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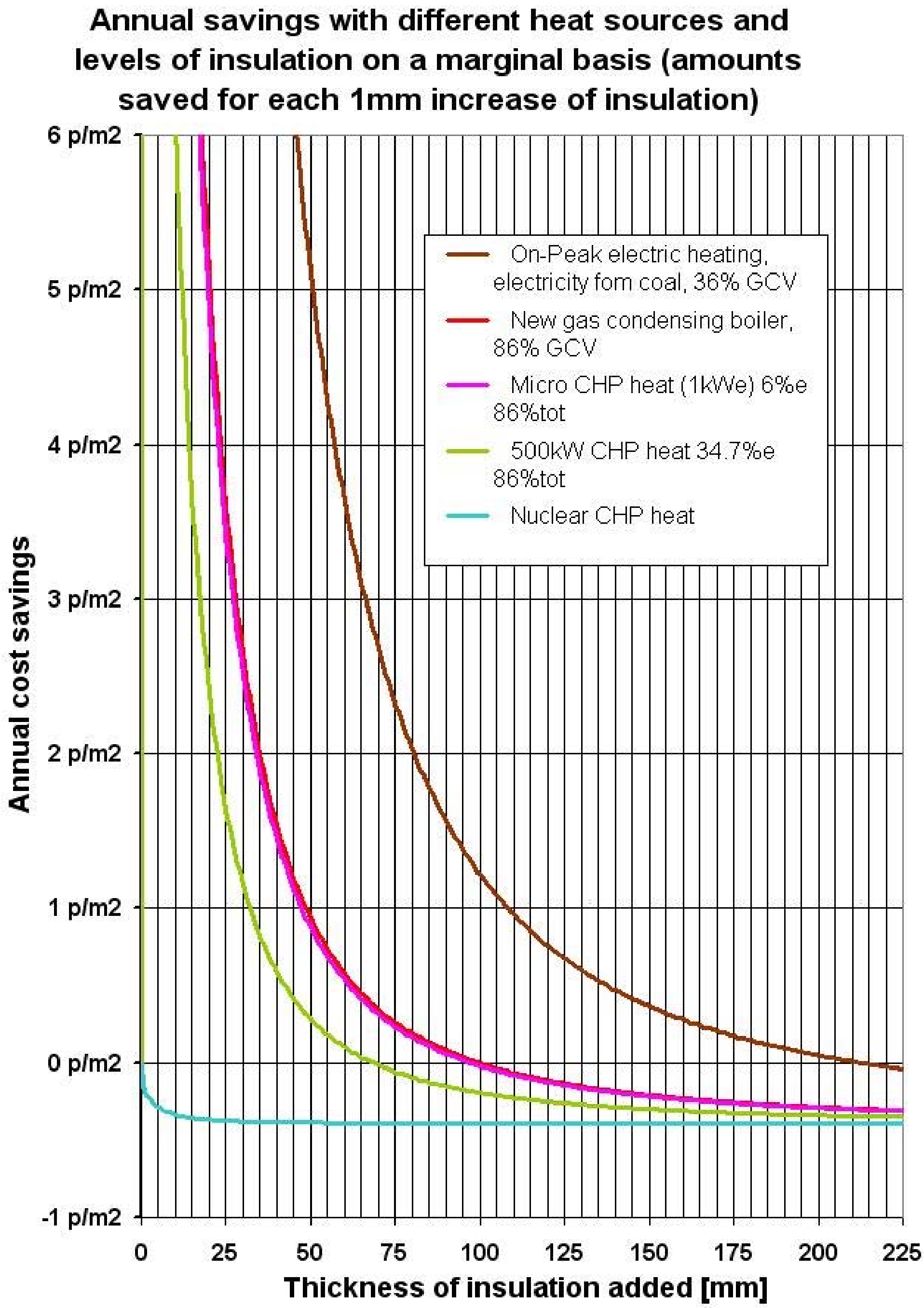
Zero Carbon Hub Consultation - Retrofit for the Future

The effect of low CO2 piped heat supply on the optimum level of fabric insulation and options for decarbonisation of domestic hot water supply and ventilation loads

November 2009



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Introduction

Low and zero CO_2 heat supply and fabric insulation fundamental principles

The paper considers the following:-

Issues arising from targeting CO2 footprints instead of energy.

Returns on investment depending on the CO_2 footprint of the energy supply vector.

Savings and returns on investment for initial thicknesses of insulation are high but incremental thicknesses offer increasingly diminishing returns.

At some point, adding further insulation achieves no payback on the incremental investment or an actual financial loss where the cost of the extra insulation exceeds the savings.

A point arises where investment in low CO2 piped heat supply has a lower cost per kW than the cost per kW of heat load displaced with incremental fabric insulation.

Low CO2 piped heat supply options address CO2 reductions for domestic hot water and ventilation loads not affected by fabric insulation.

This issue is important when considering retrofitting the existing building stock with more constrained and expensive fabric options, however it also applies to new build particularly where there is a source of low CO2 footprint heat.

