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A review of methodologies analysing electricity and heat production from Combined Heat and Power, CHP, and their signals to heat and electricity sectors.
Cross subsidy of electricity sector by heat sector.

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This paper is part of the output from an EU project Ecostiler analysing how heat normally rejected to the environment in electricity generation, can decarbonise urban domestic dwellings in city areas in the UK, by retrofitting them with low temperature heat networks as practiced in Denmark.
Waste heat from electricity generation is a very large low grade energy resource; it exceeds the total supply of gas to the UK domestic sector. The Danes upgrade this heat with CHP fired by fossil, biomass and waste. Other heat comes from solar thermal, geothermal and heat pumps.
The paper explains the need for a new "EU Heat Network Directive" to replace the mixed signals and differing formulas for this sector. The formula for CHP in the European Emissions Trading Scheme signals, that by using waste heat from any power plant to grow tomatoes, one reduces the emissions for its electricity. This formula contravenes the second law of thermodynamics.

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Abstract and Overview

Our EU funded Ecostiler project evaluates a low temperature, low CO_2, heat network option to decarbonize UK urban dwellings. We examine common modelling assumptions and methods to analyze the joint heat and power products from Combined Heat and Power "CHP".

We show how EUETS, the EU Cogeneration Directive, DUKES, CHPQA, and the EU "Carnot method for renewable CHP" all signal reductions in fuel and primary energy for incremental electricity generation, contravening the second law of thermodynamics which requires heat rejection as part of the thermal power generation process. This reject heat exceeds UK domestic gas supply in quantity though not in quality and exergy.

CHP, a "Virtual heat pump" (ref [i] & ref [ii]) , can in practice decarbonize dwellings heated by gas retrofitted as at Odense in Denmark to the coal fired CHP and district heat where ten units of waste heat are upgraded using one unit of electricity. The ten is directly comparable to coefficients of performance for air source electric heat pumps of two to four driven by the plants electricity.

We suggest CHP can be modelled simply, using this "COP" or Z factor, to generate fuel use, CO_2 overhead and marginal cost of heat to optimize CHP and heat networks in models such as Markal/Times. Sofia Simoes at JRC Petten simplified this concept by suggesting that waste heat be treated as a potential low grade energy source in models. We explore Exergy methods for CHP.

We further propose Modular Energy Hubs incorporating 500 kW-2000kW CHP, heat pumps, fuel and heat stores, with battery storage and exchange for Electric Vehicles. The Hubs optimize intermittent renewable electricity from wind and solar PV, minimizing electrical infrastructure investment for 2050. Large scale solar thermal feeds the 75C flow 30C return heat networks.

Methods

Analysis was carried out with spreadsheets. Thermodynamic analysis also for power plants heat networks and retrofitting options for UK domestic housing stock.

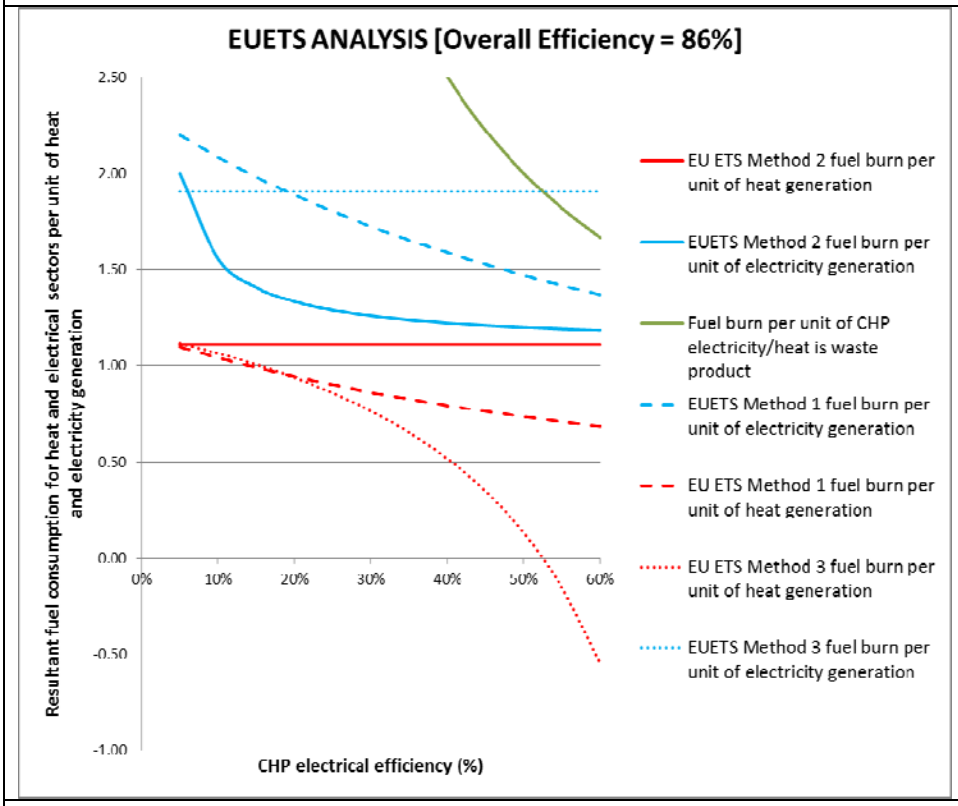
Results

Figure 1 Analyses the impact of three alternative methods considered for Emissions Trading EUETS Ref [iii] .

Method 2 is currently adopted by EUETS. For heat consumers it signals the fuel burn in a boiler as their emissions, reflected by the solid horizontal red line. For the electricity consumers it signals significant reductions in fuel use per unit of electricity shown by the difference between the green line, the actual fuel burn per unit of electricity, and the EUETS solid blue line. The result is inconsistent with a marginal economic analysis for joint products under conditions, where there is marginal increase in electricity demand with no change in heat demand, it follows the green line.

Method three more closely reflects the "perfect market condition" ref [iv] where CHPs compete against each other, as well as electric heat pumps to meet changes in demand and summer domestic hot water loads.

Figure 1: Comparison of fuel consumption allocation to heat and electricity using EUETS methods



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Conclusions

1) EUETS may be suited to industrial sites where overall emissions are the target and how the savings from CHP are calculated may not matter. It is not fit for purpose for district heating from CHP or the formulation of policy for that option. We recommend a news district heat directive to specifically address heat networks and to stimulate heat and CO2 trading.
2) CHP is to be defined as "renewable" as electric heat pumps, as in practice it can generate higher CO_2 emissions than fossil CHP, where electricity for the heat pump is fossil-derived.
3) The 2004 EU directive ref v requires a 10% saving for electricity combined with heat. Given CHP only delivers heat sector savings, this should be revised to a 10% heat sector saving.
4) The EU renewable CHP "Carnot method" disadvantages Danish low temperature district heat. The arbitrary 150C assumption for CHP for district heat should be revised to use actual temperatures.
5) The EUETS, EU CHP Directive and Carnot methods should be integrated into a single consistent method.
6) The Hub concept should be reviewed to increase security of supply of heat gas and electricity infrastructures, and its emergency liquid fuel stores.

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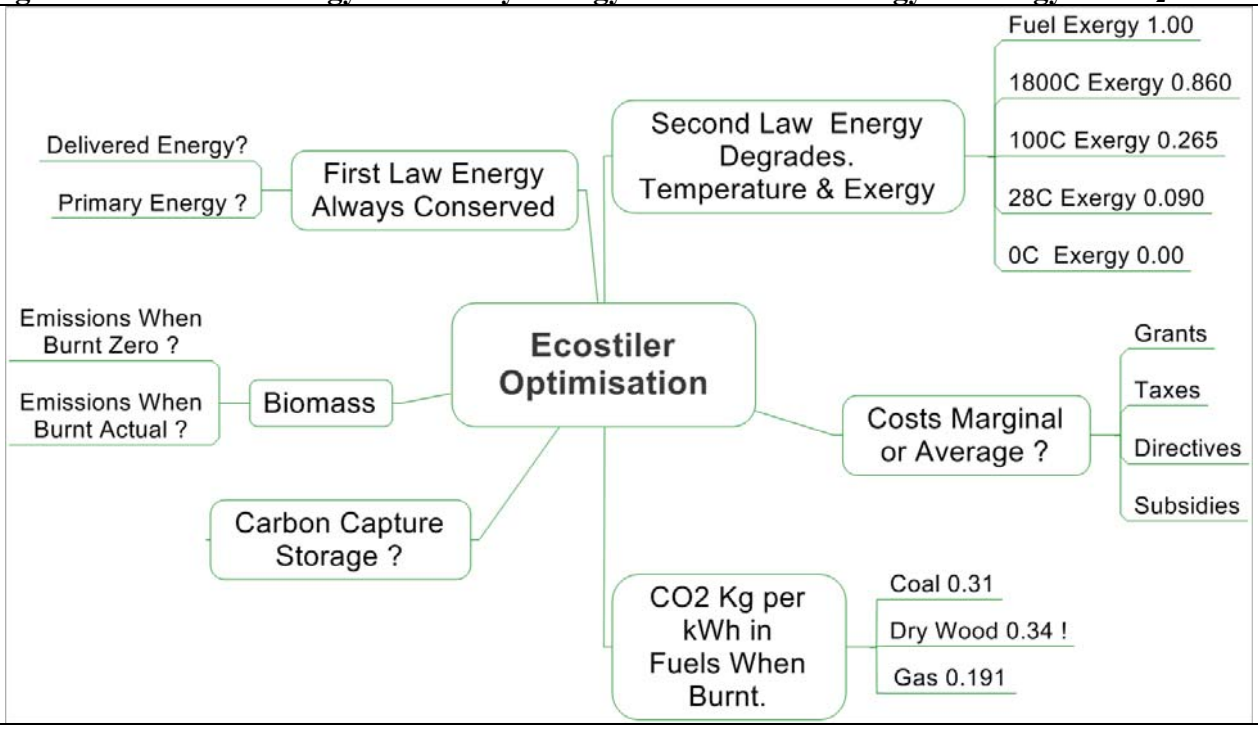
2. Objectives for energy economists. Have they changed? How might EU policies change?

Figure 2: Delivered Energy to Primary Energy to Renewable Energy to Exergy to CO_2?



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When we started the Ecostiler project seven years ago, reporting was framed in delivered energy terms as the target and not CO_2 emissions per unit of energy.

Legislation and incentives over time change as the policy changes. Clearly in delivered energy terms the optimal passive house was all electric for its heating. In primary energy terms, gas boilers are better, or use of reject heat from CHP or electric heat pumps. The situation becomes more complex with biomass. EU policy signals low CO_2 emissions when burnt not the actual CO2 emitted in the combustion process. An error that results in poor use of this scarce resource as it reduces the impact of the efficiency of conversion. Accounting the emissions when the material is burnt then taking off the renewable carbon dioxide factor, is a better way to do it.

It analyses in some detail how the joint products of electricity and heat can be analysed. We recommend a "perfect market" approach. Competition between CHP plants for the respective heat and electricity markets and networks. The normal method for determining the marginal cost of the respective products is to evaluate how the cost for each product changes when one increases demand for one product when there is no change in demand for the other product.

Energy economists who drive motor vehicles can test this principle for themselves. Checking the effect on the fuel consumption for powering their journey when their car heater on and when it is off. They will find it makes no difference to the fuel use for the journey as the heat has to be rejected through the car's heater then to the environment or directly to the environment from exhaust and radiator.

The marginal cost of this heat is zero. Its value however depends on the cost of the alternative means to achieve the same objective.

Some economists reason they have to allocate some fuel to the heat when it is used to reflect the value signal, for the reason there is an economic benefit that has to be valued in some way.

We reason that this "value" thinking, which usually assumes a particular alternative source of heat, is not appropriate in policy models for district heating and heat networks where, whilst a boiler or an electric heat pump or some other source of heat may well be displaced when the heat reaches the consumer, the economic case for the heat supply depends on the cost and CO_2 overhead for the heat.

We set out in this paper a simple methodology consistent with the analysis of electric heat pumps that use power to upgrade heat and large scale CHP (virtual electric heat pump). The method simply accounts for the amount of electricity or power utilized to upgrade heat to a useful temperature and is the equivalent of the z factor used to determine the fuel use per unit of heat for large scale CHP and the Coefficient of Performance for heat pumps.

3. Second Law of Thermodynamics - the key to optimising useful energy and exergy from heat pumps and CHP.

The fundamental Thermodynamics Law for the analysis of CHP is the Second Law of Thermodynamics. This is the law that governs production of power from heat, CHP and heat from power heat pumps.

The first law, which dictates that energy is always conserved, cannot give correct signals, as it does not differentiate between different forms of energy and their "value" in thermodynamic terms, which in perfect market conditions should convert into "economic value".

The first law does not signal the quality of different forms of energy. It treats a unit of electrical energy as identical to a unit of chemical energy and a unit of heat energy.

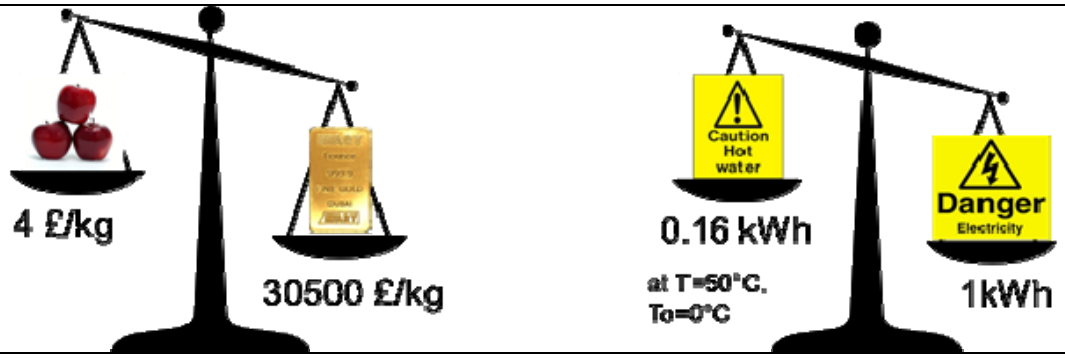
Exergy, a concept arising from the Second Law and the Carnot Cycle, is a way to value energy as a function of its usefulness to produce power from heat. To grasp the scale electricity has exergy value of one. Heat at the temperature of the environment has an exergy value of zero.

Dr Audrius Bagdanavicius CSci MEI, a Research Fellow at the Institute of Energy of the Cardiff School of Engineering, has captured the concepts in Figure 2 and Figure 3.

Figure 3: First Law Energy Analysis

Source: Dr Audrius Bagdanavicius, Institute of Energy of the Cardiff School of Engineering

Figure 4: Second Law Exergy analysis for water at 50C with reference Carnot temperature zero C



Source: Dr Audrius Bagdanavicius, Institute of Energy of the Cardiff School of Engineering

To indicate the scale of such heat rejection, for the UK, this heat measured in First Law terms is greater than the energy available in our total supply of gas to the domestic sector. In exergy terms this is a valuable source of heat, where its temperature is greater than that of the environment and it can be used for horticulture. It is also a more valuable source of heat at 28-32C for upgrading either with electric heat pumps or with CHP, a virtual heat pump, for space and domestic water heating for cities than electric heat pumps accessing heat in the environment at lower temperatures, typically 8-12C (depending on depth of source) for ground source heat pumps and down to minus 10C for air source heat pumps under the cold conditions that affect their performance.

4. Electricity networks - the reason why their primary energy and exergy loss is greater than heat networks.

Network loss information is essential to evaluate network effects when optimizing the benefits of the integration of heat and electricity networks to serve consumers, with their fundamental requirements of high grade exergy in the form of electricity and low grade exergy in a form suitable for space and domestic hot water heating.

Readers should be aware that the characteristics for heat and electricity networks are very different. This in turn affects investment in capacity to meet peak loads and its optimal location.
For electricity networks, losses rise as a square law function of electrical power (e.g. twice the power gives four times the loss). This results in marginal losses to meet peak demand being significantly higher than average losses with impacts on capacity of generation and its location.

Losses from heat networks remain relatively constant, independent of load, as a function of distance and the surface temperature of the insulated pipes. Therefore average losses are high and marginal losses tend to zero.

Heat and electricity networks also have different impacts on tariff signals to consumers. The tariff signals for heat losses are thus lowest per unit of heat delivered on the coldest days, whereas for electricity networks they are at their highest exceeding 20%. The tariff signals for heat compared to electricity are further benefitted by the factors of: low fuel use for heat supply from CHP (e.g. 0.28 units of fuel per unit of heat); the higher two to three units of fuel use per unit of electricity fuel loss

and also the fact that CO_2 overheads for energy from heat networks tends to be significantly lower than for electricity networks, particularly in winter.

For exergy a heat loss of 10% for heat at 100C amounts to 0.0265 units of exergy. A 10% loss on an electrical network amounts to 0.1 units of exergy. This is a factor of four signal when optimizing exergy.

5. A review of different analytical approaches to the joint products, electricity and heat from CHP.

Some analysts view investment in CHP as only reducing fuel use and emissions for electricity production. Other analysts view investment in CHP as only reducing fuel use and emissions for heat production. Others produce arbitrary methods to allocate benefit to the respective products and to check the CHP delivers overall savings of fuel from its use compared to other supply options for heat and electricity supply to consumers.

Use of the EUETS method of allocation has led to poor investment decisions in CHP technologies, particularly through small scale CHP product development, as well as sub optimal dispatching of CHP plants with different electrical efficiencies feeding into a common heat network. In this case the methodology has indicated that the lowest fuel use for electricity was from low electrical efficiency CHP units, with the result that they were dispatched first. However when analysed for least cost heat they should have been dispatched last.

The Orchard CHP convention was developed for energy policy work for Lithuania when this problem was recognised by the team. The problem was also found in models evaluating district heat for Lithuania. A tool for modeling and evaluation of CHP as well as heat and electricity network investments has been developed, which we describe in this paper. It signals a fuel use per unit of heat when one CHP feeding a heat network competes with another CHP for the same market. Its methods reflect the fundamental laws of thermodynamics and the nature of the waste product, heat. It also accords with results from a marginal fuel burn analysis for the respective heat and electrical products.

Contenders for capital investment to decarbonize the large UK domestic sector at the dwelling level are: insulation, solar thermal, domestic electric heat pumps and domestic CHP at dwelling level. Low CO_2 heat supply from heat networks at community and city scale using the Danish model, fed by large scale solar thermal, electric heat pumps, biomass boilers or biomass/fossil/nuclear CHP is currently attracting much more interest in recent publications with discussion now focusing more on the *extent* of economic district heat, rather than just whether it should be installed in the first place.

Recognition of the potential to fit carbon capture and storage (CCS) to large scale CHP feeding cities, offers a prospect of negative CO_2 emissions where the fuel is biomass, maximizing the fuel's value through conversion to high exergy value electricity and low exergy value, but useful, heat.

A Danish practice of using directly connected low temperature heat networks, with pressure control between high pressure transmission and low pressure distribution instead of heat exchangers, is optimal thermodynamically. At Odense (population 175,000) in Denmark, the treated heating water in consumers' radiators is the same as the water in the district heating condensers at the large power plant.

Heat exchangers require higher temperature heat from CHP and higher heat loss from piping systems. If heating return water temperatures are higher than 50C boilers will not condense.

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Optimal solutions from the Ecostiler Project work will be for both the bulk transmissions system and the local lower pressure distribution system to run at low temperature 70C flow/30C return for the majority of the year. Under peak load conditions on the coldest days the local network is to be raised to 90C, as practised in Odense Denmark. This district heat proposal for London from the Ecostiler project work is illustrated in a graphic in Appendix C.

In Finland and other countries, high temperature systems with a flow temperature of 110C- 120C installed with heat exchange are used.

A District Heating Manual has been prepared for the Greater London Authority by Arup (released in February 2013). This manual proposes heat networks that have a maximum temperature of 140C and operating temperatures of 110C flow 55C return. The author's view is that these design temperatures are too high for a district heating system fit for 2050, where sources of heat for the network may well be electric heat pumps, and solar thermal as well as nuclear CHP, should nuclear electricity generation prove to be economic.

