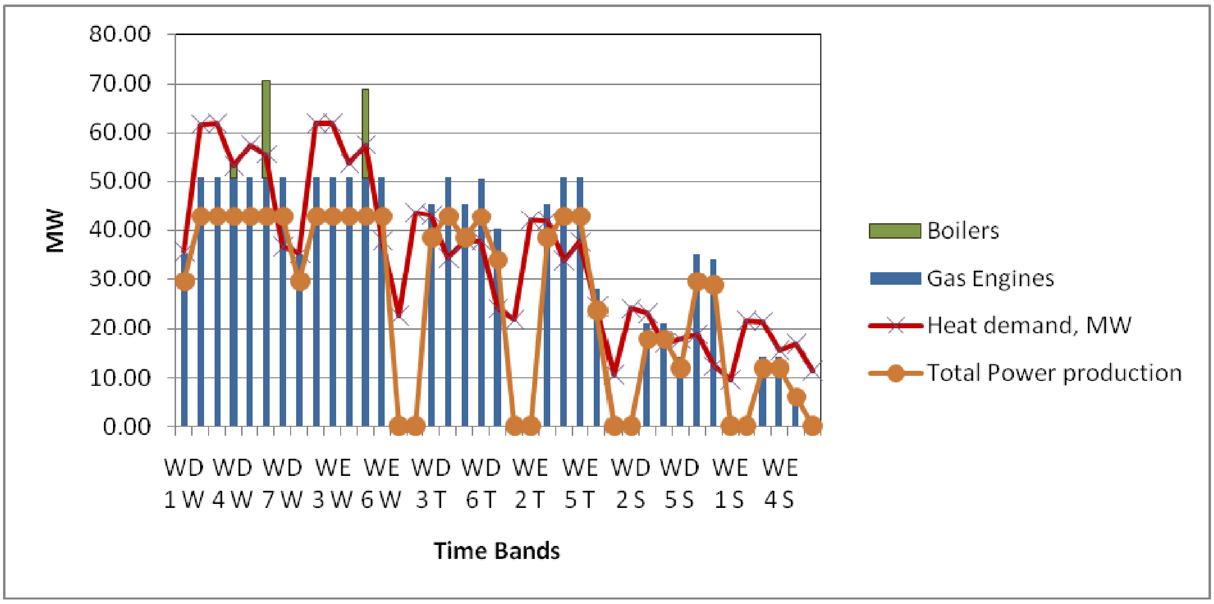

Figure C.18 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 547 (Class 18)

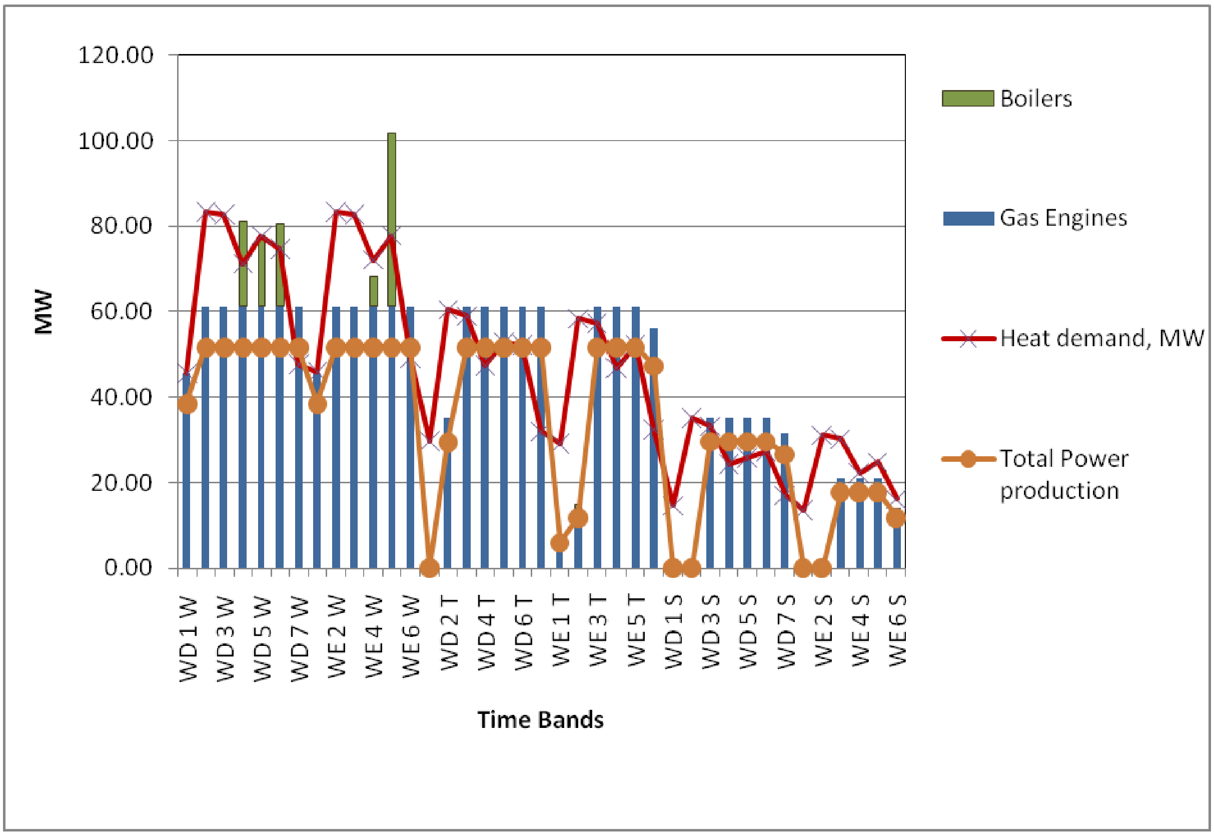

Figure C.19 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 701 (Class 19)