The paper suggests that fabric insulation standards being considered by the Hub should take account of the CO2 footprint of the heat supply system as part of any future changes to the Building Regulations and evaluate the marginal costs of increasing the capacity of piped heat supply systems meeting domestic hot water loads and ventilation loads compared to increasing investment in higher levels of fabric insulation.

The analytical process

The spreadsheet provides a simple tool to signal the optimal balance for different CO_2 energy supply options and investment in incremental fabric measures to reduce demand.

It has been developed as part of our Retrofit for the Future Feasibility work where exisitng built form is a constraint.

An existing structural element in a building is analysed and improved to determine the balance between investments in low CO_2 heat supply options to minimise CO_2 emissions for each element in the heat load of the dwelling.

The domestic hot water load is an annual base load is only slightly influenced temperature due to changes in the temperature of the cold water supply. The number of residents and their behaviour patterns are the major factor influencing demand.

The heating and domestic hot water loads for a terraced house built in the 1960s with three occupants as part of a Retrofit for the Future feasibility, show that the CO2 emissions for various uses of electricity, are greater than emissions from for their gas fired space and water heating.

The ventilation load is temperature based, with or without mechanical heat recovery ventilation (MHRV). This load also reflects a load that has an energy requirement unrelated to the fabric insulation.

The charts in this paper illustrate how the marginal cost for insulation rises from £1000 per kW of heat load displaced at 60mm of insulation to £9000 per kW of heat load displaced at 200mm of insulation.

Cost inputs to the spreadsheet can be readily changed to those used in the Hub’s spreadsheet for insulation of walls as its structure is the same as the method used by the Hub as it takes a two brick wall and analyses the effect of adding Celotex insulation to increase the width of the cavity filled with insulation.

The analysis in this spreadsheet is based on the costs for incremental thicknesses of Celotex a PIR foam insulation.

The benefit from the insulation is measured by a value of CO_2 displaced using a figure of £100 per tonne of CO_2.

An example when no fabric insulation is optimal for a low CO_2 energy supply vector

A simple example of optimal insulation being zero is the use of reject heat from power generation in motor vehicles.

The heat rejected from any engine has to be rejected to an environmental lower temperature heat sink to produce power in accordance with fundamental laws of thermodynamics.

In thermodynamics the greater, the difference in temperature between the heat source and the heat sink (the environment) the greater the potential power production.

The heat has a zero marginal cost, as the use of heat does not change the fuel for the journey.

Whether the heat is used to heat the passengers or is rejected to the environment through the cars exhaust or radiator and fan has no impact on the CO_2 emitted by the car to the local environment and biosphere.

Waste heat within the boundary of a vehicle is thus a "Zero CO_2" form of energy, despite the fact that the vehicle itself is using a fossil fuel for its power production.

There is no benefit in insulating the car, as insulation of the car will only increase costs and CO_2 emissions depending on the amount of CO_2 emitted because of the manufacture of the insulation and its installation.

The use of reject heat from all forms of thermal electricity generation follows similar principles and is our largest potential source of zero and low CO_2 energy in the UK.

The city of Odense in Denmark is a model that demonstrates how piped waste heat systems can be retrofitted to heat a city replacing heating from electricity and boilers with their much higher CO_2 footprints, illustrated in this paper.

Energy supply from Gas engine driven heat pumps and electrically driven heat pumps

Heat pumps are mechanical devices driven by engines or electric motors.

CO_2 savings with heat pumps tend to be maximised where they are directly driven by engines, as the waste heat from the engine itself can top up the temperature of heat from the heat pump.

Energy supply from City wide CHP low CO_2 piped heat and electric heat pumps

For city wide CHP the temperature of the heat source at 30°C is higher than the temperature sources for air and ground source heat pumps. Typically, for ground source heat pumps it can be at say 8°C, and air varying from 16°C to minus 4°C for the heating load, and minus 4°C to say 24°C for the domestic hot water load over the year.

Both electric heat pumps and CHP use electricity to upgrade heat from the environment.

In the case of citywide CHP, some electricity production is sacrificed to raise the temperature of rejecting heat to the environment from 30°C to 95°C. It then becomes economic to heat cities with this waste product.

A special type of steam turbine is used that can change its operation so that it can either just produce electricity and reject heat to the biosphere at 30°C or pass out steam to district heating condensers to produce heat at 95°C to heat cities. The city therefore becomes the heat sink that is required by physical laws.

The electrical Coefficient of Performance "COP" for heat from such large CHP units, i.e. electricity used in ratio to heat gained is between 10 and 12.

For air and ground source electric heat pumps, the electricity is transmitted from the power station with associated losses and further losses to drive the mechanical heat pump.

The coefficient of performance of these electric heat pumps producing heat at around 45°C compared to 95°C from the CHP is between 2.5 and 5. When producing heat at higher temperatures required for domestic hot water i.e. above 60°C to avoid legionella, the coefficient of performance is lower.