The 55C design for return water is too high for condensing operation of boilers and is above return temperatures being achieved for the city of Odense of around 40C, where the design for the old heat network is 95C flow / 45C return and new areas are connected at lower flow and return temperatures. The following sections explain the link between temperature of heat supply and CO_2 displacement with CHP and the reasoning why lower temperature heat networks are preferable. Our Ecostiler conference on the 30th of May 2013 was chaired by Peter North of the Greater London Authority and our Ecostiler findings were reviewed and discussed with leading expert practitioners.

6. A perfect market approach to competition between electricity only generation servicing heat and electricity networks. The Orchard convention.

The high value primary product, electricity dictates market trading. We thus simply evaluates the situation where the fuel use per unit of electricity is higher than the fuel use for electricity from a competing plant how much fuel needs to be allocated to any useful waste heat to equalize the fuel use per unit of electricity.

We reason all thermal power generation is CHP, due to the fundamental second law requirement to reject heat to the environment. We model the heat normally rejected from cooling towers as a potential heat source, either for direct use in horticulture or as a source for upgrading by either "virtual" heat pump CHP or electric heat pumps, as this higher temperature heat is a superior heat source to heat at minus 10C in winter (which air source heat pumps would need to ordinarily need to use).

The Orchard CHP convention determines the fuel use per unit of heat and electricity when CHP plants compete against each other for the respective markets feeding into a common heat network and a common electricity network.

The convention simplifies modelling and comparisons between heat from CHP and heat from electric heat pumps by representing the performance of the systems in the same terms - their coefficient of performance (COP) is a measure of useful units of heat produced per unit of electricity sacrificed.

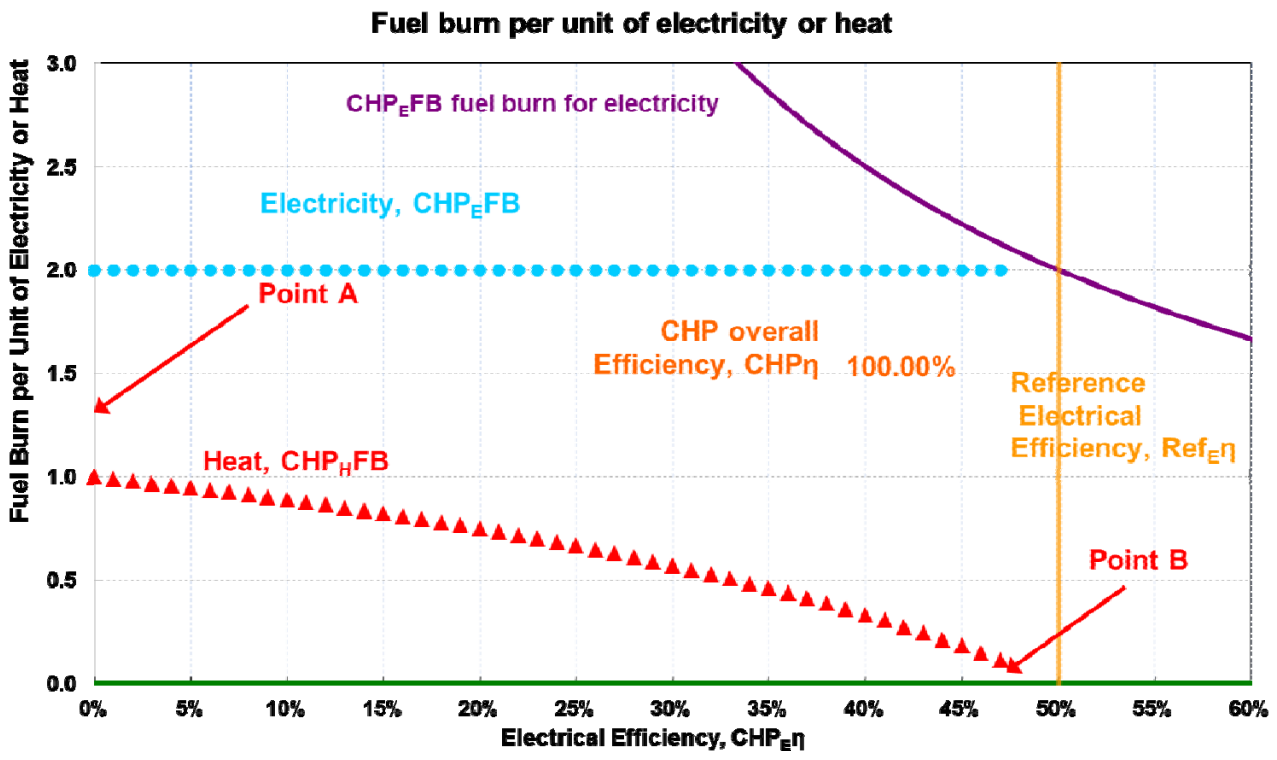
Figure 5 illustrates this principle graphically. It assumes all the energy in the fuel is available to convert to electricity and heat.

The purple curve signals the fuel use for electricity production for electricity generation, read on the vertical axis, for power plants with electrical efficiencies ranging from 0% to 60%, shown on the horizontal axis.

The purple curve rises exponentially to an infinite use of fuel per unit of electricity as the electrical efficiency approaches zero. The purple curve reflects the fuel required per unit of electricity when the demand for electricity increases, with no change in market demand for heat.

The yellow vertical line, RefEn for a 50% efficient electricity generator, reflects the perfect market competitor to other generators. Where the yellow vertical line crosses the purple curve shows the amount of fuel per unit of electricity, 1/50% - two units of fuel per unit of electricity.

Figure 5: Orchard CHP Convention. Fuel for additional units of electricity and fuel required per unit of heat for competition with reference electricity generator, 2012



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The blue horizontal dotted line shows two units of fuel per unit of electricity as the target fuel per unit of electricity from competing CHP plants.

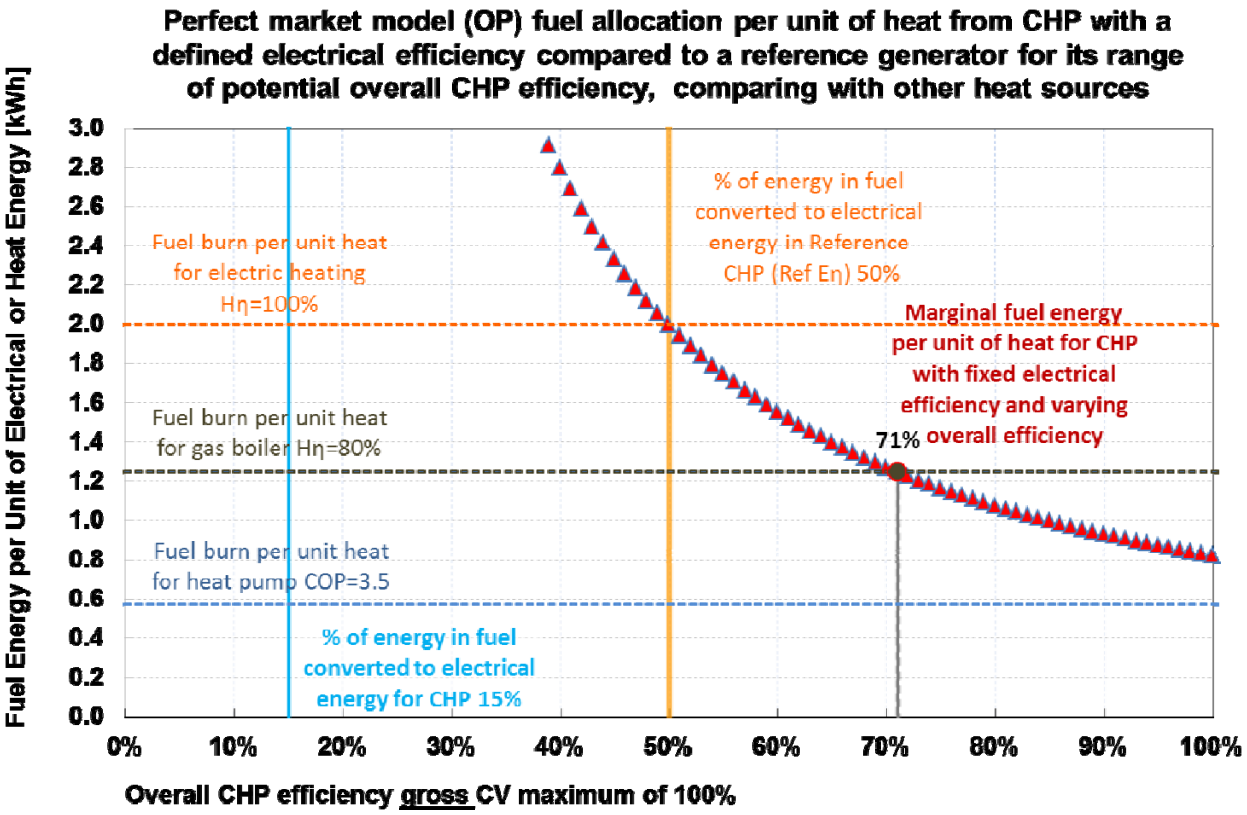
The red curve of triangles simply represents the amount of fuel one needs to allocate to the reject heat so that the lower electrical efficiency CHP delivers electricity for the same fuel burn per unit of electricity as the reference CHP. When no electricity is required and the conversion per unit of fuel is 100%, then the red curve signals one unit of fuel per unit of heat. Equally at the other end of the red curve, where heat is being rejected at a temperature optimal for electricity only generation by the reference CHP, there is no change in fuel use per unit of electricity with an increase in demand for heat and so there is no fuel use per unit of heat. Examples of this are where heat normally rejected to the environment from large scale CHP is used for horticulture e.g. heat from Drax B at one stage was used for tomato growing.

The chart and the fuel per unit of heat shown are based on all the fuel being converted to useful products.

In practice there are limitations on the useful amount of heat, as not all the energy in the fuel rejected as heat can be recovered. This is reflected by the overall efficiency of the CHP in converting fuel to electricity and heat, which in practice will be in the range of 75- 86%, based on the gross calorific value (GCV) of the fuel. A further factor is the actual amount of heat required by the heat market.

Figure 6 illustrates this situation where a small gas CHP plant has been selected with a 15% electrical efficiency to compete with a 50% efficient CCGT.

Figure 6: Orchard CHP Convention low electrical efficiency CHP compared to CCGT Impact of heat utilised reflected for varying overall efficiency for electricity and heat (fuel energy per unit output energy)



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The vertical (y) axis reflects fuel per unit of heat and fuel per unit of electricity. To provide a reference to other heating options, fuel use per unit of heat is also shown for: 1) Gas boiler (black dotted line); 2) Electric heat pump with a COP of 3.5 (blue dotted line); 3) Direct electric heating (yellow dotted line). Electric heating and heat pump source 50% efficient CCGT.

The red curve plots the fuel use per unit of heat for the 15% electrically efficient CHP competing with the CCGT as a function of the amount of the available heat utilized, reflected by the overall

efficiency on the horizontal axis. The maximum amount of heat available in practice, the difference between the electrical efficiency of the CHP and its overall efficiency is likely to fall within a range dictated by the overall efficiency (typically 70% to 86%).

The curve shows that, for an overall efficiency of less than 71%, a CHP plant with electrical efficiency of 15% has a higher fuel burn per unit of heat supplied than a boiler with an efficiency of 80%. Old boilers typically have an efficiency of 75% and new condensing boilers have efficiency nearer to 86%.

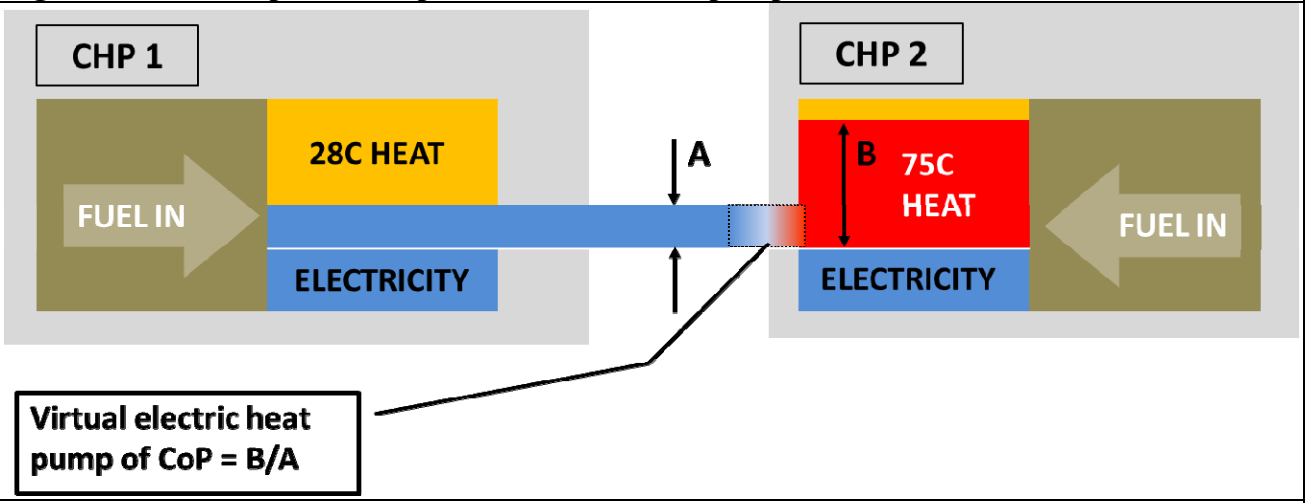
For more information on the Orchard CHP Convention see the paper to the British Institute of Energy Economists (WRH Orchard 1998).

7. CHP a "Virtual heat pump" how Coefficient of Performance compares CO2 overhead for heat from CHP and heat pumps.

In this paper we refer to the Coefficient of Performance (or COP) for heat from CHP. This is a measure of the number of units of useful heat from the CHP consumed per unit of electricity to upgrade heat to a useful temperature. This COP is identical to methods used for the evaluation of the performance of electric heat pumps. Identification of CHP as a "virtual" electric heat pump can be found in work by Professor Robert Lowe (2010) of the University College London, Professor David Mackay, Government Chief Scientist (2012), and WRH Orchard (2010).

A power station in CHP mode may be considered to operate as a virtual heat pump for which the coefficient of performance may be defined as the ratio between the marginal useful heat supplied (compared to the electricity generation only mode) and the sacrifice in electricity output (compared to the electricity generation only mode). The same principle may be applied when comparing different CHP plants, as is illustrated in Figure 7 below.

Figure 7: CHP plants compared as virtual heat pumps



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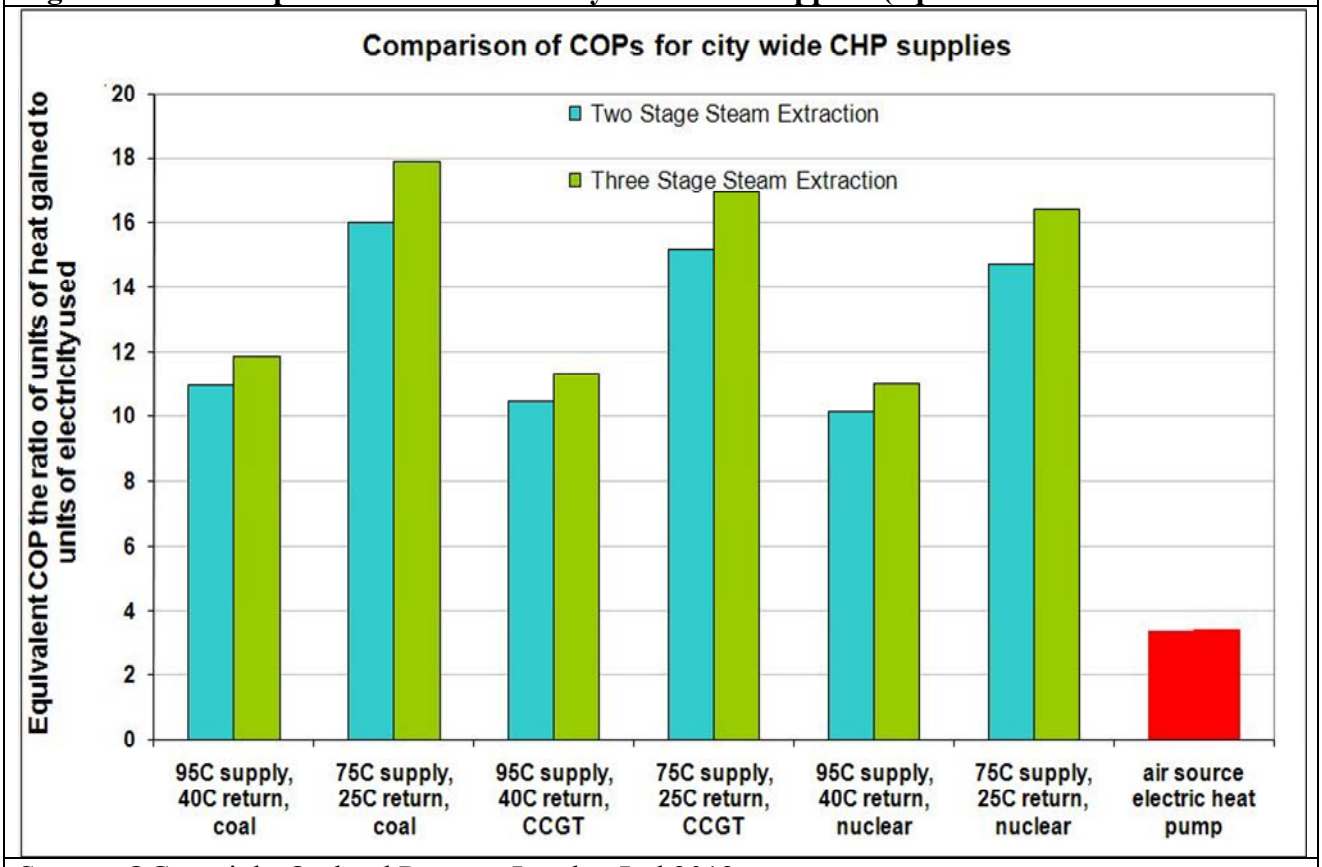
Distributed peak load plant generation may well be the least cost way to provide back-up for intermittent renewable sources such as wind, to meet peak demands for heat and electricity during the coldest periods of the year, as well as to reduce investment in electrical networks to meet increases in demand for electricity for electric cars and electric heat pumps. The hub concept formulated in response to this during the Ecostiler optimisation work is illustrated in Appendix C.

A further factor in favour of such solutions is the negligible contribution from renewable generation, such as wind coupled with reduced output from solar PV, due to shorter and weaker daylight periods, to meet annual coldest days and the one in twenty year cold snap that infrastructure may need to meet.

8. Heat network flow and return temperature. COP of heat from CHP and stages of heat extraction from steam turbine. Air source heat pump COP.