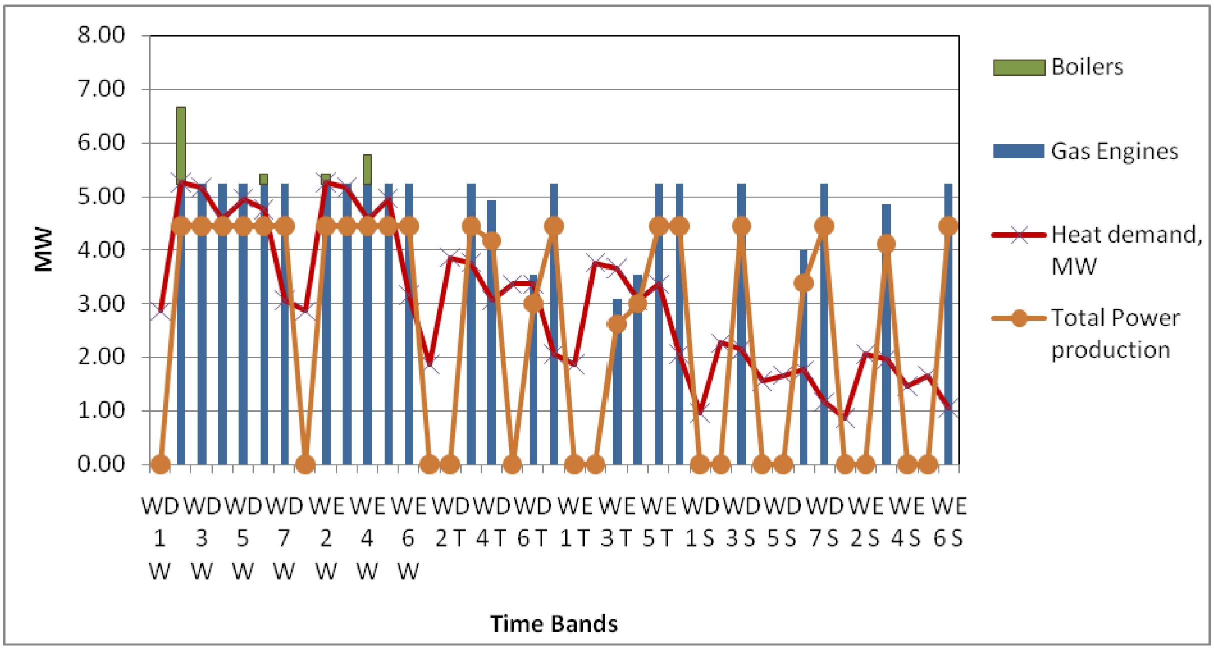

Figure C.20 Optimised energy centre design, showing DE systems and operating schedule by time band for CZ 909 (Class 20)

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1. Deliverable 4.1 Macro DE Project: Description of design methodology and tool effectiveness, February 2011
2. Deliverable 2.3 Macro DE Project: Energy Demand Analysis in GB, January 2012.
3. Macro DE Report, D.H. Construction Costs in the UK, Mooney Kelly Niras, March 2011
4. Macro DE Report, D.H. Construction Costs in the UK, Mooney Kelly Niras, March 2011. In line with typical temperature difference used in Denmark.
5. Woods et al., 2005, District Heating and Cooling Project – A comparison of distributed CHP/DH with large-scale CHP/DH, IEA Report 8DHC-05.01
6. DECC Interdepartmental Analysts Group (IAG) (www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/valuation/valuation.aspx)

   (DECC IAG variable element: industrial for 2010)

   Supply cost reflects long-term variable cost components of energy supply, and excludes costs that do not change with level of demand. The DECC IAG variable costs include costs of energy inputs; conversion, transmission and distribution costs, including costs of capital and operating expenditure associated with the supply network. The wholesale price of electricity (paid by the industrial sector) is applied; losses on the local distribution network are taken to be 5%. Most transmission costs (90%) are included, but only 10% of distribution costs are included as variable costs.

   Note that this electricity price is above that which is commercially available in the current market; however, it aims to represent the value of the electricity generated in terms of the national economy.
7. DECC Interdepartmental Analysts Group (IAG) (see reference 5)
8. Peters, M.; Timmerhaus, K.; West, R.; Plant Design and Economics for Chemical Engineers, McGraw Hill, 5th edition, 2003.
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