The directly driven heat pump was widely promoted by the Gas industry as part of their opposition to the recommendations of Energy Paper 35 that piped heat supplies and a Heat Board should be set up to implement retrofitting parts of all UK major cities to accept heat supplied from CHP. The paper projected carbon savings of 30 million tonnes of coal equivalent per annum in the heat sector for the retrofitting of district heating in our cities.

Typical figures are illustrated of the relative actual CO_2 footprints from the different options in the following table, which also includes information on COPs for different options as well as efficiencies.

Table of CO_2 footprints for different energy supply vectors for buildings

CO2 Footprints for Heat Supplies to buildings

CO2 footprint for fuels and heat sources
Clean piped heat supply systems and domestic options.
CHP heat no different to an electric heat pump. Electricity upgrades heat. Note COPs
Tax signal is for heat, electricity or fuel when CO2 is valued at £100 per tonne.

Heat supply options gross (higher) calorific value (CV) basis and efficiency (eff)	$kg/CO_2/kWh$ per unit of Energy	Distribution losses: Energy Average loss %	Distribution losses: CO_2 Average loss kg	$kg/CO_2/kWh$ Energy delivered	Tax signal pence per kWh
Hydrogen fuel electrical production 80%(eff)	1.046				10.463
Biogas burnt in 86% (eff) domestic boiler.	NA	NA	NA	1.008	10.081
Electricity from coal 36%	0.837	10	0.084	0.920	9.200
Biogas as a fuel 40% (eff) conversion from biomass (Lund University Maria Berglund Pal Borjesson)	0.850	2	0.017	0.867	8.670
Biomass wood boiler 78%? (eff).	0.436	5	0.022	0.458	4.577
Electricity from gas 48% (eff)	0.397	10	0.040	0.437	4.370
Biomass (wood) as a fuel	0.340	NA	NA	0.340	3.400
Air source heat pump COP 2.5 (Electricity from coal)	0.335	0	0.000	0.335	3.348
Coal as fuel	0.301	NA	NA	0.301	3.010
Old gas boiler	NA	NA	NA	0.255	2.550
New condensing natural gas boiler 86% (eff)	NA	NA	NA	0.222	2.220
Heat micro CHP 1kWel 6% (el) (eff) 86% (eff) overall	0.212	NA	NA	0.212	2.120
Natural gas as fuel	0.191	2	0.004	0.195	1.950
Heat pump very good heat source, COP 5 electricity from coal	0.167	0	0.000	0.167	1.674
Piped heat from gas fired 500 kWel CHP 34.7 % (el) (eff) 86% (eff) overall	0.103	10	0.010	0.113	1.130
Piped heating from very large biomass CHP co fired with coal.	0.075	20	0.015	0.089	0.895
Piped urban district heating from coal fired CHP equivalent COP 12.7	0.066	20	0.013	0.079	0.790
Piped urban district heating from gas fired CCGT CHP equivalent COP 12	0.033	20	0.007	0.040	0.400
Electricity from wind, DTI Future of Nuclear Power page 49	0.020?	10	0.002	0.022	0.220
Electricity from nuclear 0.006 to 0.026 DTI Future of Nuclear Power page 49	0.010	10	0.001	0.011	0.110
Piped district heat from nuclear fired CHP equivalent COP 10	0.001	20	0.000	0.001	0.012

Note Table signals CO2 emitted when bio fuel is burnt to signal optimal use. The Building Regultations might consider some similar methodology so that poor utilisation of this scarce resource is prevented. Growing wood to store its CO2 in our buildings gives greater CO2 savings than burning it. 2009-11-03

This table sets out the CO_2 footprints of different energy vectors and the assumptions behind the calculations. For comparison purposes, it signals the relevant tax that would apply to each supply energy vector or fuel if a CO_2 tax were set at £100 per tonne of CO_2. This is similar to the incentives given under ROCs of £80 per tonne and is less than other recent incentives for low CO_2 technologies.

The column "Energy average loss" and "CO_2 average loss" is included to show how different the CO_2 losses from piped heat supply systems are compared to electrical CO_2 losses.

Piped heat supply systems have marginal losses that tend to zero as for the same temperature of heat supply the losses remain relatively constant. For electricity supply the losses rise to 20 to 25 % at times of peak power demand, due to power being a function of current squared multiplied by voltage.

Biomass and waste heat from electricity generation

Waste heat from power generation, whatever the fuel, has a relatively small impact on the biosphere when one compares burning wood to using it as a building material. This use stores its carbon instead of returning it to the biosphere.

The table has been structured to show the actual CO_2 emissions for various conversions of biomass, assuming that dry wood is the input fuel. Actual emissions are greater where the biomass is wet and when biomass of a lower calorific value in relation to its carbon content than dry wood is the feedstock.

It is interesting to note that CO_2 emissions per kWh of energy in the fuel are greater for dry wood than they are for coal. This came as a surprise to the author.