Figure 8: Comparison of COPs for city-wide CHP supplies (equivalent COP



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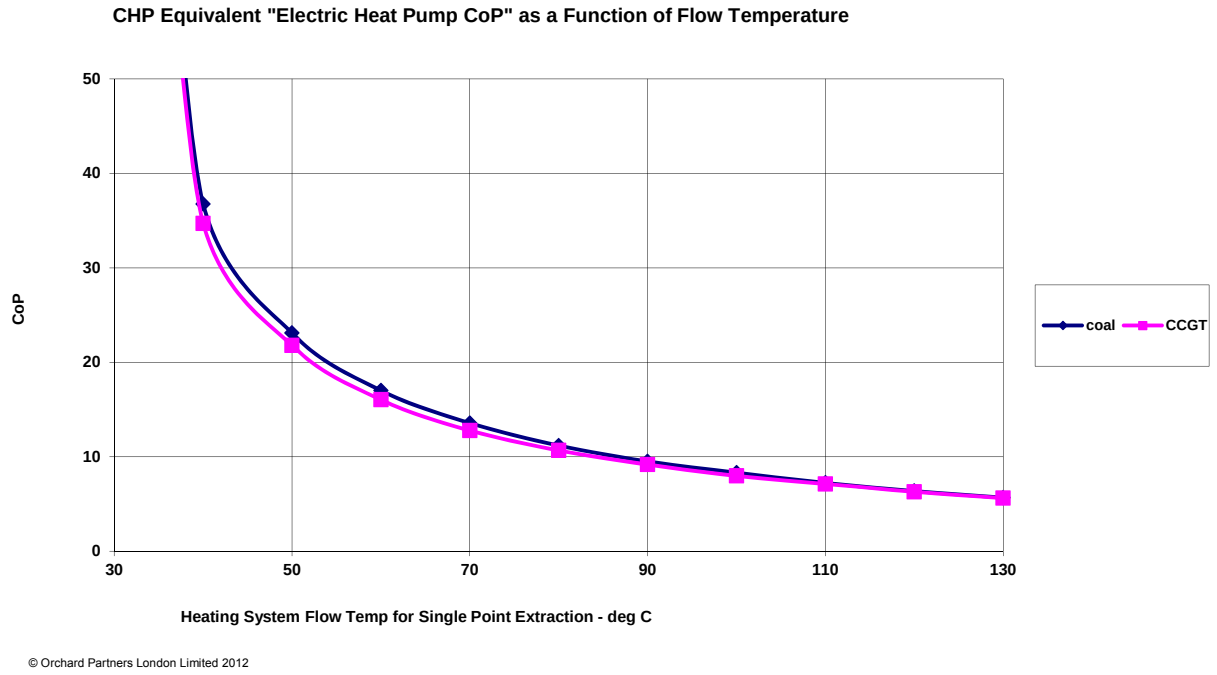
The influence of the operating temperature for heat networks on the decarbonising effect of the networks is illustrated in Figure 8.

The variation of the COP for upgrading heat rejected from steam turbines at 32C as a function of the heating flow temperature to district heat is illustrated in Figure 9. Readers should note that using a district heating using flow temperature of 120C from the large CHP plants common in Finland and also in EU countries delivers a COP of around 6 for the heat, using a single stage of extraction for the steam.

The same steam turbine supplying heat too much of UK's existing housing at a base load flow temperature of 75, adequate to meet domestic hot water and heating loads, offers a COP of over 12. Therefore by reducing the flow temperature, the CO_2 and fuel savings from CHP with district heating are doubled. The trend for district heat is thus to lower flow and return temperature systems, as practised in Denmark as a result of this effect. Other factors also favour lower temperatures, such as a much longer lifetime for pre-insulated steel underground pipelines to over 100 years, as well as the use of lower cost flexible plastic piping solutions.

Figure 9: CHP Equivalent "electric heat pump COP" as a function of flow temperature for heat in heat networks (COP)



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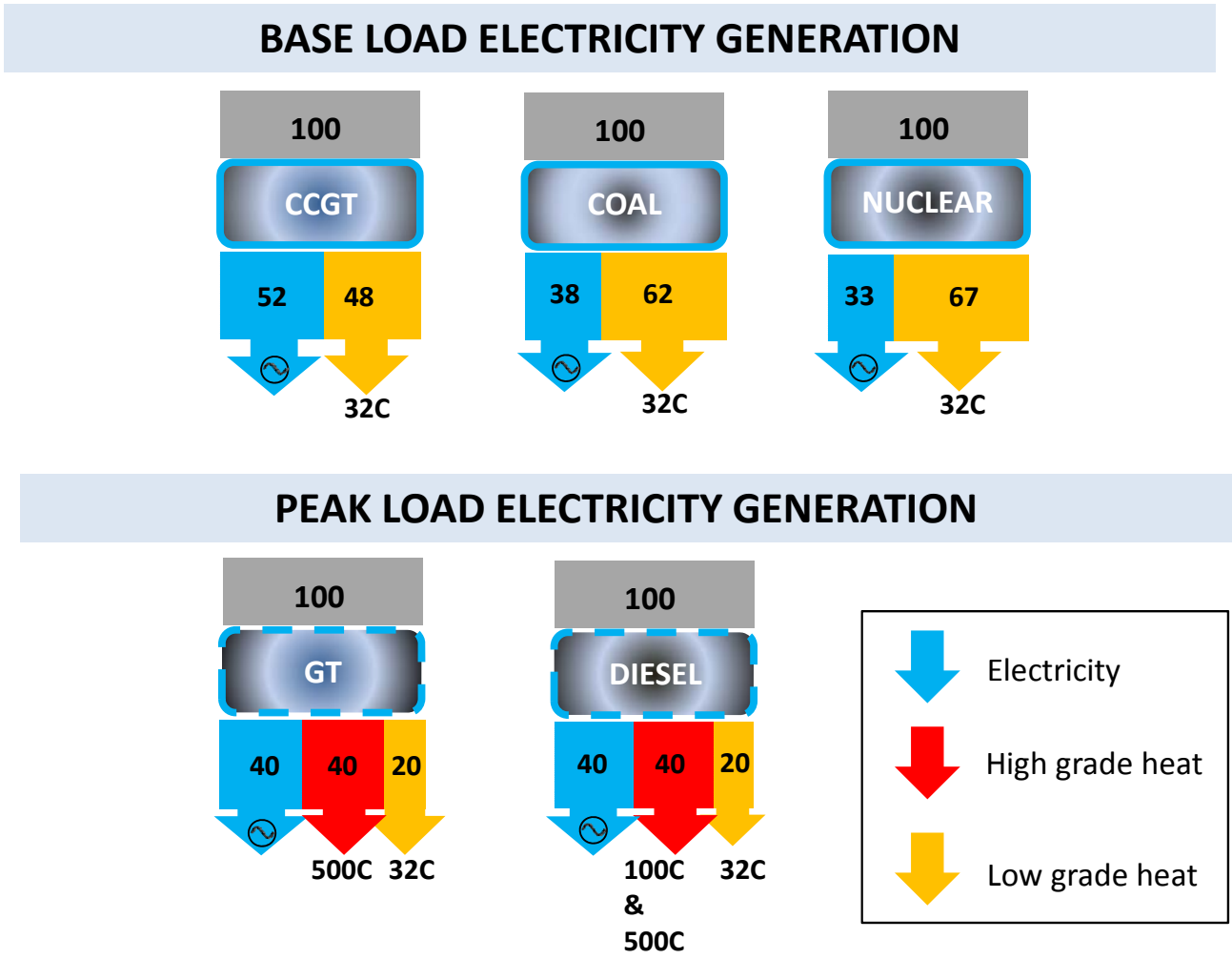
In Figure 10 common steam turbine plant of different types is compared for base load electricity generation with peak load plant. These systems reject high grade heat suitable for immediate use for meeting space heating and domestic hot water loads. When integrated into an optimised heat and electricity network they effectively deliver heat with no incremental fuel burn at times of peak demand on the coldest days. Under these conditions the COP of the heat is infinite.

Figure 10: Comparison of heat and electricity products from steam turbine base load low grade heat suitable for upgrading and peak load power plants with heat ready to use, 2012



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However when a gas turbine (GT) of 40% electrical efficiency competes with a base load CCGT of 52% electrical efficiency, fuel use has to be allocated to their heat production so that their electrical output can compete with large scale base load generators.

This situation is the equivalent of the virtual heat pump effect found in large CHP steam turbines, which operate such that at one time they can generate electricity only rejecting heat at 32C and can then move to conditions where they generate less electricity but pass out the steam for condensation in the district heating condensers at a higher temperature, such as 75C.

9. Electric heat pump COP discussion and trial results in UK.

A series of trials on heat pumps were carried out by the Energy Savings Trust (http://www.decc.gov.uk/assets/decc/11/meeting-energy-demand/microgeneration/5045-heat-pump-field-trials.pdf). The trials were disappointing compared to manufacturer's expectations. Installation and other technical issues were also identified during the trials. The average system performances reported on page 23 of the report indicated an average COP for the air source units of 1.82, with a range from 1.37 to 3.37 for both technologies (air source and ground source) for a range of different types of installation.

Further trials are being carried out and some improvement in results is anticipated from the technology. However the technology is not compatible with a simple retrofitting of an electric heat pump to replace boilers feeding the current stock of radiators in the majority of domestic sector installations. It is however compatible when utilising as a source the higher temperature heat from micro and large scale CHP heat supply from district heating.

10.Exergy - a way to value energy

The EU proposed a new "Carnot Efficiency" allocation method in its report entitled "Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling. SEC (2010) 65 SEC (2010) 66. It proposes to use "exergy" as a basis for allocation of emissions between electricity and heat in CHP.

Sample exergy factors for an EU assumption of a heat sink at 0C, 273 K absolute are shown below.

Chemical exergy in fuel one.	Exergy--1.000.
Electrical energy, exergy in electricity one.	Exergy--1.000.
Heat energy in a gas flame at 1800C, exergy 0.860.	Exergy--0.860.
Energy as 100C heat to a building exergy, 0.265.	Exergy--0.265
Energy as heat rejected in electricity generation at 28C, exergy 0.090.	Exergy--0.090.
Energy as heat at 0C and reference for EU exergy calculations, zero.	Exergy--0.000.

Table 1 – Sample exergy factors.

The allocation method which assumes a temperature of 150 C for heat for district heating does not reflect the low temperature renewable condensing CHP where return water temperatures of 30C and flow temperatures of 75C are practical. As a result it misallocates benefit to electricity.

A further factor in the method is the assumption of a base temperature of zero centigrade for heat rejection from electricity generation, which is impractical, as most power plants operate both in the summer and the winter, and have to reject heat at above the summer ambient temperature.

Further there are practical issues of condensing steam at such low temperatures, due to the very high steam volume. For these reasons we recommend that if an exergy method is to be used, the base temperature should be 30C, as in the following table.

Temperature of heat rejection C	Base temperature 0C	Base temperature 0C	Base temperature 30C	Base temperature 30C
	ECel Fuel per unit electricity	ECh Fuel per unit heat	ECel Fuel per unit electricity	ECh Fuel per unit heat
0.00	2.86	0.00		
20.00	2.60	0.18		
30.00	2.50	0.25	2.86	0.00
40.00	2.41	0.31	2.44	0.28
60.00	2.26	0.41	2.30	0.38
80.00	2.15	0.49	2.19	0.46
100.00	2.05	0.55	2.10	0.52
120.00	1.98	0.60	2.02	0.57

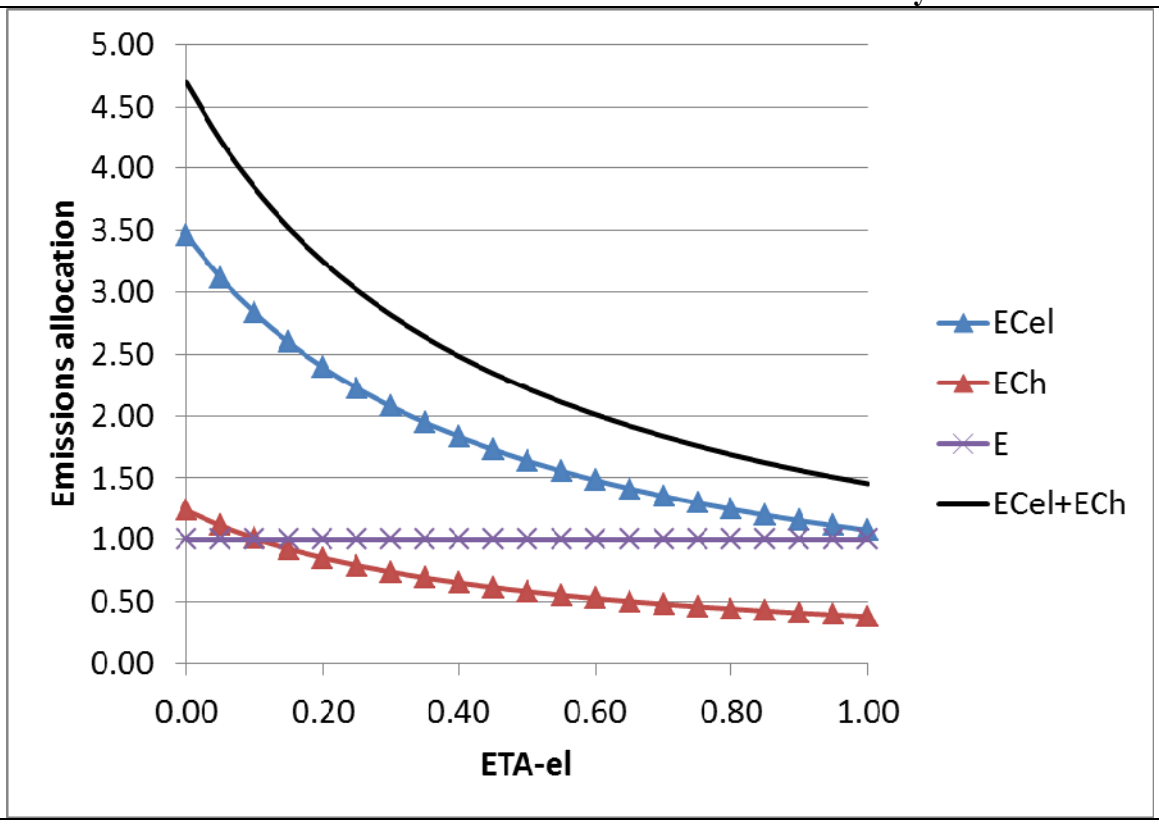
Temperature of heat rejection C	Base temperature 0C	Base temperature 0C	Base temperature 30C	Base temperature 30C
140.00	1.91	0.65	1.96	0.62
150.00	1.88	0.67	1.93	0.64
160.00	1.86	0.69	1.90	0.66

Table 2 – Greenhouse gas emissions for different base temperatures using EU allocation method

For allocation on an exergy basis we have applied the same principles for electric heat pumps to CHP to see the balance between the electricity sacrifice of exergy and the exergy gain for the heat from CHP.

The current EU formula as illustrated in the chart below (Figure 11) results in allocation of emissions in a way that the allocation does not equate to the actual total emissions from the CHP.

Figure 11 – EU variation in emissions allocation with electrical efficiency



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This is explained as follows:

Taking the exergy formula from "Report from the commission to the council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling":

$$EC_{el} = \frac{E}{\eta_{el}}\left(\frac{C_{el}\cdot\eta_{el}}{C_{el}\cdot\eta_{el} + C_h\cdot\eta_h}\right)$$

$$EC_h = \frac{E}{\eta_h}\left(\frac{C_h \cdot \eta_h}{C_{el} \cdot \eta_{el} + C_h \cdot \eta_h}\right)$$

$$\therefore EC_{el} + EC_h = \frac{E}{\eta_{el}}\left(\frac{C_{el} \cdot \eta_{el}}{C_{el} \cdot \eta_{el} + C_h \cdot \eta_h}\right) + \frac{E}{\eta_h}\left(\frac{C_h \cdot \eta_h}{C_{el} \cdot \eta_{el} + C_h \cdot \eta_h}\right)$$

$$= \frac{E(C_{el} + C_h)}{C_{el} \cdot \eta_{el} + C_h \cdot \eta_h}$$

The above expression has to be greater than the total emissions 'E', as since η_{el} and η_h are both less than one and therefore:

$$C_{el} \cdot \eta_{el} + C_h \cdot \eta_h < (C_{el} + C_h)$$

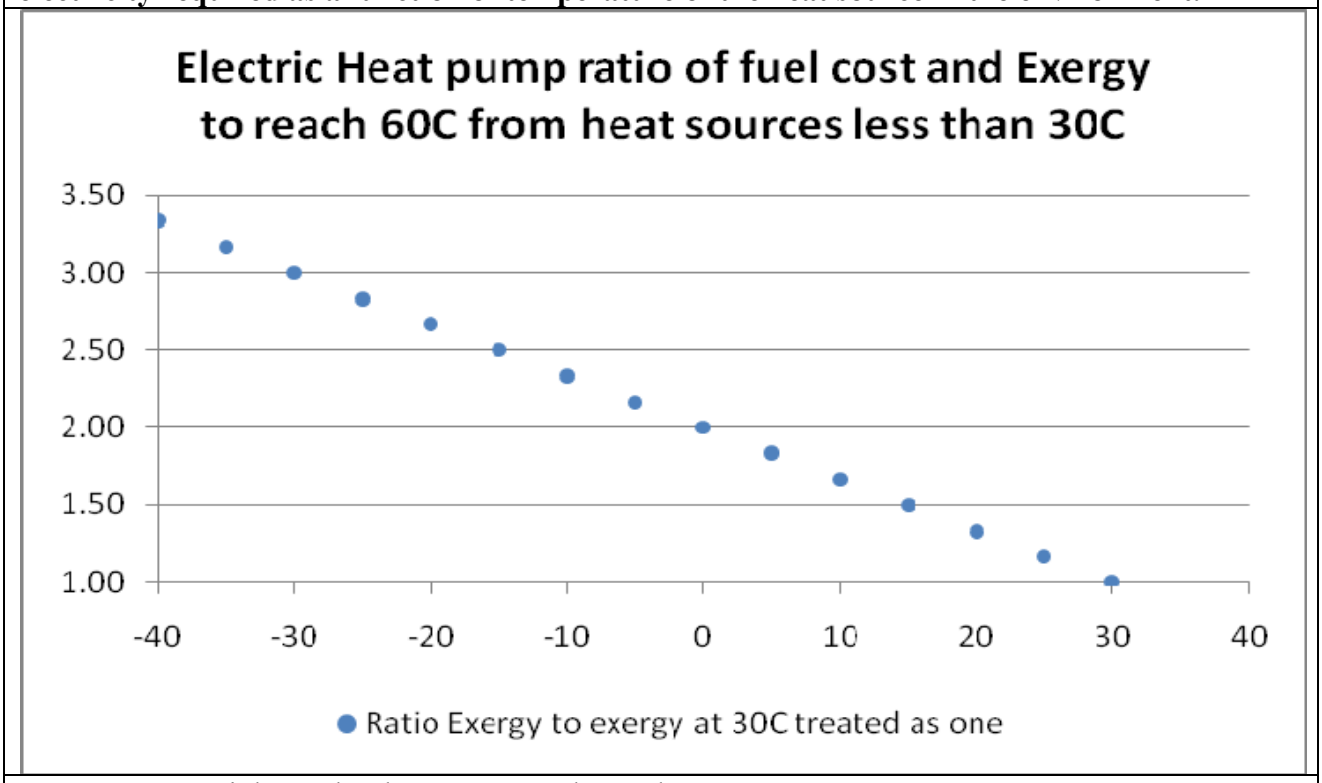
Therefore $EC_{el} + EC_h > E$. There appears to be an anomaly here, as the sum of the emissions allocation to the electricity and heat products should not be greater than the emissions associated with the fuel.

The following chart (Figure 12) uses exergy principles to evaluate the theoretical effect of the exergy required for an electric heat pump using heat sources at different temperatures to raise domestic hot water to 60C by comparing a waste heat source of 30C from electricity generation to air sources at lower temperatures.

The purpose here is to evaluate the difference in fuel requirement for a heat pump using reject heat from power generation as its heat source, compared to air or ground sources at temperatures down to minus 40C.

The chart in Figure 12 plots the relative exergy or electricity consumption to raise heat to 60C from lower temperature sources in the environment.

Figure 12 – Electric Heat pump heating domestic hot water to 60C. Exergy analysis of electricity required as a function of temperature of the heat source in the environment.



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This signals the benefit of using higher temperature sources of heat for heat pumps and the relative cost of reaching 60C with a source of heat at 30C (cost index one) and a source of heat at 0C (cost index 2).

Long term UK thermal electricity generation can be large scale CHP burning bio fuels or nuclear.

We have analysed a CHP plant to show the effect of exergy loss as a result of operating in CHP mode and heat exergy gain. What is interesting in this new work is the significant benefit from rejecting heat at low temperatures moving it from a waste to a useful product.

Figure 13 - Variation in heat and electricity exergy with flow temperature of district heating system supplied by CHP (for base temperature of 30C)

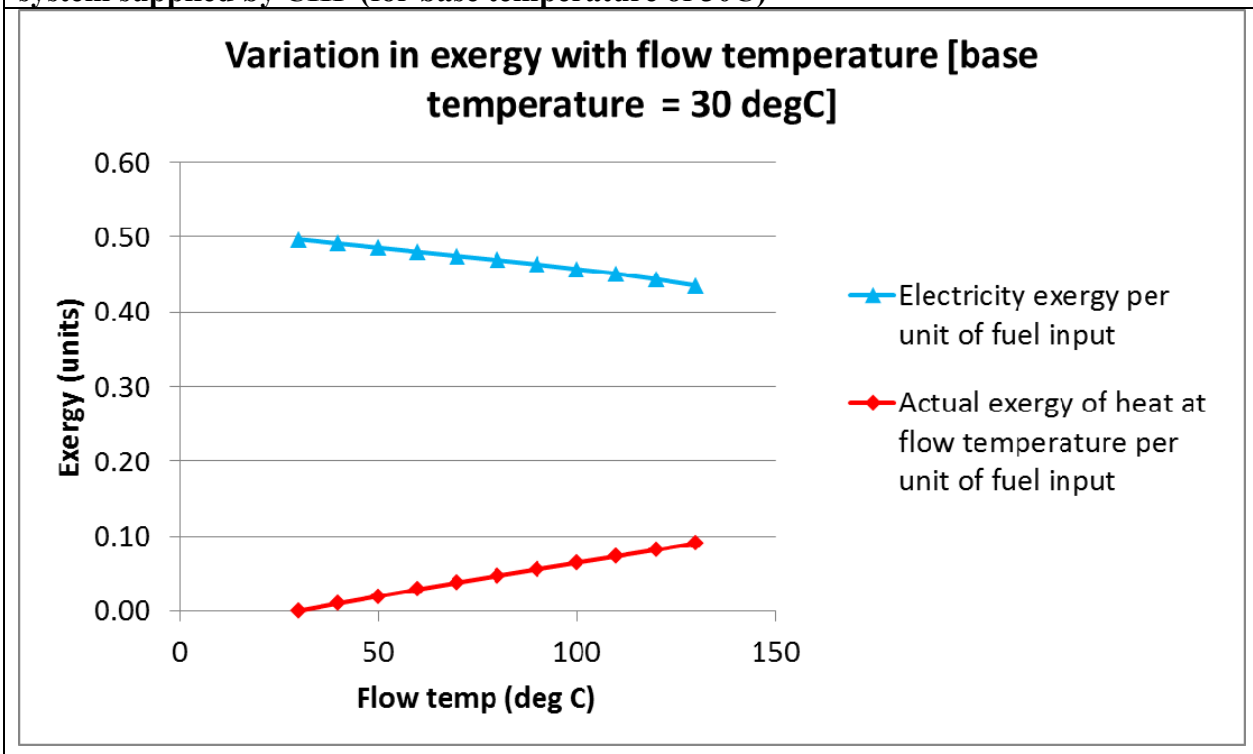

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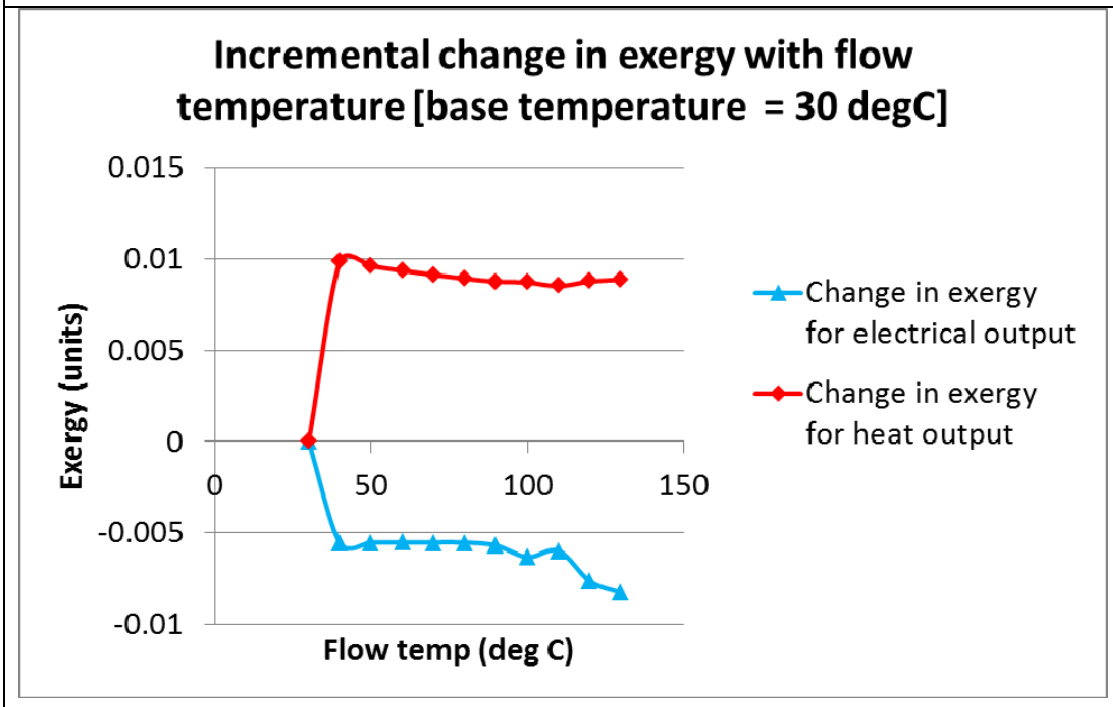
Figure 14 – Incremental change in exergy with flow temperature for a base temperature of 30°C



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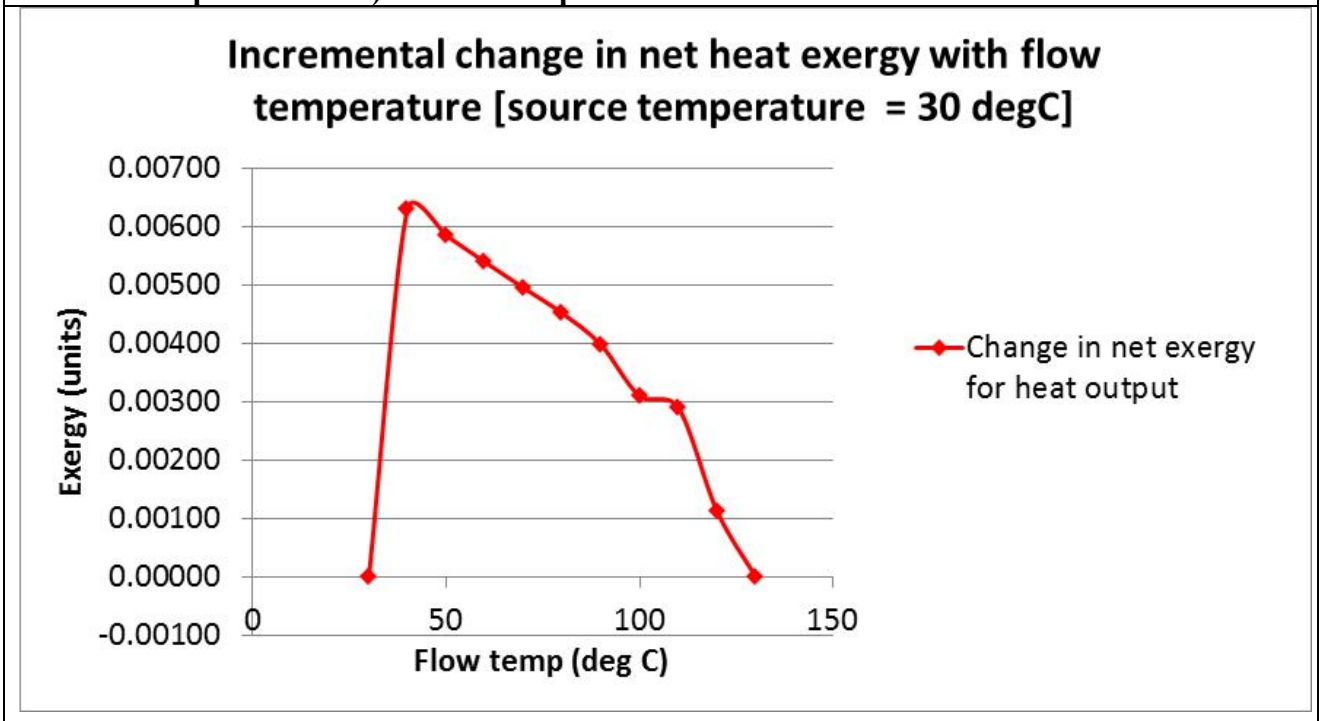
The graphs in Figure 13 and Figure 14 show the variation in heat and electrical exergy with flow temperature for a base temperature of 30C (total and incremental variation respectively). With the flow temperature close to the base temperature, for a small sacrifice in electrical exergy there is a large gain in heat exergy. As the flow temperature increases, the increase in heat exergy per unit sacrifice of electrical exergy decreases. This is further demonstrated by the graph in Figure 15, for which the electricity exergy sacrifice to produce heat has been subtracted from the heat exergy gain.

Figure 15 – incremental change in net heat exergy (actual exergy – electricity exergy sacrificed to produce heat) for base temperature of 30°C



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We question methods that add energy, exergy or fuel for one energy product heat to another quite different energy product power. Electrical energy and heat energy are as different as chemical energy is from either electricity or heat.

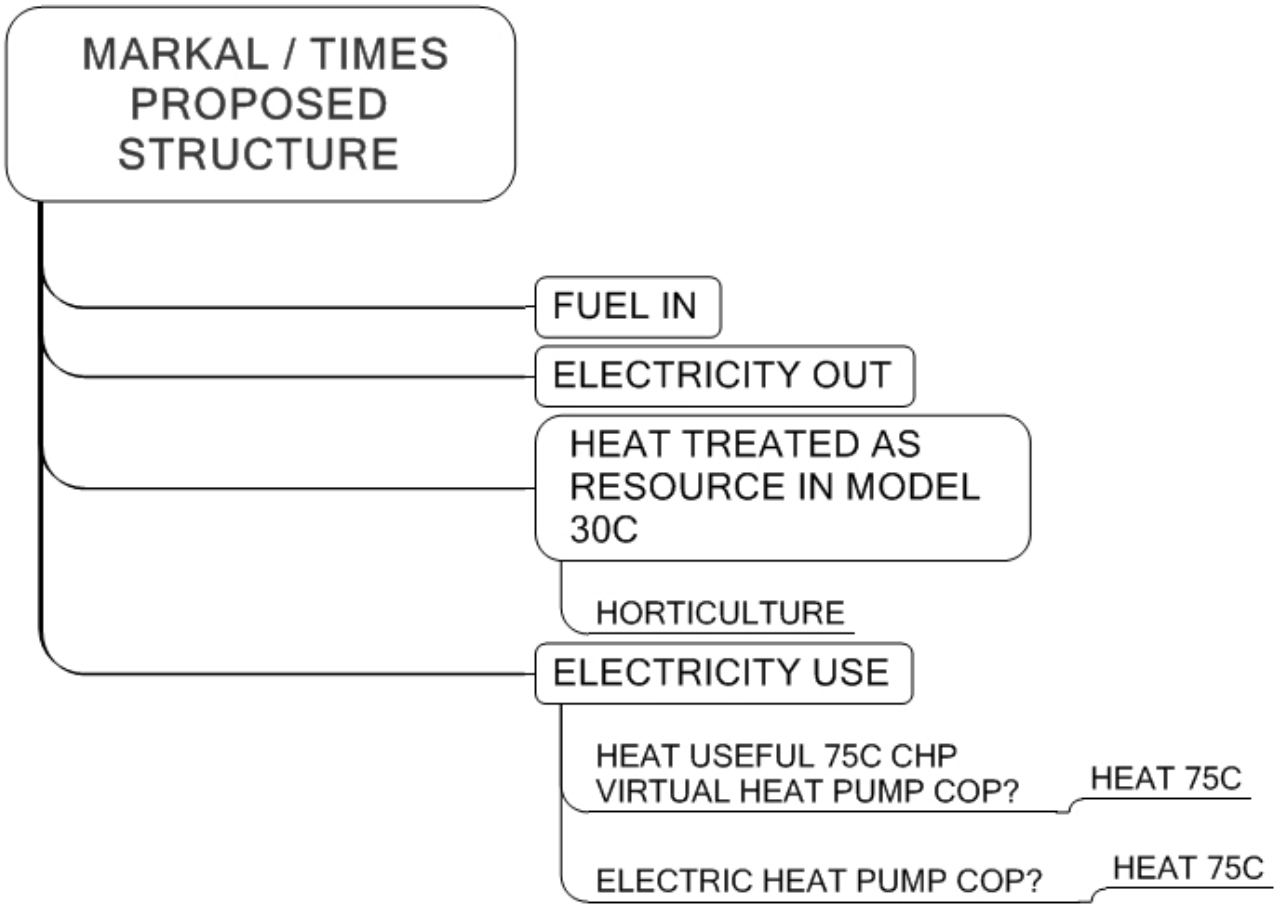
The premise for the EU exergy allocation formula is that heat rejected at a high temperature can in practice be utilised at that temperature for further work or electricity production. We question this assumption, due the practicalities of converting heat back to work and the exergy losses in that process.

The author is concerned that the current formula discourages investment in low temperature citywide heating, as well as the use of reject heat from CHP for horticulture and investment in piped heat. It is possible the formula will actually increase emissions, due to its effect of artificially increasing the efficiency of the conversion of fuel to electricity in its emission calculations for electricity.

The author is also concerned that it will allocate emissions to heat in situations where the marginal fuel burn for the heat in practice is zero. The formula will affect and distort this cost signal, which applies to peak load electricity generation operating in practice in networks for which the generators are likely to be gas turbine or diesel engines, as such plant for security of supply tends to use liquid fuels.

11. MARKAL modifications to make CHP compatible with electric heat pumps and generate a fuel use per unit of heat to balance of investment in zero CO2 heat supply and demand side.

Figure 16 – Proposed modification to Markal to signal fuel burn per unit of heat from CHP on identical basis to fuel burn from electric heat pumps



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This proposed method will allow modelers more effectively to model heat networks fed by large scale electric heat pumps, CHP and solar thermal, coupled with the effects from different locations of electricity generation in an electricity network. This will also take into account the different characteristics of electricity generators and the quality of their heat output, with base load plants tending to be built as steam turbine plants normally rejecting heat at 30°C, whereas peak load electricity generation plant close to consumers generally reject heat at between 30°C and 600°C. See the "Energy Hub" concept, section 22 where optimal heat load and base load electricity generation are integrated with electricity networks to maximize security of heat and electricity supplies and exergy and optimal use of available exergy.

12. European emissions trading scheme and Electricity Market reform formula for allocation of emissions to heat and electricity as subsidy for Electricity.

An AEA report "EU Emissions Trading System, June 2010 evaluated three different methods for treating emissions from CHP, and recommended method two, the current methodology adopted by the EU. This method does not signal the actual emissions when the heat is utilized which in the case of use for horticulture is zero.

Method three, which is considered in the report, is the appropriate method to apply, as it reflects the market condition when CHP units compete with each other to meet demand from the respective heat and electricity networks they serve.

13. Evaluation of Method 1 arbitrary allocation of benefit. 2/3 to heat one third to electricity.

In calculating how much fuel is to be attributed to electricity and heat, method one assumes that twice as many units of fuel are used to generate each unit of electricity, compared to the fuel required to produce a unit of heat. This comes from the assumption that the ratio between fuel and heat generated in a boiler is one and the fuel for electricity generated in power plants to serve consumers is two.

In practice, typical fuel use for a boiler would be 1.2 units of fuel per unit of heat and for electricity generation the fuel burn is more variable due to the range of electrical efficiency of power plant, from around 33% for nuclear and biomass (i.e. 3 units of fuel per unit of electricity) to 50% for CCGT (2 units of fuel per unit of electricity), using the higher, or gross, calorific value of the fuel.

In the formulas taken from the report, the term "heat energy" is used, which in some cases refers to the heat rejected by the CHP to perform a useful purpose and at other times refers to the amount of fuel per unit of heat. Where it refers to the fuel, we identify it as fuel for heat energy.

The method one formula for allocation is shown in Figure 17.

Figure 17: EU ETS Method 1 formulae for allocation of CHP fuel burn to electricity and heat products an arbitrary (⅓ ⅔ Method)

$$\text{Fuel for } \textbf{Heat} \text{ Energy} = \frac{\text{Total Fuel Input}}{(2 \times \text{Electricity Output}) + \text{Heat Output}} \times \textbf{Heat Output}$$

$$\text{Fuel for } \textbf{Electricity} \text{ Energy} = \frac{2 \times \text{Total Fuel Input}}{(2 \times \text{Power Output}) + \text{Heat Output}} \times \textbf{Electricity Output}$$

Source: AEA report EU Emissions Trading System, June 2010 / Orchard Partners London Ltd representation

Out of 100 units of fuel with an overall efficiency of 86% and an electrical efficiency of 10% the CHP delivers 10 units of electricity and 76 units of heat. Figure 18 shows the percentage of the fuel input allocated to the respective products.

Figure 18: EU ETS Method 1 Chart to show the percentage of fuel input allocated to the respective heat and electricity products as a result of the formula for CHP with an overall efficiency for electricity and heat of 86% (fuel allocation per unit fuel input)

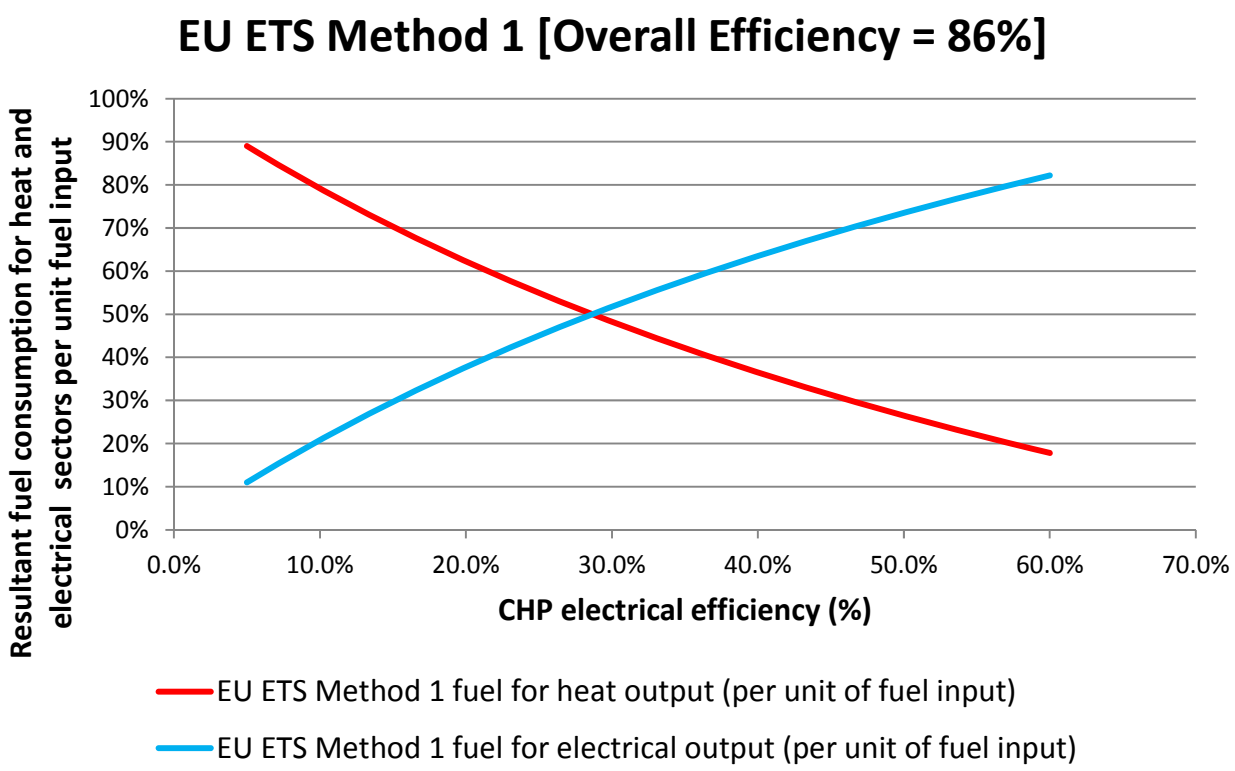

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Figure 19 and Figure 20 (a close-up of Figure 19) illustrate graphically the effect of the formula on CHP plants with differing electrical efficiencies. The overall conversion of fuel to electricity and heat in this example is taken as 86%. Figure 18 and Figure 19 show the fuel use per unit of heat and electricity and compares the fuel allocation to electricity produced from CHP to the actual fuel use per unit of incremental electricity (the green curve). This shows how the allocations change with the electrical efficiency of the CHP and the severe cross-subsidy for the electrical element of the joint products.