Explanation of the spreadsheet

The spreadsheet calculates the effect of adding one mm thick layers of a selected insulation material to improve the thermal properties of an existing structure of a defined U value. For the economic analysis, the savings achievable with the insulation of different thickness is then compared with the cost of the insulation. As the carbon content and costs of different heat sources are different, the spreadsheet gives the opportunity to select a number of heat sources for comparison.

To examine the effect of a structure built entirely of a selected insulation material and its optimum thickness the U value can be set to a high value.

The spreadsheet as supplied follows the same basis as the model used in the Hub's consultation of a two brick cavity construction and then an increasing amount of insulation in the cavity.

Structure of spreadsheet

The spreadsheet is divided into several tabs.

A table for the input data for the wall structure and insulation

A table for input data for heat sources

A large table, in which all calculations are carried out

Tabs of the spreadsheet with various charts presenting results of calculations.

Input data tab for temperature conditions, wall structure and insulation

On this first tab of the spreadsheet, the wall to which the insulation is added can be defined by putting in the U-value of the un-insulated wall.

Secondly, the design conditions can be defined by defining the external and internal temperature for the design conditions of the building. These values determine the temperature difference between the inside and outside of the wall in question and are used to calculate the heat loss under design conditions.

Next, the annual degree hours are required. The Technology Strategy Boards Retrofit for the Future Programme is using a figure of 95000-Kelvin hours reflecting the Manchester area as a basis for comparisons for projects. We have adopted this figure.

This value is used to estimate the annual energy losses through walls and other elements measured in kWh per square metre.

The required pay pack time is used to convert the capital cost of the insulation measure into an annual cost stream for the capital. This is then used to compare the cost of the insulation measure with the annual savings.

To convert real rates of return and lifetime to payback, the table in the second tab can be used. The real rate of return is in the left column and the lifetime of insulation or other capital investment is in the top row. E.g. if the real rate of return is 3.0% and the life expectancy of the insulation is 60 years, the equivalent pay back time for a regular income is 24.94 years.

The insulation type can be selected by typing a reference number out of the list of insulation materials that is given in the table (see cells G14 to V14) into cell E14.

Note that this table is work in progress; the only option currently is Celotex. Other options are being considered and we would be grateful if we could be sent Hub assumptions to add to the spreadsheet.

Values of the insulation material that go into the calculation are the thermal resistance of the insulation, the installation cost and the material cost. For the installation cost, it is assumed that this is independent of the thickness of the insulation as a first approximation but the sheet allows for changes in fixed cost with thickness to be added.

The sheet assumes that the material costs rise with the thickness of the insulation. This marginal material cost is calculated by dividing the cost difference of insulation with the thicknesses A and thickness B, by the difference in thickness.

Where a specific marginal cost of the material is known the marginal cost figure can be inserted.

Any additional material cost that is independent of the thickness will be included in the initial installation cost.

The spreadsheet also gives the opportunity to account for additional installation cost that may apply from a certain thickness on (e.g. if the thickness of any structural beams is exceeded).

Note: if you want to run the numbers with a different insulation material, define your insulation in one of the columns G to V and select the equivalent insulation reference in cell E14.

Input data tab for heat sources

In this table, the carbon value or tax can be selected (cell E1).

In cells E7 to I7, five different heat sources can be selected by typing the equivalent reference numbers into them.

The heat sources can be defined in the table next to it. Costs other than costs associated with the CO_2 emissions can be defined in lines 12 to 14. The following table shows typical CO_2 footprints of different heat sources.

Please note that all the information in this document is based on the gross or higher calorific value of the fuel. The gross calorific value reflects the maximum value that can be taken out of the fuel by condensing the products of combustion to STP.

Table with calculations tab

This table calculates all values used in subsequent charts. All values like U-values, heat losses, annual energy, costs etc. are calculated for each insulation thickness starting from 0mm to 2000mm (2 metre). See column B.

Note that the calculation for the U value uses a simplified formula[1].

[1] U value of insulated wall = 1 / ((1/U-Value of insulation) + (1/ U-Value of wall))

Chart number 1: U-Value of new structure showing total and average cost of insulation depending on insulation thickness

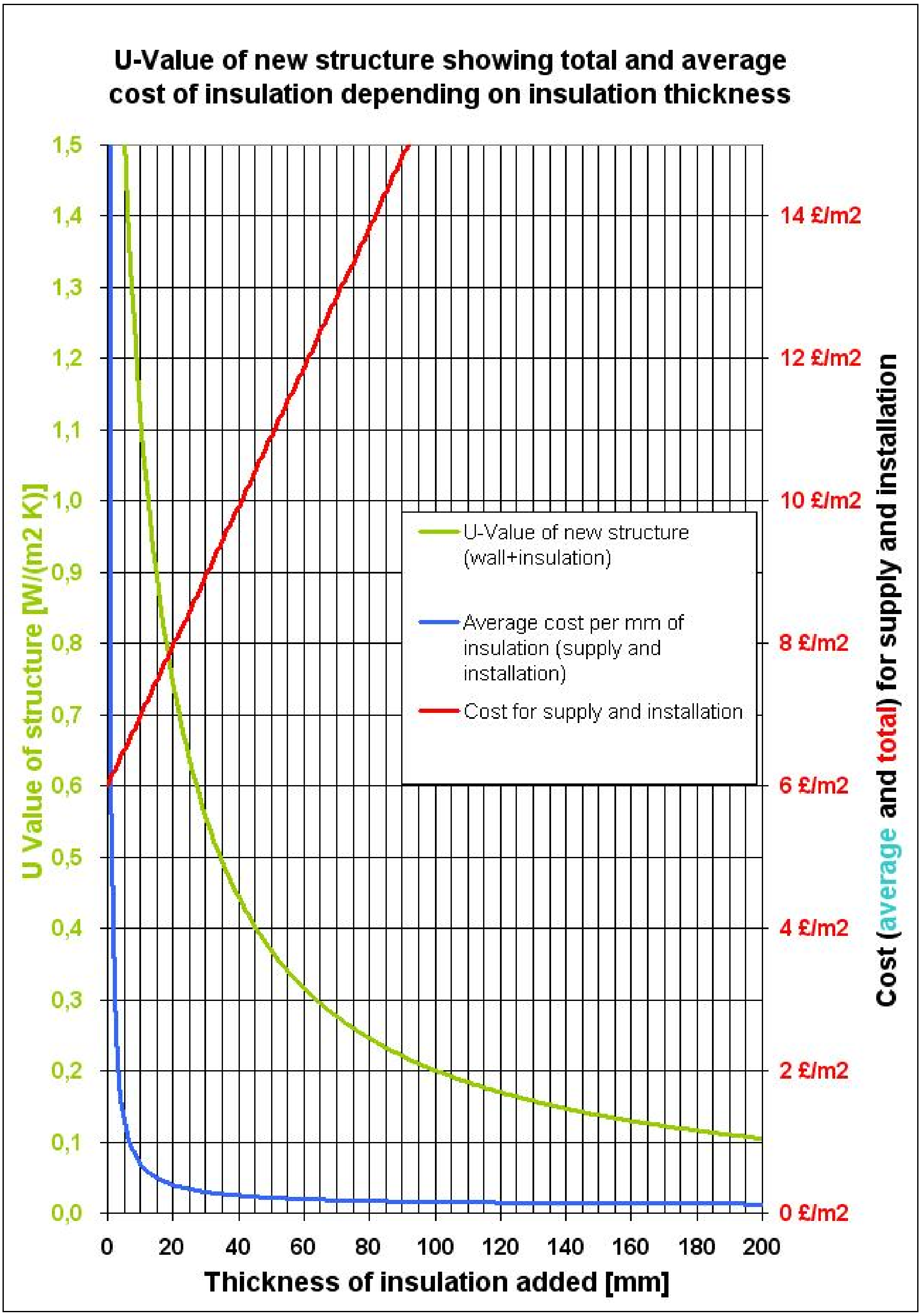

Figure 1: U-Value of new structure showing total and average cost of insulation depending on insulation thickness

On this chart, the changing U-Value of the insulated wall is plotted against the left axis. It can be seen that the U-Value reduces dramatically when adding the first millimetres of insulation, but the more insulation is added the flatter the curve becomes, meaning that the benefits of adding more and more insulation become smaller and smaller.

The red line, plotted against the axis on the right, shows the cost of the installation, starting with the fixed installation cost and rising linear with the insulation thickness reflecting the cost of the material.

The blue line, plotted against the right axis shows the average cost of insulation per mm of insulation thickness. The first mm of insulation added costs the most, because all the fixed cost is allocated to it. As more mm are added, the cost per mm reduces as the fixed costs are distributed to each mm of insulation.

(e.g. if an insulation thickness of 10mm is added, each mm will cost the equivalent material cost per mm plus 1/10th of the fixed costs).

Chart number 2: Load reduction kW per m_2 and capital cost per kW of heat load displaced for each total thickness"