Figure 19: AEA EU EUETS Method One illustration of CHP fuel burn allocation to electricity and heat products per unit of heat and electricity for different electrical efficiencies and an overall fuel conversion efficiency fixed at 86% for joint products (fuel consumption per unit of energy generation)

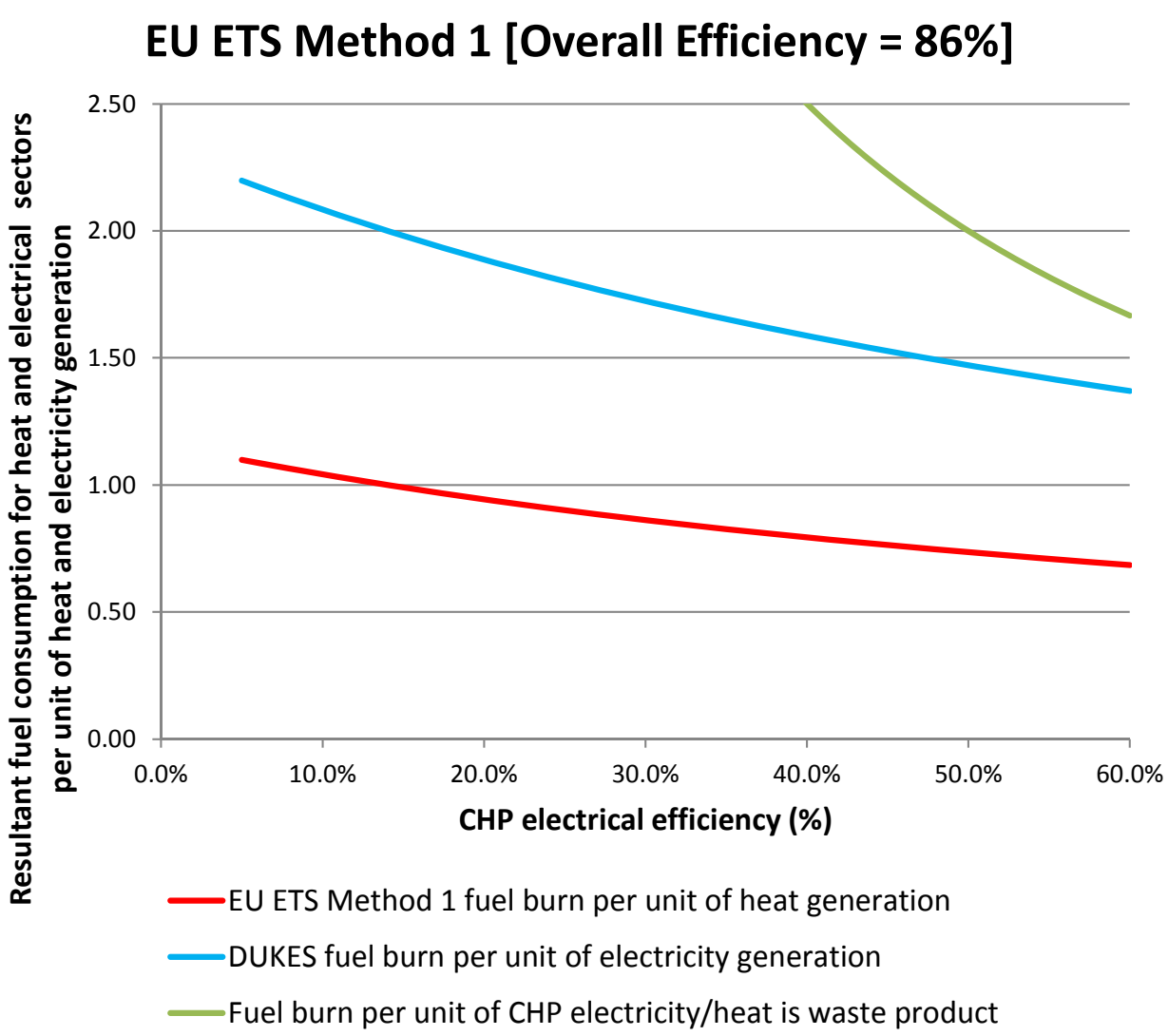

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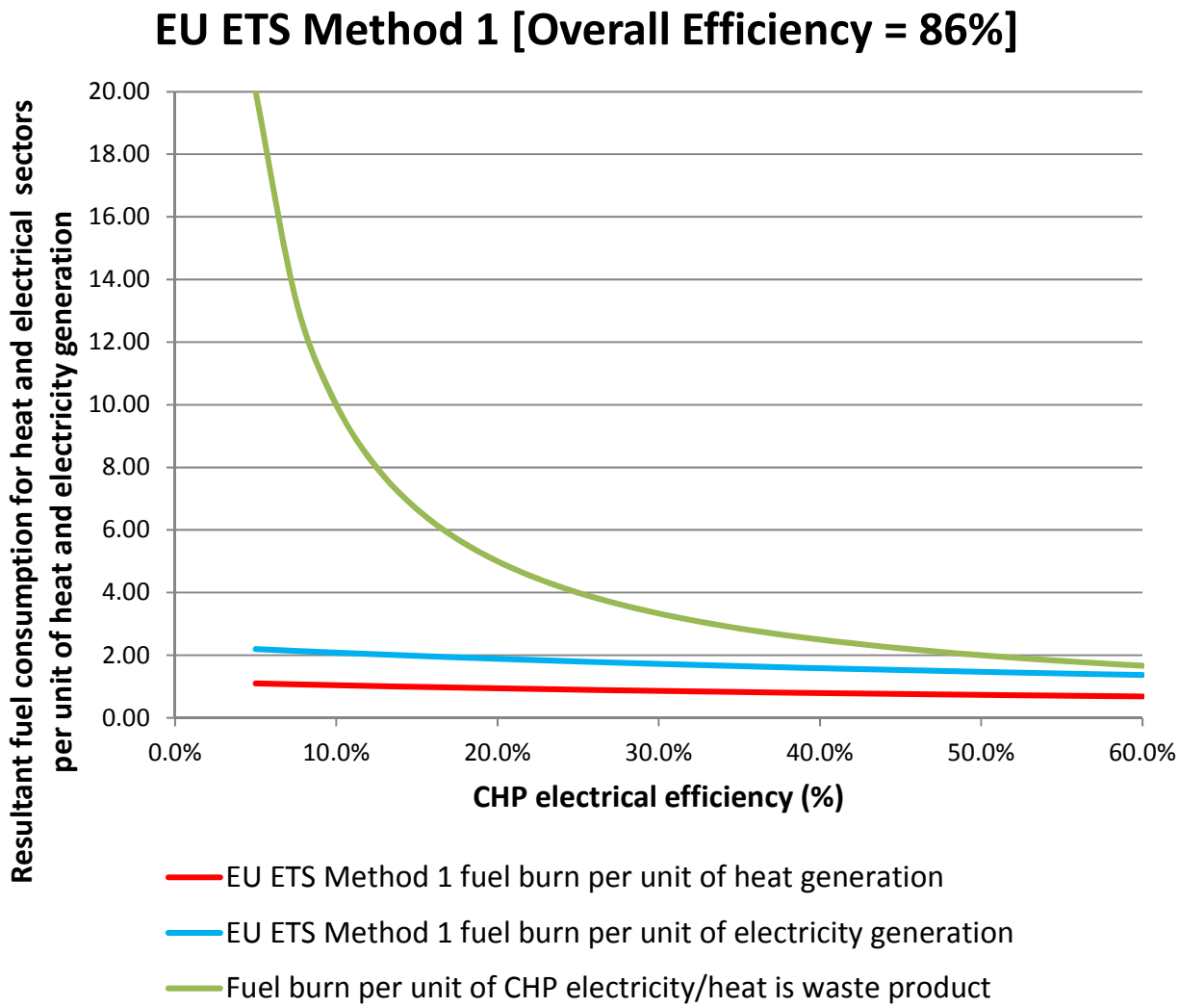
Figure 20: AEA EU EUETS Method One illustration of CHP fuel burn allocation to electricity and heat products per unit of heat and electricity for different electrical efficiencies and an overall fuel conversion efficiency fixed at 86% for joint products – close-up (fuel consumption per unit of energy generation)



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The blue line shows the effect of the formula on the fuel for electricity. If we take the example of a 10% efficient micro CHP, the formula signals a fuel use of 2.08, whilst the actual fuel use per unit of electricity is 10. The formula signals that the fuel use for heat from CHP is 1.04 - only slightly lower than 86% efficient boiler at 1.16 units of fuel.

Method one is used under the UK's Climate Change Agreements and for the Digest of UK Energy Statistics (DUKES). Whilst the simplifying assumptions for the preparation of UK Energy Statistics are clearly set out, readers should be aware of the limitations of the methodology when evaluating the effect of CHP on the respective heat and electricity sectors and its CO_2 displacement potential.

The formula underestimates the benefit from CHP for the heat sector, where for large scale CHP a COP of over 10 is achieved for Danish city heating. A COP of 10 for a 50% efficient CCGT equates to a fuel burn per unit of heat of 0.2. The red line for this formula signals a fuel burn of 0.74 units of fuel per unit of heat. Dukes therefore underestimates the benefit to the heat sector by a factor of three. If the formula is applied to the Nuclear CHP option, where the electrical efficiency of the

CHP for electricity is lower at 33%, but more heat is produced, then for this condition the formula signals a fuel burn per unit of heat of 0.84, whereas the actual fuel per unit of heat for a COP of 10 will be 0.3

Method 1 was developed for statistical purposes when the original method for preparing statistics for CHP was modified. The original method was based on a system developed in the Soviet Union to demonstrate that Soviet electricity generation was more efficient than other countries' generation.

The Dukes method at that time was consistent with a view held by some economists that, when operating in CHP mode, the prime product was the heat and the waste product the electricity.

14.Evaluation of Method 2 prime product boiler waste product electricity.

Method 2 works out the fuel allocation to heat from CHP by assuming that the heat generated by the CHP displaces fuel from a boiler generating the same amount of heat at 90% efficiency (Net Calorific Value basis) when using the same fuel type as the CHP.

The heat from the CHP may be represented using the formula in Figure 21.

Figure 21: Method 2 for calculating heat sector primary fuel displacement

$$Fuel\ use\ for\ heat\ energy = \frac{Heat\ energy\ output}{0.9}$$

$$Fuel\ use\ for\ electrical\ energy = Fuel\ input\ to\ power\ plant - fuel\ use\ for\ heat\ energy$$

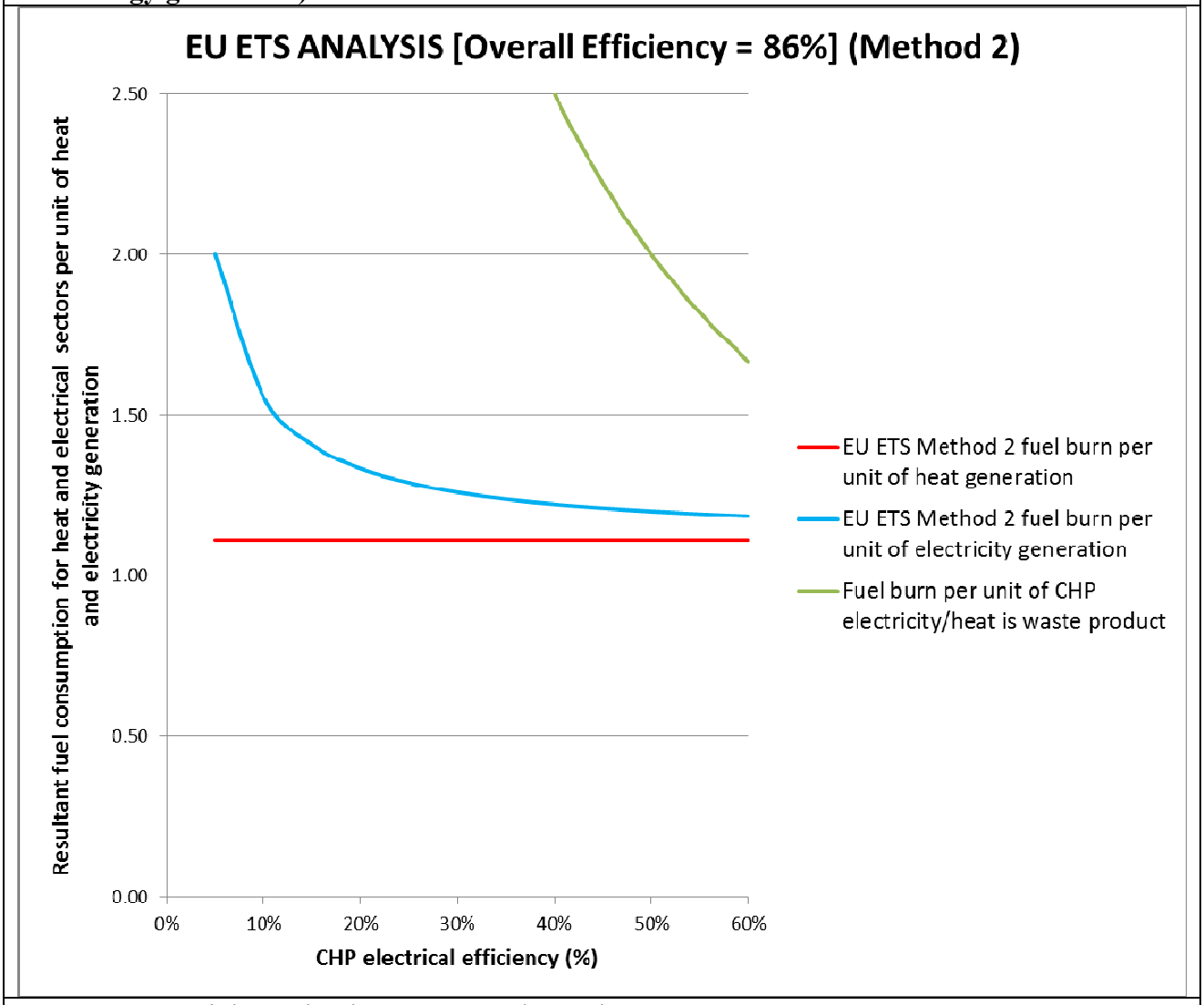
Source: AEA report EU Emissions Trading System, June 2010 / Orchard Partners representation

The fuel for the imaginary boiler that is displaced is subtracted from the total fuel to the CHP and the remaining fuel is then allocated to the electricity produced. The methodology is impractical for use in modelling where the models wish to compare CHP heat to heat from other sources, such as electric heat pumps, or other low CO_2 heat sources, such as biomass boilers.

This method results in a signal of no benefit to the heat sector from the use of heat rejected in electricity generation compared to heat from a boiler, and a significant reduction in the fuel use per unit of electricity. It was adopted in Russia, as the effect of the formula was to signal a high electrical efficiency for Russian CHP electricity generation, compared to countries operating electricity only power plants. It resulted in onerous tariff structures for heat consumers and incorrect dispatching of CHP to minimise overall use of fuel, as well as misallocation of investment by banks in CHP plants with a low electrical efficiencies, where the formula was adopted for the economic evaluation of alternative CHP options.

This effect is illustrated in Figure 22.

Figure 22: EUETS Method 2 fuel burn per unit of heat and electricity generation (fuel per unit energy generation)



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It can quite clearly be seen from this chart that Method 2 gives the signal that if you invest in a CHP with a low electrical efficiency and use the heat, then the fuel burn allocated to the electricity is significantly lower than the actual fuel per unit of electricity, represented by the green line. The formula leaves readers at risk, as the apparently lower fuel use per unit of electricity depends on an assumption that the heat load continues and further that the alternative source of heat is a boiler and not some other heat source (e.g. another CHP plant and/or electric heat pump or solar thermal system). This method cannot be recommended for investment decisions in heat networks, as it signals no benefit from the waste product of the process heat.

A further feature of the formula is how results can change depending on assumptions made about the relative overall efficiency and the efficiency of boiler plant displaced by heat from the CHP.

15.Evaluation of Method 3 prime product electricity waste product heat.

Method 3 assumes that the electricity generated by the CHP displaces electricity generated from a specific conventional electricity-only power plant with a fixed efficiency, using gas, with nett efficiency of 52.5% (47.1% gross efficiency). Such power plants also reject heat, but at a

temperature useful only for horticulture, as it is at around 28C. If this heat is utilised then there is no change in fuel use for electricity generation.

Figure 23 reflects the formula and the graph in Figure 24 shows its effect on the respective sectors.

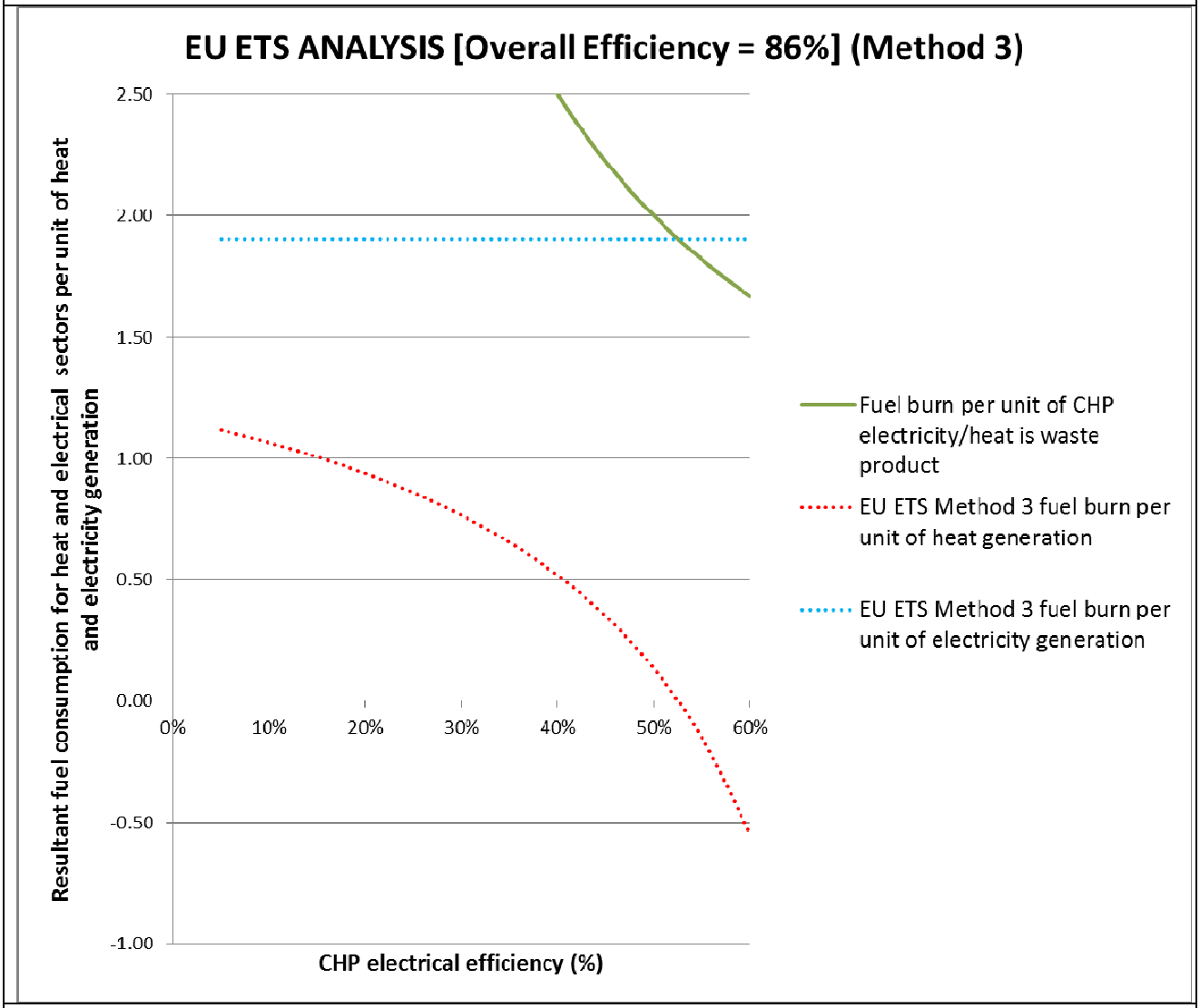
Figure 23: EU ETS Method 3 (Power Station Displacement Method) formula

$$Fuel\ use\ for\ heat\ Energy = Total\ Fuel\ Input - \left(\frac{Electricity\ output}{0.525}\right)$$

Source: AEA report EU Emissions Trading System, June 2010

Note: this formula, unlike methods one and two, makes no assumptions about the fuel use for alternative sources of heat in the heat sector.