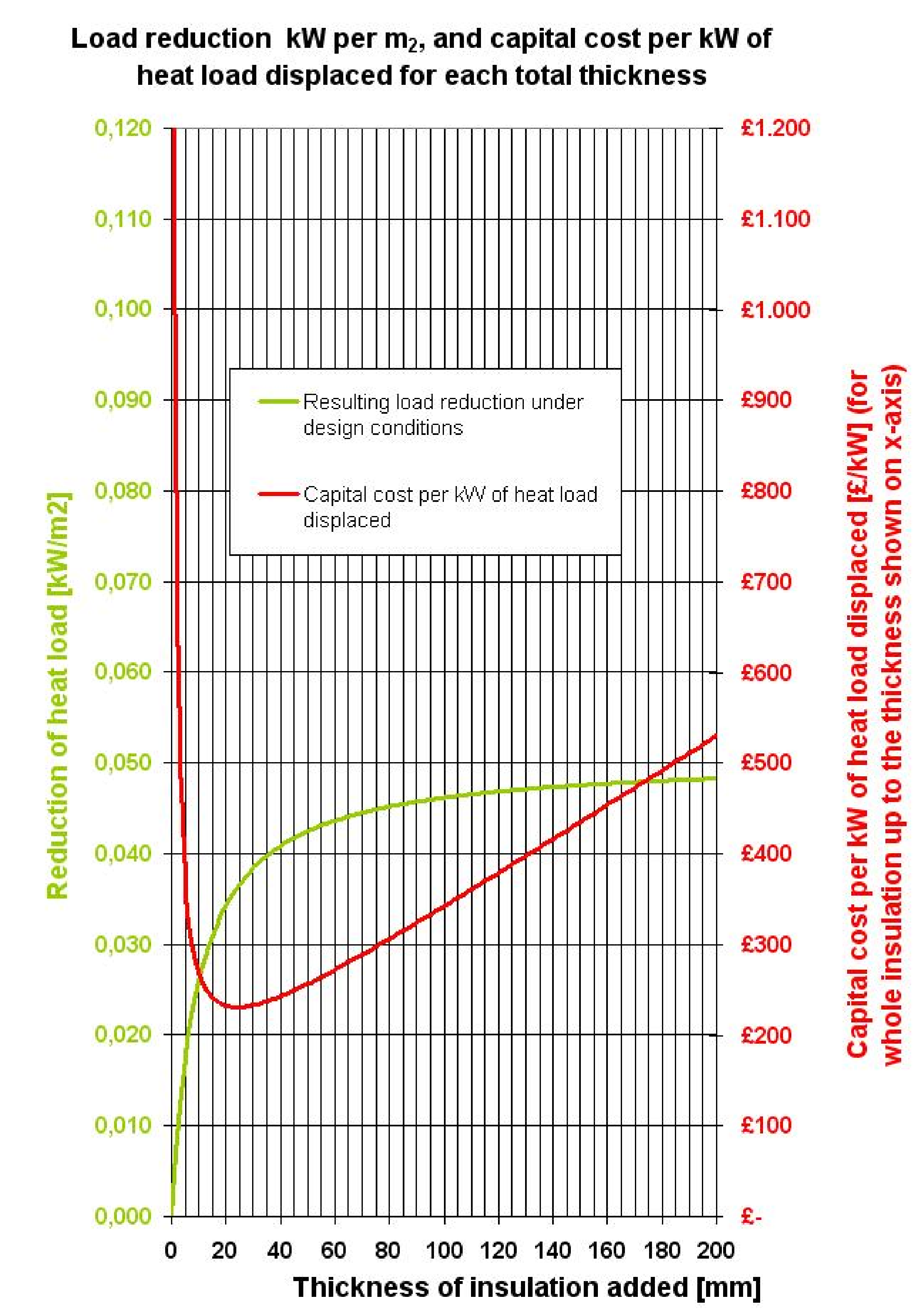

Figure 2: Load reduction kW per m2, and capital cost per kW of heat load displaced for each total thickness

This chart shows the reduction of the heat load for the different insulation thickness (green line, plotted against the left axis) and the capital cost per kW of heat load reduction (red line, plotted against the right axis). As it could be seen on the first chart, the reduction of the U-value is significant for the first number of millimetres, but gets very small for very high insulation levels. As a result, the curve showing the reduction of the heat load is steep for the first number of millimetres, and gets less and less steep for higher insulation levels.

The capital cost of the insulation on the other hand follows a linear function (except for the initial fixed cost). As a result, the line showing the capital cost per kW is strongly influenced by the high reduction of the heat load from the first millimetres of insulation (left side of chart). It follows an increasingly linear pattern at the higher insulation levels (right part of chart as the heat as the heat load does not change very much, whilst the capital cost "keeps rising").

The point where the red line is at its lowest shows the level of insulation with the lowest cost per kW of heat load displaced. Note that this is not necessarily the most economic level of insulation, as this depends on the cost of the heat supply (if the heat is completely free it wont be cost efficient to insulate at all, if however the heat is very expensive the most economic level of insulation will be higher). See further charts that include the heat supply side.