Figure 24: EUETS Method 3 fuel consumption per unit of heat and electricity generation, 2012



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The fuel is allocated to the electricity generated by the CHP plant by calculating how much fuel would be required by a benchmark power plant to generate the equivalent amount of electricity (i.e. the electrical output of the CHP divided by the electrical efficiency of the reference power plant

(52.5% – the right hand term in the formula in Figure 23). This is subtracted from the total fuel and the balance of fuel is then allocated to heat production.

The method generates a fuel burn per unit of heat suitable for modelling of CHP and comparing it with other options. It has one defect, in that it generates negative fuel allocation of heat for CHP plants with a higher electrical efficiency than the benchmark power plant.

EU ETS Method 3 assumes fuel can be burnt most efficiently in gas fired combined cycle plant with efficiency of 52.5%. It does not address the significantly lower electrical efficiencies in practice of nuclear (e.g. 33% efficiency), coal (e.g. 38% efficiency) or biomass (e.g. 33% efficiency) power plants. With these forms of generation the practical electrical efficiency is limited by power cycles and combustion processes dictated by the fuel.

The Orchard CHP convention takes the principle of Method 3, which is sound, but extends them so that the approach can be used effectively when modelling CHP, by introducing alternative reference plants to reflect different conditions and to resolve the problem of negative fuel burns per unit of heat. The results from the Orchard CHP Convention are shown in Figure 25, where the formula for the Orchard convention treats the fuel per unit of heat for higher electrical efficiency CHP plants as zero, with the potential to operate as CHP; however if they are only operating in the electricity only mode, all benefits of their higher electrical efficiency are reflected in the fuel use per unit of electricity curve.

Figure 25: Orchard CHP convention CCGT coal and peak load engine or GT

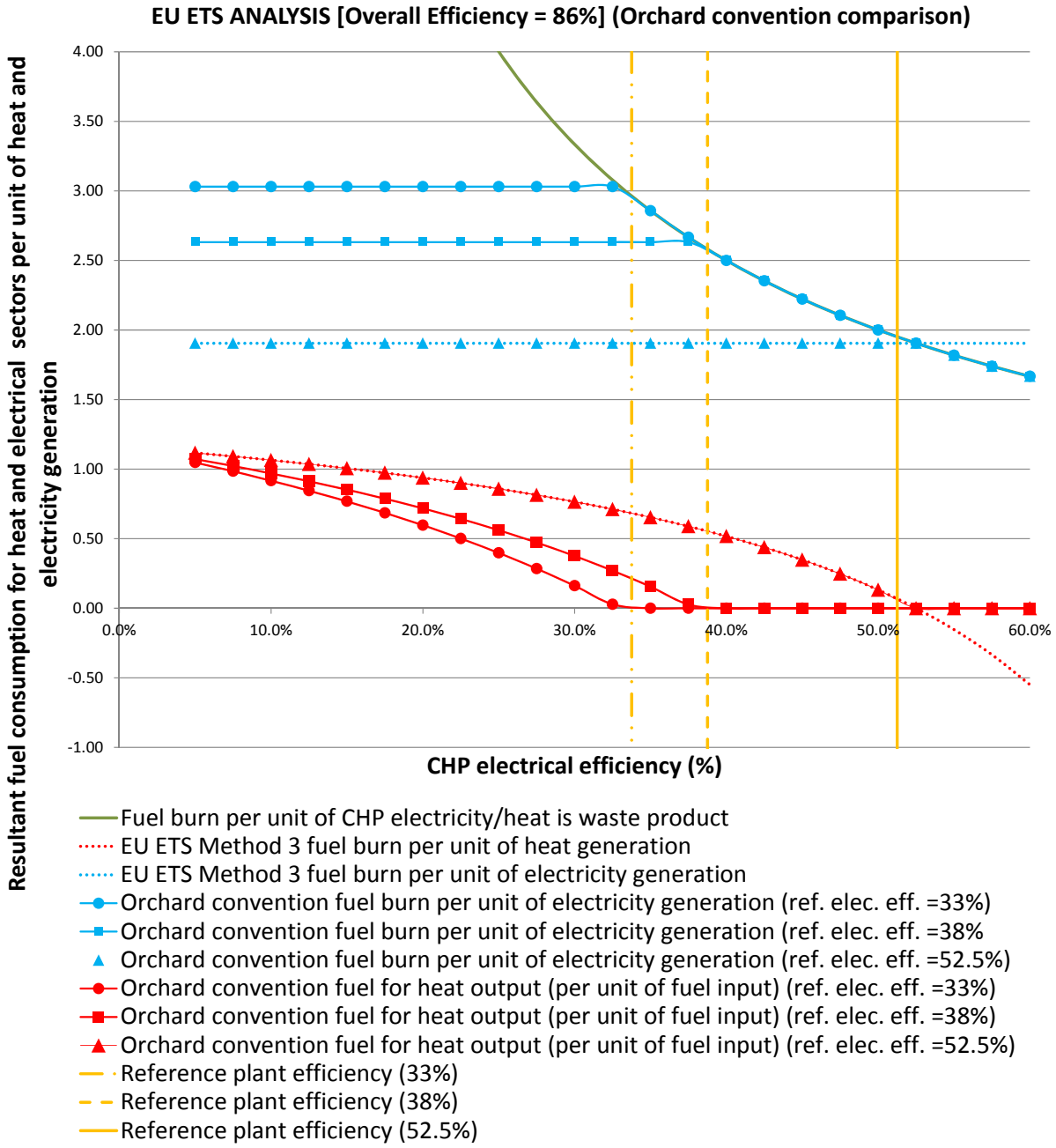

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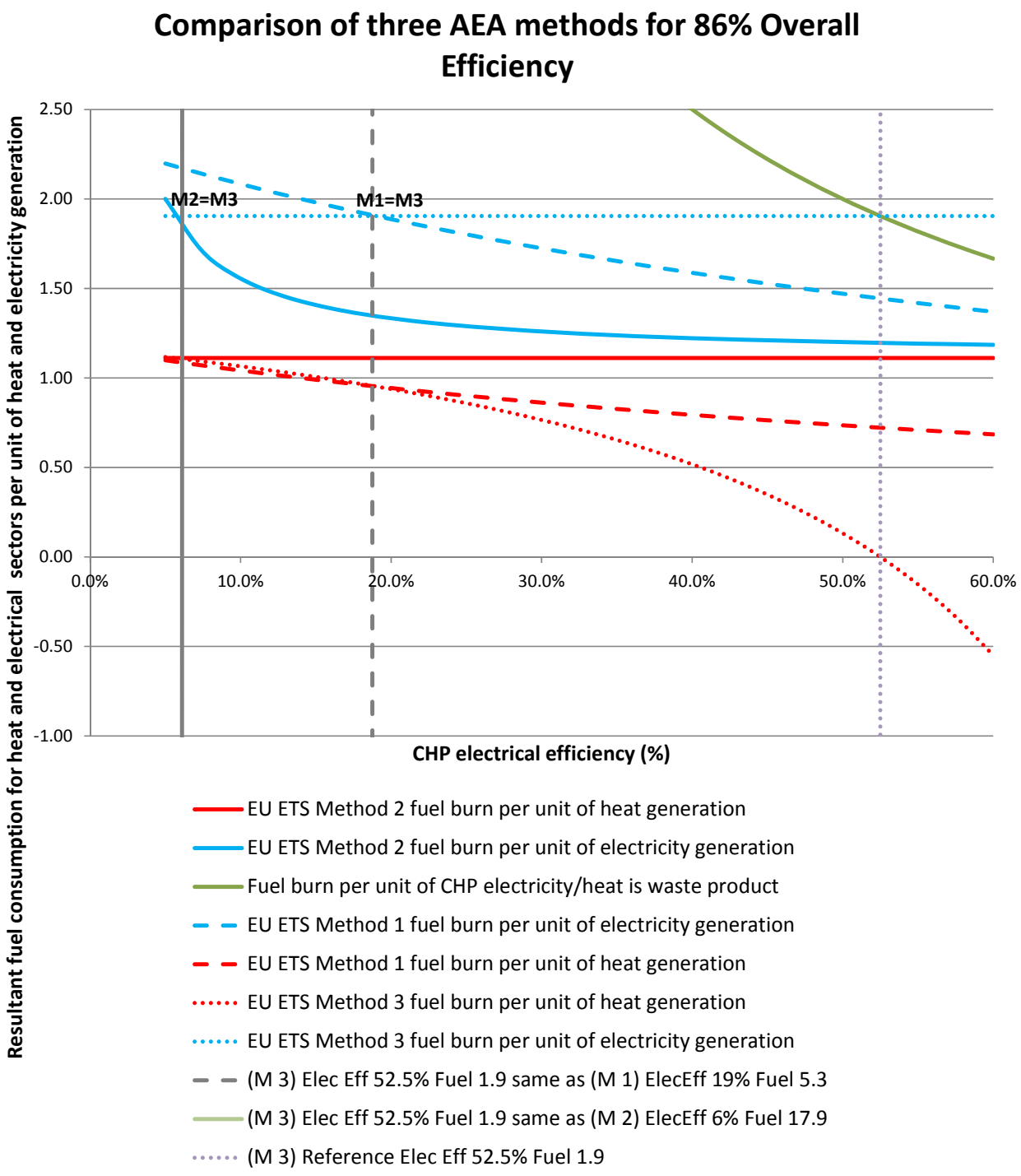
Figure 26: EU ETS (All Methods) variation in CHP fuel burn allocation to electricity and heat products per unit of heat and electricity produced with variation in CHP electrical efficiency for overall CHP efficiency fixed at 86% + comparison with plant prioritising electricity generation -close-up (fuel consumption per unit energy generated



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A comparison of fuel allocation per unit heat and electricity for all three methods in the AEA report EU ETS report (June 2010) is given in Figure 26.
The chart illustrates the variety of approaches to the analysis of CHP and further illustrates the effect on policies, depending on which formula is accepted by those analysing the technology as reflecting the impact of the technology on emissions for the respective heat and electricity sectors.

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Methods 1 and 2, in the author's opinion, are not suited to the modelling of CHP, as they do not allow ready comparisons between heat from CHP and heat from other sources, due to the assumption that the alternative heat source is a boiler with a fixed thermal efficiency, when in practice this depends on whether heat from CHP is displacing old or new boilers, or heat from other sources such as direct electric heating.

Method 2, from the author's experience, has misled investment analysts investing in low electrical efficiency CHP options, when higher electrical efficiency options were available.

It is clear that, if there is an increase in demand for electricity with no change in demand for heat, CHP with higher electrical efficiency is optimal. The view when the small Stirling engine CHP was being promoted in the UK was that it was a boiler that delivered free electricity - an assumption that the prime product was heat instead of electricity. This view, still prevalent in some quarters, is however at odds with the Second Law of Thermodynamics.

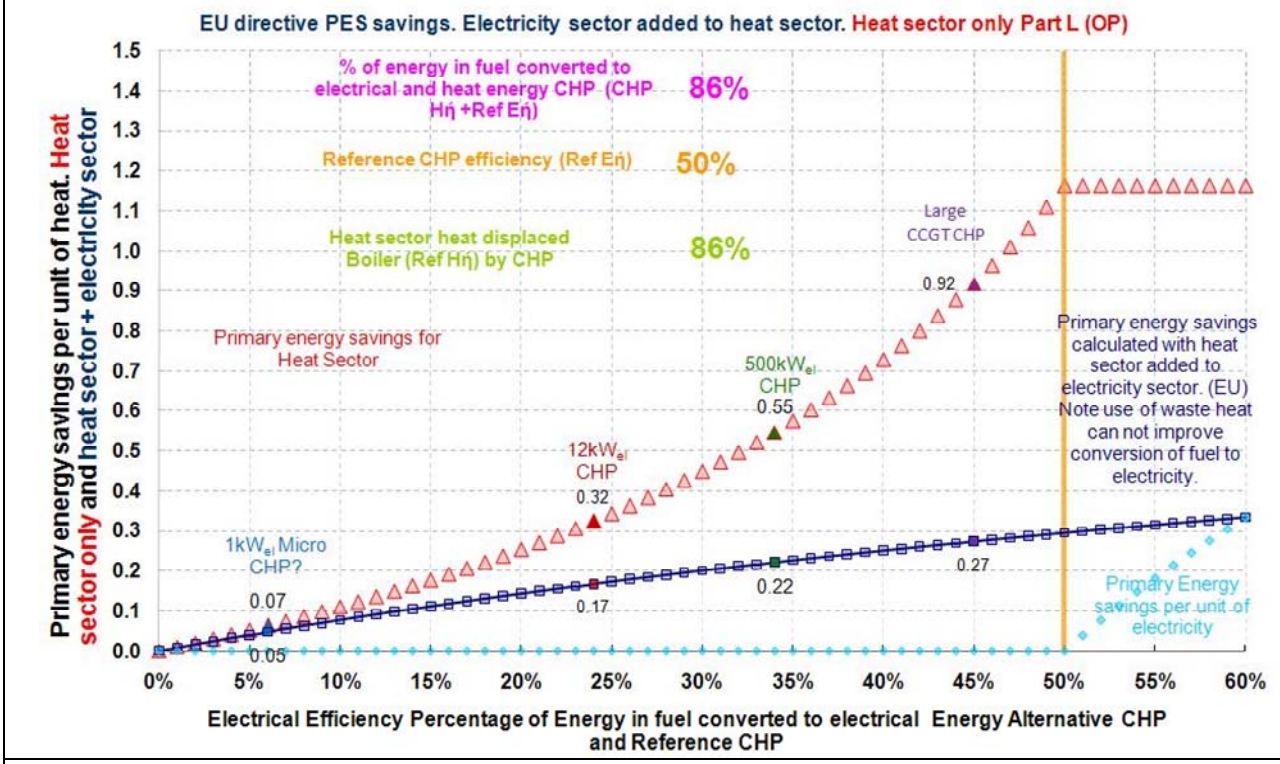
Method 2 has been adopted for the current European Emissions Trading Scheme. It does signal an emissions benefit for CHP and may be the simplest way to deal with an isolated site where all the electricity and heat are utilised within the site boundary. It is, however, not suitable for conditions where multiple CHP plants and other low CO_2 sources of heat compete to feed into heat networks, with the need to signal the fuel burn and CO_2 overhead for the heat. The Orchard CHP convention and Method 3 are optimal for this purpose and are commended to readers as a modelling approach when evaluating CHP opportunities.

Where:

- PES = primary energy savings
- CHP Hη = CHP heat efficiency
- CHP Eη =CHP electrical efficiency
- Ref Hη = Reference heat plant efficiency (to be decided by member state)
- Ref Eη = Reference electrical plant efficiency (to be decided by member state)

The difference in signals between analysis under the Directive and by using the Orchard CHP convention and AEA Method 3 is illustrated in Figure 27.

Figure 27: Comparison EU Cogeneration directive and Orchard CHP Convention (primary energy savings per unit of heat)



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In this chart the fuel use per unit of heat is converted into a primary energy saving by comparing it with heat from a boiler with an 86% efficiency.

The red curve illustrates the savings in the heat sector as a result of utilising heat from CHP.

The blue curve shows how the EU formula allocates savings allocating the actual savings that as an example arise when the reject heat is used directly for horticulture across the joint products electricity and heat. The effect of this can be seen at the vertical line reflecting horticultural use where there is a saving of 1.2 units of primary energy in the heat sector but only 0.3 units of primary energy for the combined heat and electricity sectors.
The EU Directive requires that the primary energy savings from the production of heat and electricity from CHP compared to the production of the same quantity of heat and electricity from a reference plant are to be at least 10%, based on the total fuel input to the reference heat and electricity plants to produce the equivalent heat and electricity products. This is a high target when applying the blue curve, when no savings for the electricity sector arise with CHP.

Readers should note the significant difference in signals from the two approaches. The EU Directive approach signals a maximum saving of 30%, whereas the Orchard Convention signals a maximum saving of 100%. The chart illustrates the relative heat sector savings from different sizes of CHP as a function of their electrical efficiency.

16. UK CHPQA Combined Heat and Power Quality Assurance the case for change.

CHPQA is the UK methodology intended to encourage use of heat from CHP in line with EU requirements to maximise the use of reject heat from electricity generation. It is consistent in its outcome with EU directives and in particular the fundamental requirement for CHP to be rewarded only if it results in a threshold reduction in primary energy demand consistent with EU Directive 2004/8/EC and amending Directive 92/42/EEC (11 February 2004). This analysis illustrates the difficulty where an incentive to use waste heat is rewarded through extra payment per unit of electricity instead of a simple incentive per unit of waste heat utilized, as for the renewable heat incentive (RHI) scheme.

The incentive is paid per unit of electricity and beyond a 'good quality threshold'; all units of electricity are eligible for exemption from the Climate Change Levy (CCL). The payment of incentive per unit of electricity results in an incentive cut-off point at an overall efficiency of 60% to 70%, with a relatively small amount of the potential waste heat rewarded for an 86% overall efficiency. For a power plant with an electrical efficiency of 50% and thermal efficiency of 36%, only 10% of the available 36% of the heat is incentivised.

Figure 28: Climate Change Levy income per additional kWh of heat supplied from CHP for varying efficiency of a 25MW gas turbine installation

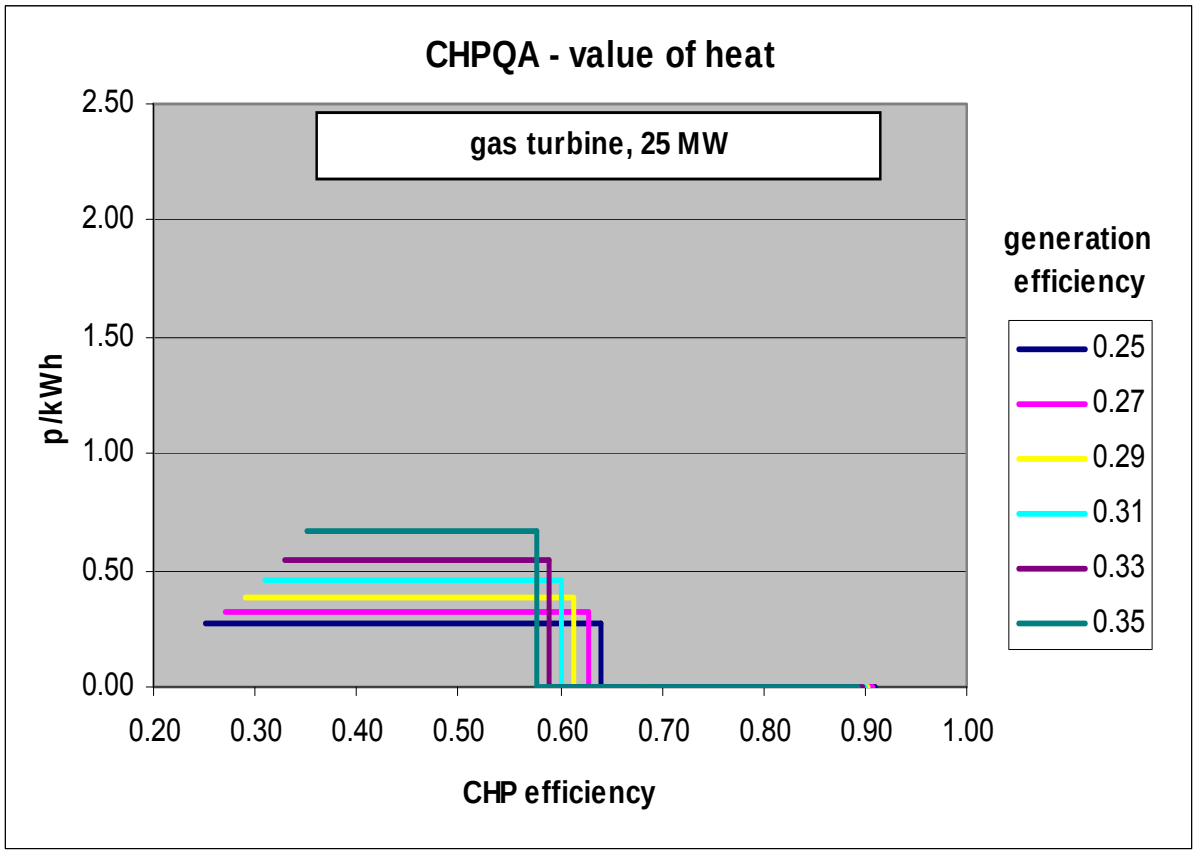

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Figure 29: Climate Change Levy income per additional kWh of heat supplied from CHP for varying efficiency of a 25MW steam turbine installation with a Z factor of 6

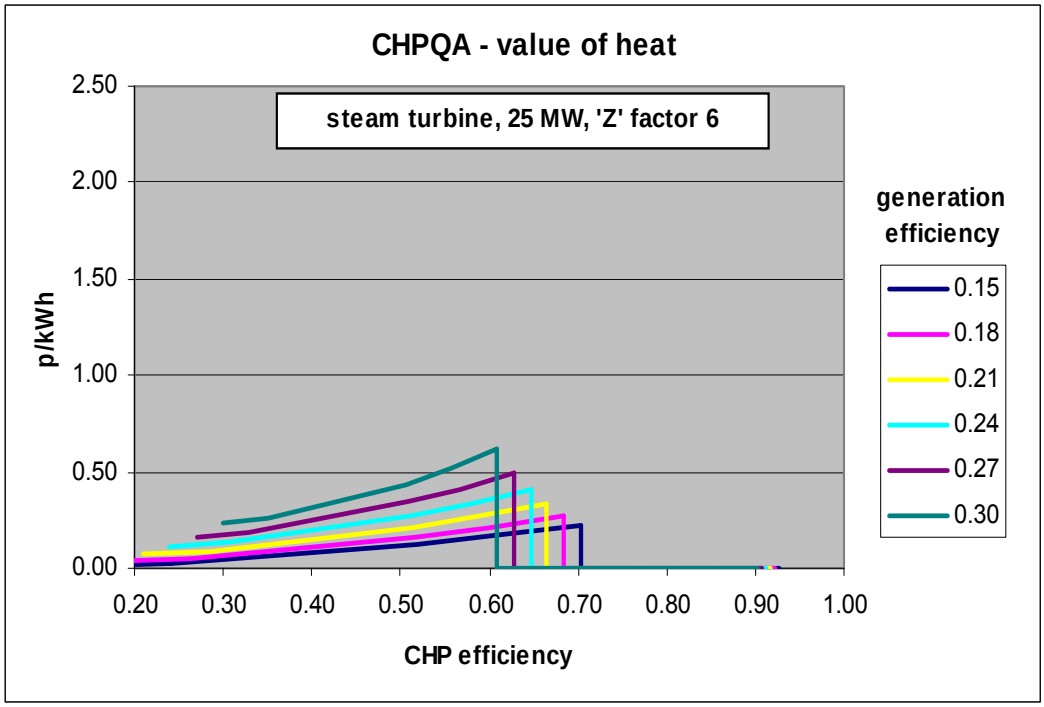

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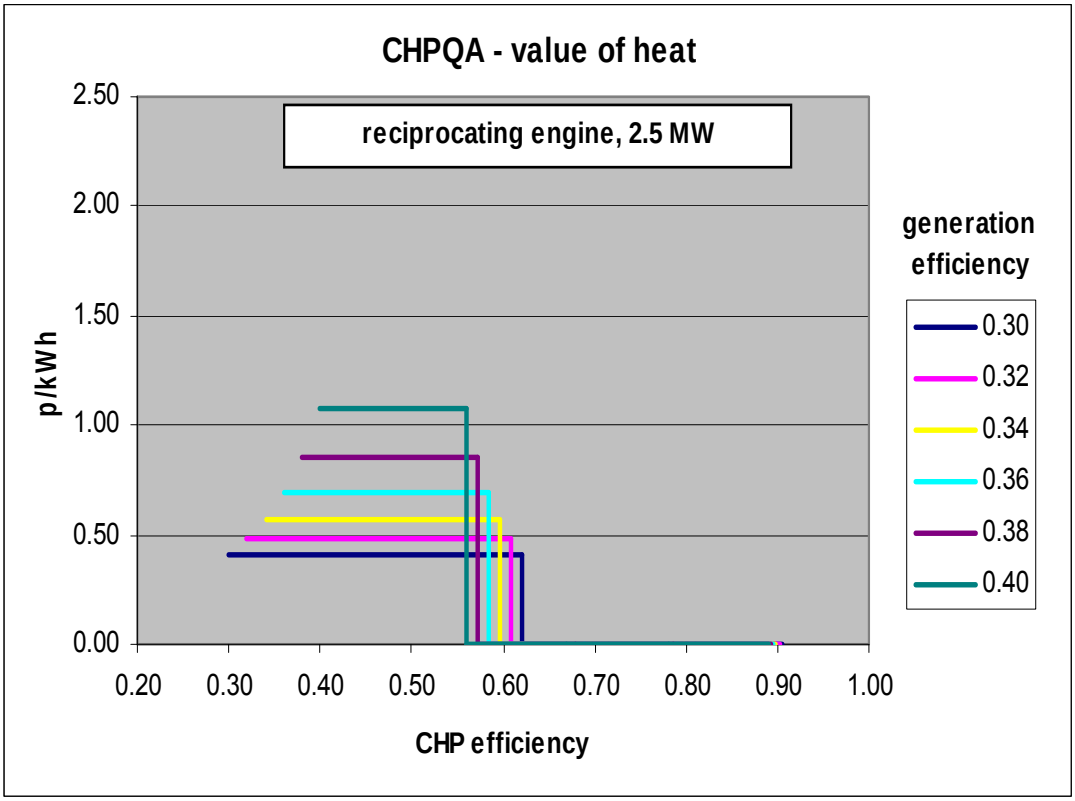
Figure 30: Climate Change Levy income per additional kWh of heat supplied from CHP for varying efficiency of a 2.5MW reciprocating gas engine installation



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An effective incentive system needs to stimulate maximum use of the waste product heat from thermal power generation and readers should be aware of the effect of current incentives and how reward systems for CHP may change as a result of Electricity Market Reform and other initiatives affecting subsidies for competition to heat from CHP at domestic level between electric heat pumps and other “renewable” heat incentives.

See:
http://www.orchardpartners.co.uk/Docs/IAEEVilniusPaperWhyHeatFromCHPisRenewableMarginalExergyAnalysis2011-09-14.pdf (Orchard Partners Ltd, 2011)

17.The EU Cogeneration Directive (2004/8/EC) the case for change.

The EU Cogeneration Directive (2004/8/EC) requires that primary energy savings from CHP are determined by assuming:

- The electricity from CHP displaces fuel consumption of a fixed reference electricity generation plant;
- The heat from CHP displaces heat from a reference heat generation plant.

The following formula calculates the overall primary energy savings for the combined heat and electricity sectors.

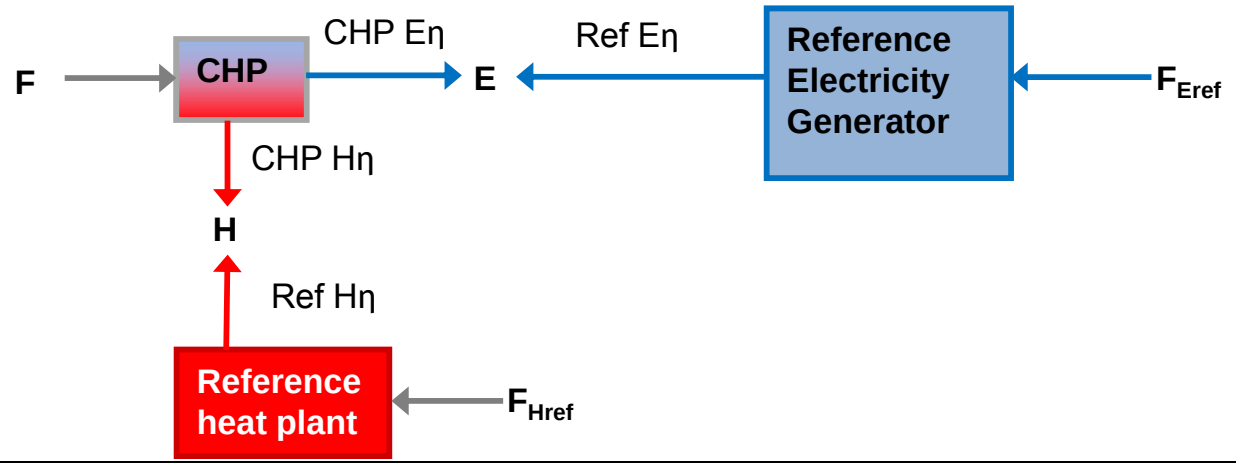
Figure 31: EU Cogeneration Directive (2004/8/EC) calculation of primary energy savings, 2004

$$PES = \left[1 - \frac{1}{\frac{CHP\ H\eta}{Ref\ H\eta} + \frac{CHP\ E\eta}{Ref\ E\eta}}\right] \times 100\%$$

Source: EU Cogeneration Directive (2004/8/EC)

The calculation of CHP primary fuel savings in the EU Cogeneration Directive (Directive 2004/8/EC of the European Parliament and of the Council, February 2004) is based the principle represented in Figure 32 below.

Figure 32: Basis of CHP primary fuel savings in the EU Cogeneration Directive



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The EU Cogeneration Directive methodology for assessing CHP expresses the primary savings for CHP as the difference between fuel input for CHP plant and the fuel input to reference heat and electrical plants. The same electricity and heat products are divided by the fuel input to the reference plants and expressed as a percentage. With reference to the flow chart above, the primary energy savings (PES) may be expressed as:

$$PES = \frac{F_{Eref} + F_{Href} - F}{F_{Eref} + F_{Href}} \times 100(\%)$$

$$\therefore PES = \left[\frac{\left(\frac{E}{Ref\ E\eta} + \frac{H}{Ref\ H\eta} \right) - \frac{E}{CHP\ E\eta}}{\frac{E}{Ref\ E\eta} + \frac{H}{Ref\ H\eta}} \right] \times 100\%$$

E = F x CHP Eη
H = F x CHP Hη

$$\therefore PES = \left[\frac{\left(\frac{F \times CHP\ E\eta}{Ref\ E\eta} + \frac{F \times CHP\ H\eta}{Ref\ H\eta} \right) - \frac{F \times CHP\ E\eta}{CHP\ E\eta}}{\frac{F \times CHP\ E\eta}{Ref\ E\eta} + \frac{F \times CHP\ H\eta}{Ref\ H\eta}} \right] \times 100\%$$

$$\therefore PES = \left[1 - \frac{1}{\frac{CHP\ H\eta}{Ref\ H\eta} + \frac{CHP\ E\eta}{Ref\ E\eta}} \right] \times 100\%$$

The above is the formula that is presented in the EU Cogeneration Directive to calculate energy savings from CHP.

The primary energy savings per unit of heat generated by CHP = primary energy savings per unit per total fuel input from the reference plant (i.e. formula above) x units of fuel input to reference plant/units of heat generated by CHP.

$$= \left[1 - \frac{1}{\frac{CHP\ H\eta}{Ref\ H\eta} + \frac{CHP\ E\eta}{Ref\ E\eta}} \right] \times \frac{F_{Eref} + F_{Href}}{H}$$

$$= \left[1 - \frac{1}{\frac{CHP\ H\eta}{Ref\ H\eta} + \frac{CHP\ E\eta}{Ref\ E\eta}} \right] \times \frac{\frac{E}{Ref\ E\eta} + \frac{H}{Ref\ H\eta}}{H}$$

$$= \left[1 - \frac{1}{\frac{CHP\ H\eta}{Ref\ H\eta} + \frac{CHP\ E\eta}{Ref\ E\eta}} \right] \times \frac{\frac{F \times CHP\ E\eta}{Ref\ E\eta} + \frac{F \times CHP\ H\eta}{Ref\ H\eta}}{F \times CHP\ H\eta}$$

$$= \frac{CHP\ E\eta}{(Ref\ E\eta \times CHP\ H\eta)} + \frac{1}{Ref\ H\eta} - \frac{1}{CHP\ H\eta}$$

$$\frac{1}{CHP\ H\eta} = Total\ fuel\ input\ to\ CHP\ per\ unit\ of\ heat\ output$$

$$\frac{CHP\ E\eta}{(Ref\ E\eta \times CHP\ H\eta)} = \frac{Electricity\ output\ from\ CHP\ per\ unit\ of\ heat\ output}{Ref\ E\eta}$$

$$\frac{1}{Ref\ H\eta} = Fuel\ input\ to\ heat\ reference\ plant\ to\ produce\ one\ unit\ of\ CHP\ heat$$

$$\therefore Primary\ energy\ savings\ per\ unit\ of\ heat\ input\ to\ CHP = Fuel\ input\ to\ heat\ reference\ plant\ to\ produce\ one\ unit\ of\ CHP\ heat - \left(Total\ fuel\ input\ to\ CHP\ per\ unit\ of\ heat\ output - \frac{Electricity\ output\ from\ CHP\ per\ unit\ of\ heat\ output}{Ref\ E\eta}\right)$$

Multiplying both sides by units of heat output and using a reference electrical generation efficiency of 0.525 gives:

$$\therefore Primary\ energy\ savings = Total\ fuel\ input\ to\ reference\ plant\ to\ produce\ same\ heat\ as\ CHP - \left(Total\ fuel\ input\ to\ CHP\ per\ unit\ of\ heat\ output - \frac{Electricity\ output\ from\ CHP\ per\ unit\ of\ heat\ output}{Ref\ E\eta}\right)$$

This second term on the right hand side of this equation is recognisable as the CHP heat product fuel allocation in accordance with Method 3 from the EU ETS report.

Some methodologies used in the UK, and indeed in other parts of Europe, used in conjunction with policy or the determination of incentives, when applied to the assessment of the benefits of combined heat and power (CHP) can give misleading results by combining assumed impacts on the electricity and heat sectors. The products are, however, different in terms of what drives their production cost and their value. The electricity product requires heat to be rejected as part of its production and therefore the heat must be treated differently from situations such as its production in a boiler, where it is the prime product. A different approach is required in order to determine the true impacts of CHP. Policy relating to CHP has evolved over time and is still doing so. Where there are current flaws, when they are recognised, this may change the drivers for CHP utilisation compared to other options.

Another fundamental consideration for CHP is whether current methodologies evaluate the differing network effects when considering an all-electric future compared to a more flexible future integrating heat electricity and gas networks, having different forms of generation connecting into the same coordinated infrastructure systems. This raises the question of what needs to be done to optimise the combined operation of these different forms of central and local production of heat and electricity to maximise national security of energy supplies, whilst also meeting EU and UK CO_2 and renewable energy targets for generation.

A further shortcoming with the current widely-used methodologies for assessing CHP is their lack of differentiation between different qualities of heat produced. The relative quality of heat from different types and configurations of CHP (related to temperature) and their role in optimal heat and electricity networks. This particularly applies to gas and diesel engines that with their high temperature heat output are ideal in the network configuration proposed for “Energy Hubs”

18.Orchard CHP convention for models and optimisation.

The symbols used in the formulae relating to the Orchard CHP Convention are given in Table 3 below.

Table 3: Symbols used in explanation of Orchard CHP Convention for assessing CHP

Symbol	*Explanation*
$CHP_{E+H}\eta$	CHP Overall Efficiency ($CHP_{E\eta}$+ $CHP_{H\eta}$)
CHP_EFB	CHP Fuel Burn per unit of Electricity
$CHP_E\eta$	CHP Electrical Efficiency
CHP_HFB	CHP Fuel Burn per unit of Heat
$CHP_H\eta$	CHP Heat or Thermal Efficiency
$Ref_E\eta$	Efficiency of reference power plant

Source: Orchard and Partners

The Equations used in the chart are as follows.

Equation 1 reflects the fuel use per unit of electricity and is a simple function of the electrical efficiency of any electricity generator on the system; it is represented in the chart by the purple curve.

Equation 1:

$$CHP_E FB = \frac{1}{CHP_E \eta}$$

Equation 2 represents the electrical efficiency of a reference power plant; this is signalled by the vertical yellow line in the chart (Figure 33). Two conditions arise for such a plant, first when it is compared to A) to CHP units with a lower electrical efficiency, and secondly B) where it is compared to power plants with a higher electrical efficiency.

Equation 2:

$$CHP_E FB = \frac{1}{\mathrm{Re}\, f_E \eta}$$

Equation 2 represents the straight blue line to the left of the vertical yellow reference marker line – this reflects graphically the fuel use per unit of electricity for the reference plant. It is plotted to show its relation to the actual electrical efficiency of lower electrical efficiency CHPs reflected by the purple line. For perfect market conditions and the same fuel cost of fuel, the CHP will need to have the same fuel use per unit of electricity as the reference plant if it is to compete with the reference plant for the electricity market. The difference between the straight blue and purple line reflects the amount of fuel per unit of electricity for allocation to heat.

Equation 3 reflects the red line which calculates the effective fuel use per unit of heat of the CHP, taking into account the difference in electrical production between the CHP and the reference plant. The other parameter (in brackets to the right of the formula) is the ratio of heat and electricity

production from the CHP, which gives conversion between fuel burn per unit electricity and fuel burn per unit heat.

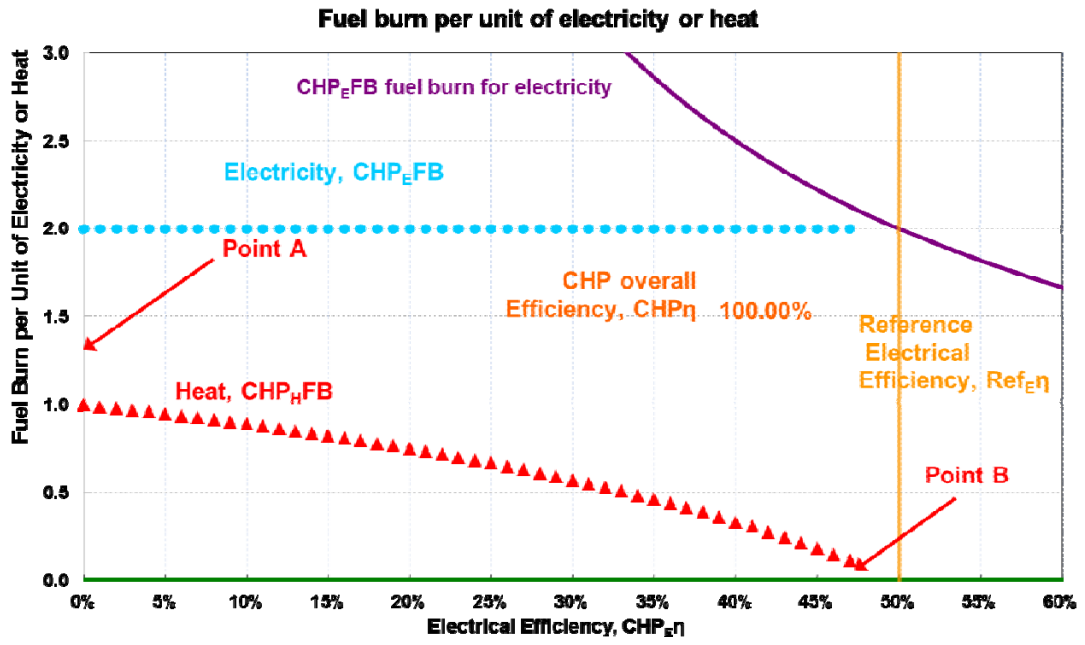
Equation 3:

$$CHP_H FB = \left(\frac{1}{CHP_E\eta} - \frac{1}{\text{Re}\, f_E\eta}\right) \times \left(\frac{CHP_E\eta}{CHP_H\eta}\right)$$

The input parameters to the chart are:

1) The electrical efficiency of the reference plant competing with the CHP in the electricity sector for consumers.
2) The electrical efficiency of the plant under consideration operating as CHP with a lower electrical efficiency.
3) The overall efficiency of the CHP plant producing both heat and electricity where subtraction of the electrical efficiency from this overall efficiency allows the amount of heat supplied to be determined. It should be noted that, whilst the electrical efficiency tends to remain constant, the amount of heat and overall efficiency depend on the amount of heat used.