Chart number 3: Marginal load reduction and capital cost per kW of heat load displaced

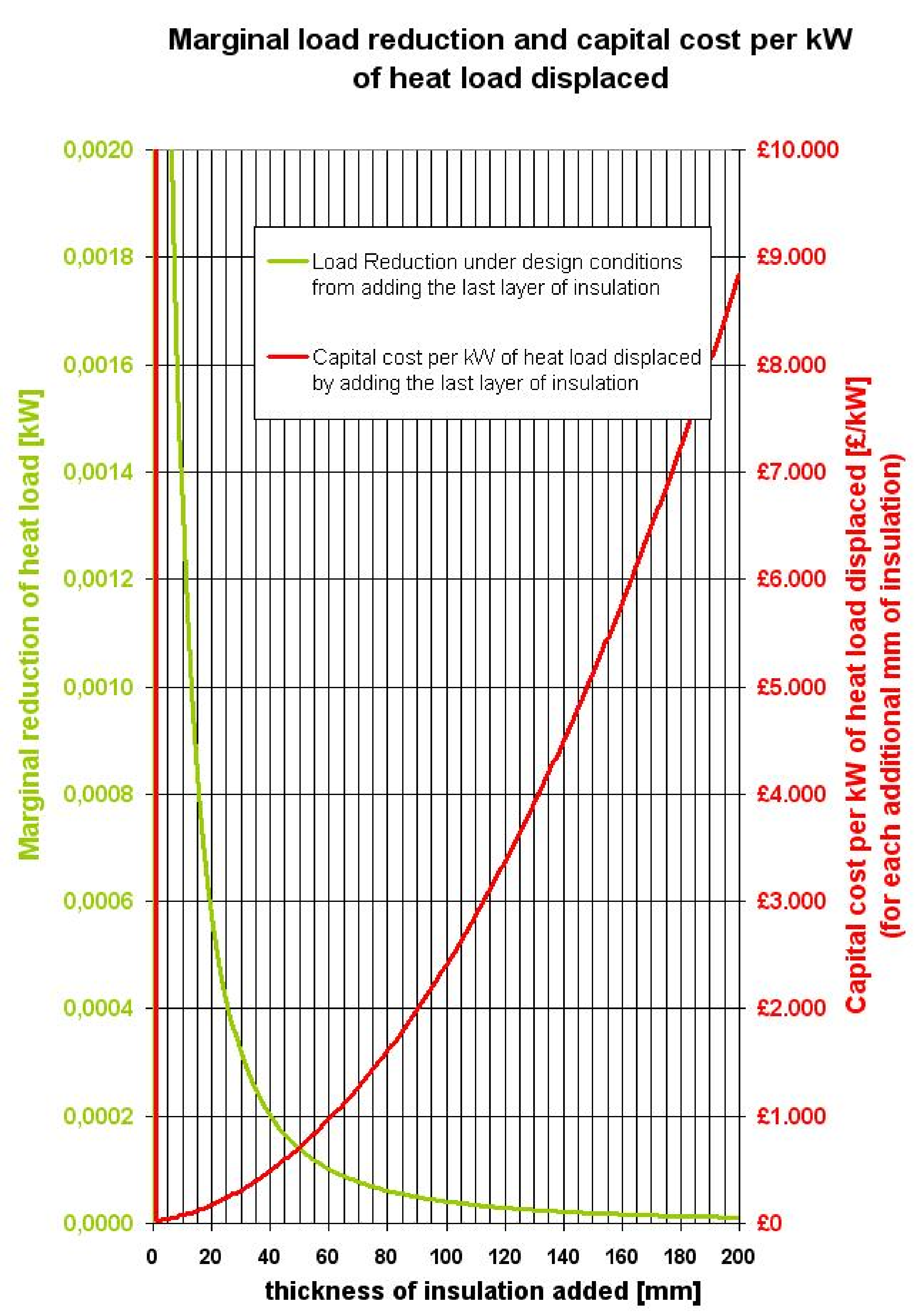

Figure 3: Marginal load reduction and capital cost per kW of heat load displaced

This chart shows the marginal load reduction and marginal capital cost per kW of heat load displaced. The green line shows the marginal load reduction, which is the additional reduction that is achieved by adding another layer of insulation to the wall that is already insulated to the level shown on the x-axis. The steep pattern in the left part of the green line in the previous chart is reflected in very high values of the green line in this chart, as each additional millimetre will achieve high load reductions. As the insulation gets thicker, the additional benefits from each new millimetre are getting smaller. Because of this sharp decline of additional load reduction, the cost per kW of heat load displaced is rising very steeply with increasing insulation thickness (red line, plotted against the right axis).

At some point this cost will exceed the cost per kW of capacity of the low CO_2 piped heat supply option.

A step change in the optimal thickness of fabric insulation takes place when an energy supply vector is changed.

SAP and PHPP suitable tools for minimising CO2 emissions from existing and new building stock?

A change in supply vector changes the CO_2 emissions from the domestic hot water and ventilation and these savings become dominant as fabric energy consumption is reduced.

Measurement per unit area of a building has little relationship to electrical appliance use of domestic hot water usage.

Further, the area depends on built form.

We suggest that possibly particularly for the retrofit market that the decisions will depend on the actual existing structure.

We suggest that the effect in this graph should be modelled as part of the Zero Carbon Hub's objective to minimise CO_2 emissions from buildings and in future Part L standards. It will mean considering different fabric standards for different heat supply options if overall minimisation of cost and CO2 emissions is to be achieved.

There is some question as to whether the current Structure of SAP or PHPP is an appropriate tool for such a task.