Figure 33: Orchard CHP Convention graph of fuel burn per unit of electricity and heat



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19.Gross and Nett calorific values caveat for modellers.

When evaluating projects, care should be taken in checking fuel conversion efficiencies and assumptions about the cost of the energy in the fuel. The gross CV measures the fuel total potential energy with any exhaust gases condensed to the temperature of the environment, which for natural gas is typically 38.0MJ/m3. The nett, or lower, CV, assumes that the heat in the vapour in the exhaust cannot be usefully recovered and is typically 34.2MJ/m3 for natural gas. Thus a gas a boiler with an efficiency of 86% on the Gross CV will have an efficiency of 95.5% on the nett CV.

Readers are advised to have all projects evaluated using gross CVs for both the energy content and cost of the fuel. “Gross” efficiencies should also be used for the conversion of the fuel to electricity

and heat in CHP and boilers. The gross to nett ratio varies for different fuels. As an example for biomaterials, which may be wet, great care, needs to be taken with efficiencies and whether the calculations assume that equipment will, in practice, condense the vapour in the exhaust gases, to extract the low grade latent heat of condensation.

20. CO_2 footprints for heat supply to buildings 2012

The following table gives a flavour of the CO_2 footprint of heat from different sources and where heat from CHP ranks, compared to other options.

The table is constructed to signal CO_2 emissions when biomass is burnt, on the basis that if carbon capture and storage became a preferred technology, then to encourage the fitting of CCS to biomass burning plants to deliver negative CO_2 emissions overall, some type of tax on unabated emissions from biomass would be necessary.

Error! Reference source not found. illustrates an important point when considering heat supply and heat networks compared to electricity supply and electricity networks. The average energy losses for a heat network can be higher than for an electricity network but the primary energy losses can be much lower for the heat than for the electricity.

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21. Table of CO2 emissions, for supply, distribution, delivery to consumers for heat and electricity and gas networks. Comparison of fuels and conversion.

Heat supply options gross (higher) calorific value (CV) efficiency (eff)	Supply	Distribution losses		Delivered
Methods of production and conversion.	**kg/CO_2 per kWh**	**Average loss %**	**CO_2 Average loss kg**	**kg/CO_2 per kWh**
Hydrogen fuel from electricity(coal) 80%(eff)	**1.046**			
Biogas burnt in 86% (eff) domestic boiler.				**1.008**
Electricity from coal 36%	**0.837**	**10**	**0.084**	**0.920**
Biogas fuel 40% (eff) from biomass (Lund University Maria Berglund Pal Borjesson)	**0.850**	**2**	**0.017**	**0.867**
Biomass wood boiler 78%? (eff).	**0.436**	**5**	**0.022**	**0.458**
Electricity from gas 48% (eff)	**0.397**	**10**	**0.040**	**0.437**
Biomass (dry wood) as a fuel	**0.340**			**0.340**
Air source heat pump COP 2.9 (Electricity from coal)				**0.317**
Coal as fuel	**0.301**			**0.301**
Old gas boiler 75% (eff)				**0.255**
New condensing natural gas boiler 86% (eff)				**0.222**
Heat micro CHP 1kWel 6% (el) (eff) 86% (eff) overall				**0.212**
Natural gas as a fuel	**0.191**	**2**	**0.004**	**0.195**
Heat pump good geothermal winter heat source, COP 4 electricity from gas.				**0.109**
Piped heat from gas fired condensing 500 kWel CHP 34.7 % (el) (eff) 86% (eff) overall	**0.103**	**10**	**0.010**	**0.113**
Piped heating from very large biomass CHP co fired with coal.	**0.075**	**20**	**0.015**	**0.089**
Piped urban district heating from coal fired CHP equivalent COP 12.7	**0.066**	**20**	**0.013**	**0.079**
Piped urban district heating from gas fired CCGT CHP equivalent COP 12	**0.033**	**20**	**0.007**	**0.040**
Electricity from wind, DTI Future of Nuclear Power page 49	**0.020**	**10**	**0.002**	**0.022**
Electricity from nuclear 0.006 to 0.026 DTI Future of Nuclear Power page 49	**0.010**	**10**	**0.001**	**0.011**
Piped district heat from nuclear fired CHP equivalent COP 10	**0.001**	**20**	**0.000**	**0.001**

Note on table: This signals CO_2 emitted when biomass is burnt. It signals the extra CO_2 displacement from burning biomass in CHP compared to boilers, to optimise the use of this scarce resource. Growing wood and storing its CO_2 in buildings and burning a low CO_2 fossil fuel,

counter-intuitively, gives a greater CO_2 reduction. Current mechanisms do not adequately encourage the effective use of biomass by signalling a very low CO_2 overhead for the fuel at the grate, thereby discouraging efficient conversion.

The same table can be used to consider the marginal losses for heat and electricity networks where the significant factor is the negligible marginal distribution loss for heat networks and the significant loss for electricity networks illustrated for the alternatives of heat supply from gas fired CCGT as direct electric heating and heat supply from the same plant operating as CHP.

Heat supply options gross (higher) calorific value (CV) efficiency (eff)	**Supply**	**Distribution losses**		**Delivered**
Methods of production and conversion.	**kg/CO_2 per kWh**	**Marginal loss %**	**CO_2 Marginal loss kg**	**kg/CO_2 per kWh**
Electricity from gas 48% (eff)	**0.397**	**20**	**0.079**	**0.437**
Piped urban district heating from gas fired CCGT CHP equivalent COP 12	**0.033**	**2**	**0.001**	**0.034**

Note the marginal losses for electricity due to losses being a function of power multiplied by power also mean that peak load electricity generation is more cost effective than remote peal load power generation which may be encouraged due to the trading structures for Electricity Market Reform for the UK which is focused on National Grid as the electricity supply route and not the distribution companies. Security of supply will be increased if EMR is modified to encourage peak load generation close to consumers as this will reduce investment requirements for National Grid and the distribution companies.

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22. The Energy Hub Concept for optimal security of supply and to minimise CO2 emissions from new UK "Fracking Gas" resources.

Introduction and summary.

The Energy Hub represents a low temperature heat network investment compatible with heat pumps, solar thermal, geothermal CHP and boilers retrofitted to current building stock. This offers the following advantages:

- Investment in heat networks avoids investment in electricity networks vulnerable to disruption, when consumers get neither heat nor power.
- Reduces dependency on gas.
- Local stored fuel meets peak demands for electricity and heat and backs up electricity when there is no wind on the coldest days.

Background to concept.

A large amount of peak load generation will be needed in 2050 to back up intermittent renewables e.g. wind. Such generation normally uses stored liquid fuels for security of supply reasons.

The optimal location to minimise electricity infrastructure investment is to locate the generation on the low voltage side of 11kV transformer close to consumers.

The concept is outlined below and is represented in the schematic in Figure 34. The Energy Hub delivers:-

- Minimal investment in electricity infrastructure to meet demand for electric vehicles and electric heat pumps.
- Large investment in heat infrastructure with significant job creation in cities;
- Savings on maintenance on gas safety payments by consumers on local gas networks;
- Retention of medium pressure gas network to serve the energy hubs, compatible with 2050 biogas and hydrogen fuel cell scenarios;
- Location for battery exchange for electric vehicles, saving investment in charging points making EVs practical for consumers.

Recommended actions are:

- We start now to locate the peak load generation required in 2050 at hubs connected to 11kV ring networks.
- Preferably locate on 415 volt side of transformer to minimise fault level effects and electrical losses.
- Generation at hub is to be a dual fuel engine of capacity 500kW-2MW.

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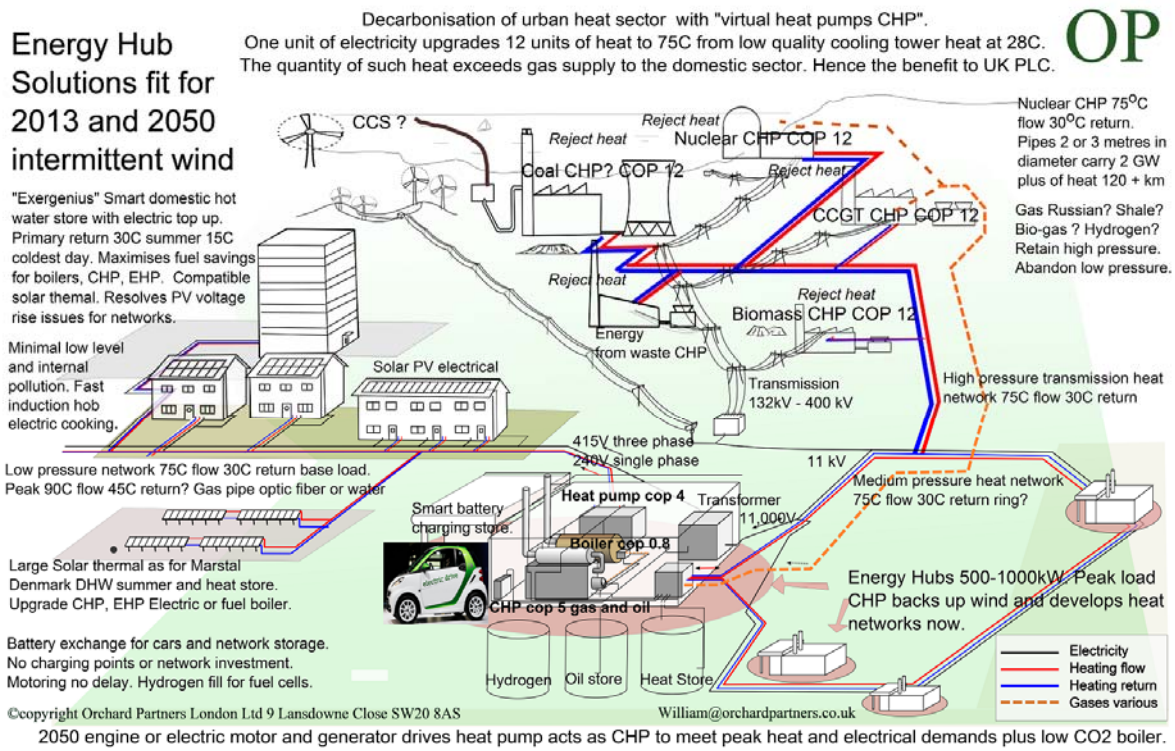
- The engine can operate on gas or liquid fuels fossil or renewable fuel and delivers emergency standby. The New York hurricane impact is the reason President Obama is investing in local generation and CHP.
- 2013: Engine is to run to decarbonise domestic sector with COP over 5 and to build local heat networks.
- Networks to be interconnected to deliver larger and larger scale heat networks served by larger scale sources of low CO_2 heat so after 10-15 years networks fed by large scale CCGT CHP with COP of 12.
- 2050 Heat networks by now are extended to new nuclear CHP at Sizewell and other locations with: COP 12-14: heat supply 75C flow 30C return; pipes 2-3 metres in diameter.
- 2050 Hub now meets peak loads for heat and electricity and acts as location for large scale electric or engine driven heat pumps to serve low temperature heat network with 75C flow and 30C return for base load. Peak flow temperature on coldest day from Hub will be 95C (City of Odense CHP DH system directly connected to minimise cost of heat and maximise exergy utilisation.)
- Boilers at energy hub act to deliver peak load heat under cold snap conditions and top up heat from heat pumps or CHP.
- Energy Hub location for underground heat storage.
- Energy Hub location for national reserve of stored standby fuel of oil to meet peak demands for electricity and heat.
- Energy Hub location for battery charging and storage and battery exchange for electric vehicles.
- Large scale Solar PV connects to heat network – this supply will be more economic than individual solar thermal.
- Battery store to resolve voltage rise systems due to peak output from solar PV.
- Infrastructure for gas: medium pressure gas supply to hubs which initially carry more gas required for electricity generation and heat.
- Low pressure gas system abandoned and used for other purposes.

Benefits from Hub concept.

- Decarbonises current buildings quickly and minimises investment in building fabric and disruption to buildings to reach code level 4.
- Capital investment in heat network results in significantly greater CO_2 savings than investment in additional insulation. The reason is that low carbon heat decarbonises all heat loads, domestic hot water, ventilation, and fabric, whereas insulation only addresses fabric load and cost increases exponentially for every kW of fabric heat load reduction.
- Low CO_2 piped heat first. This is a faster route to decarbonise domestic sector than boiler upgrades and insulation.
- Note: visit Odense in Denmark to find out how they retrofitted the city a street at a time using temporary portable equipment.
- Significantly reduces UK requirements for gas compared to new gas boiler scenarios.
- No additional investment in electrical infrastructure required meeting 2050 decarbonisation targets whether heat comes from large electric heat pumps at Hub or CHP?
- Removes UK dependency on gas by providing local reserve national liquid fuel storage.
- Heat network offers option compatible with readily stored fuel such as coal, wood, straw, and other bio products.

- Oil as a standby fuel and national emergency resource at each generation hub deals with local security of heat and electricity supplies for, shall we say, half the capacity needed to keep homes going.
- Reduces cost of investment in gas storage and costs and energy losses associated with line packing.
- Local employment installing piping and retrofitting current wet heating systems currently heated by boilers to clean piped heat; this is better for the economy than large power plant investment.
- No skill issues: plumbing and heating trades well established.
- Removes risk associated with gas supply to housing, e.g. carbon monoxide and explosion risks as well as the requirement for annual gas inspections and associated costs.
- Benefit of battery exchange - it will allow, say, eight modular batteries to be fitted under the car. A benefit of this will be that where car is not used much of their weight can be reduced and battery life extended. They can for longer trips "fill the tank" by installing eight batteries instead of one.
- The further benefit of the battery store concept at the hub is that it will be able to absorb excess wind at any time during the day as well as any PV causing voltage rise on the system. Using the actual car as a store depends on whenever it is plugged in.
- Battery life will be longer as they can be optimally charged and discharged.

Figure 34: Energy Hub concept schematic



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23.Information about the author.

William Orchard of Orchard Partners London Ltd read engineering at Oxford and was trained by BTH, AEI, and GEC in electrical and mechanical engineering. Subsequently becoming a building services engineer. His most recent engineering design work is associated with a demonstration condensing CHP designed to serve domestic premises to deliver greater savings. He is working on further improvements to the basic successful Danish model for retrofitting cities as practised for the city of Odense (population 175,000), which also serves other smaller towns.
William is one of the foremost experts in CHP in the UK. He initiated the UK Combined Heat and Power Association (CHPA), and served on EU and UK standards committees for pre-insulated underground piping utilised in district heating heat networks. He is also a contributing author to design guides for the Building Services Research and Information, on how to link CHP with boilers so the CHP takes the heat load first linked to more efficient fully variable flow heating systems for buildings and district heating.
He has carried out a number of due diligence and national energy policy studies working with teams of economists. As a result he has an extensive knowledge of different district heating systems in Europe and the former Soviet Union and the economic modelling of such systems. He is aware of the potential for district heat as an integrated utility with electricity and gas to minimise national CO_2 emissions. He thinks that a Limited Liability Partnership, LLP, or cooperative structure and ownership of new heat networks where the gas and electricity utilities become partners in the network could provide an attractive proposal for infrastructure investors, consumers and gas supplies due to a higher income stream per unit of gas with CHP.

It will however require a politician of sufficient stature to implement such a radical change to UK urban infrastructure as enshrined in the Energy Hub Proposal for UK cities.

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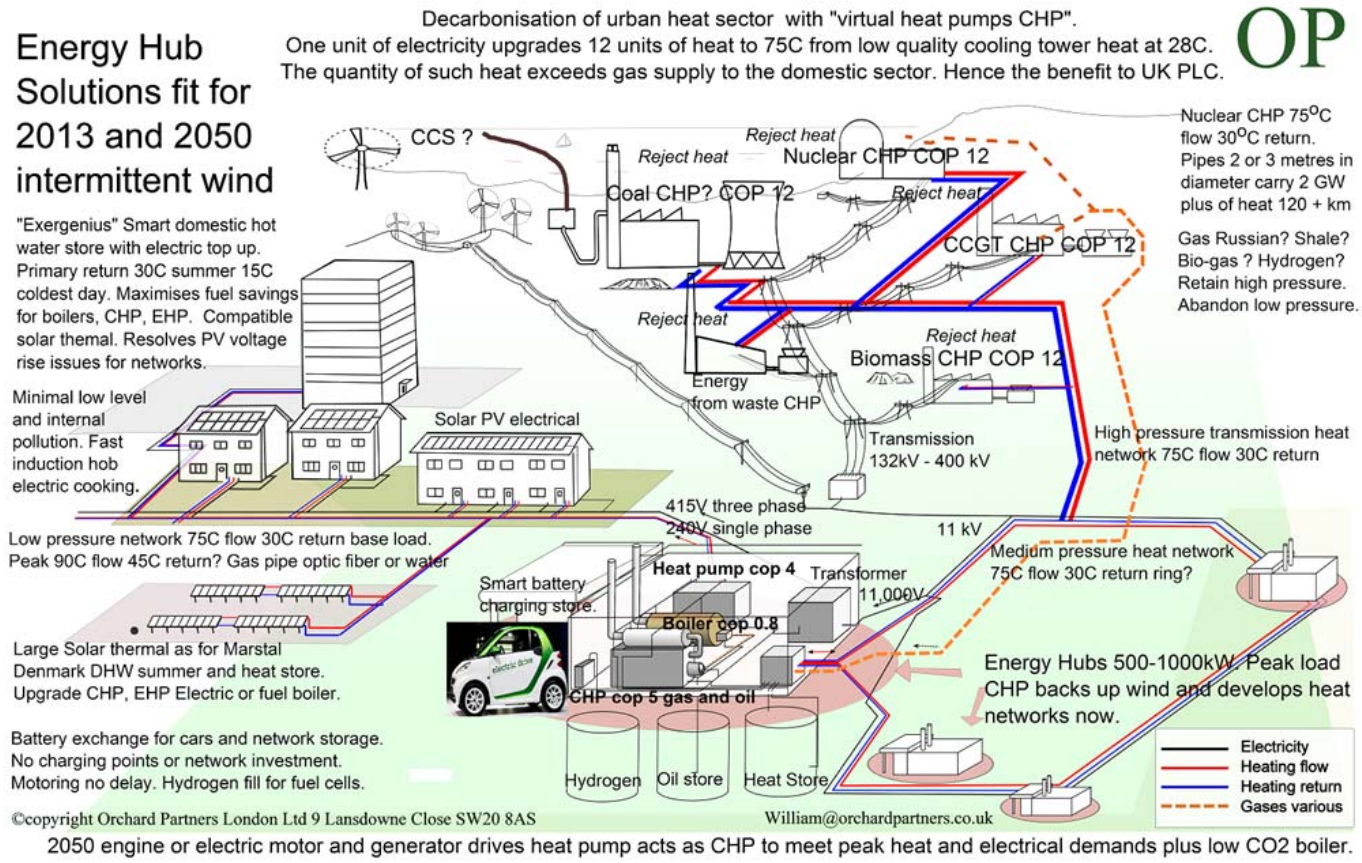
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