We recommend that consideration should be given to a fresh approach and structure to take account of the changes arising from the increasing use of piped heat supplies in the future whether from biomass heat pumps or CHP.

Building regulations are currently structured just to consider a specific dwelling. There are benefits in analysing communities of dwellings or blocks of flats and even cities as this allows more low CO_2 supply options to be evaluated.

Chart number 4: Square metres needed to displace one kW of heat

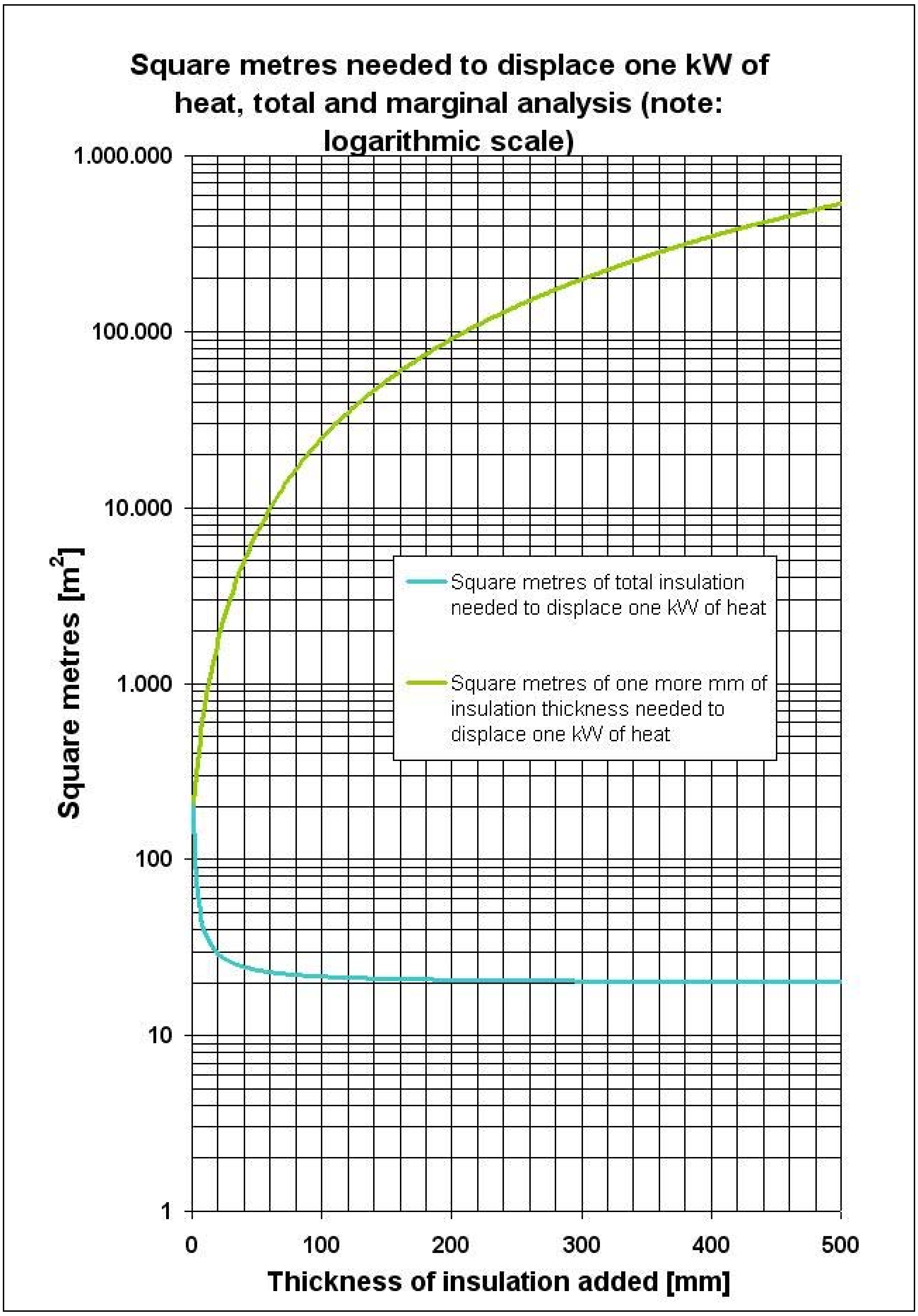

Figure 4: Square metres needed to displace one kW of heat, total and marginal analysis (note: logarithmic scale)

This chart shows the square metres needed to displace one kW of heat load, both on a total and marginal analysis[2]. The blue line signals the square metres of total insulation needed to displace one kW of heat load for the insulation thickness shown on the x-axis. The green line looks at the square metres of wall that are needed to displace one kW of heat load by adding one more millimetre to the wall at the insulation thickness on the x-axis.

[2] This is the reciprocal of the kW displaced per square metre showed on the previous charts

Chart number 7: Annual savings with different heat sources and levels of insulation (total savings for the thickness of insulation indicated on x axis)

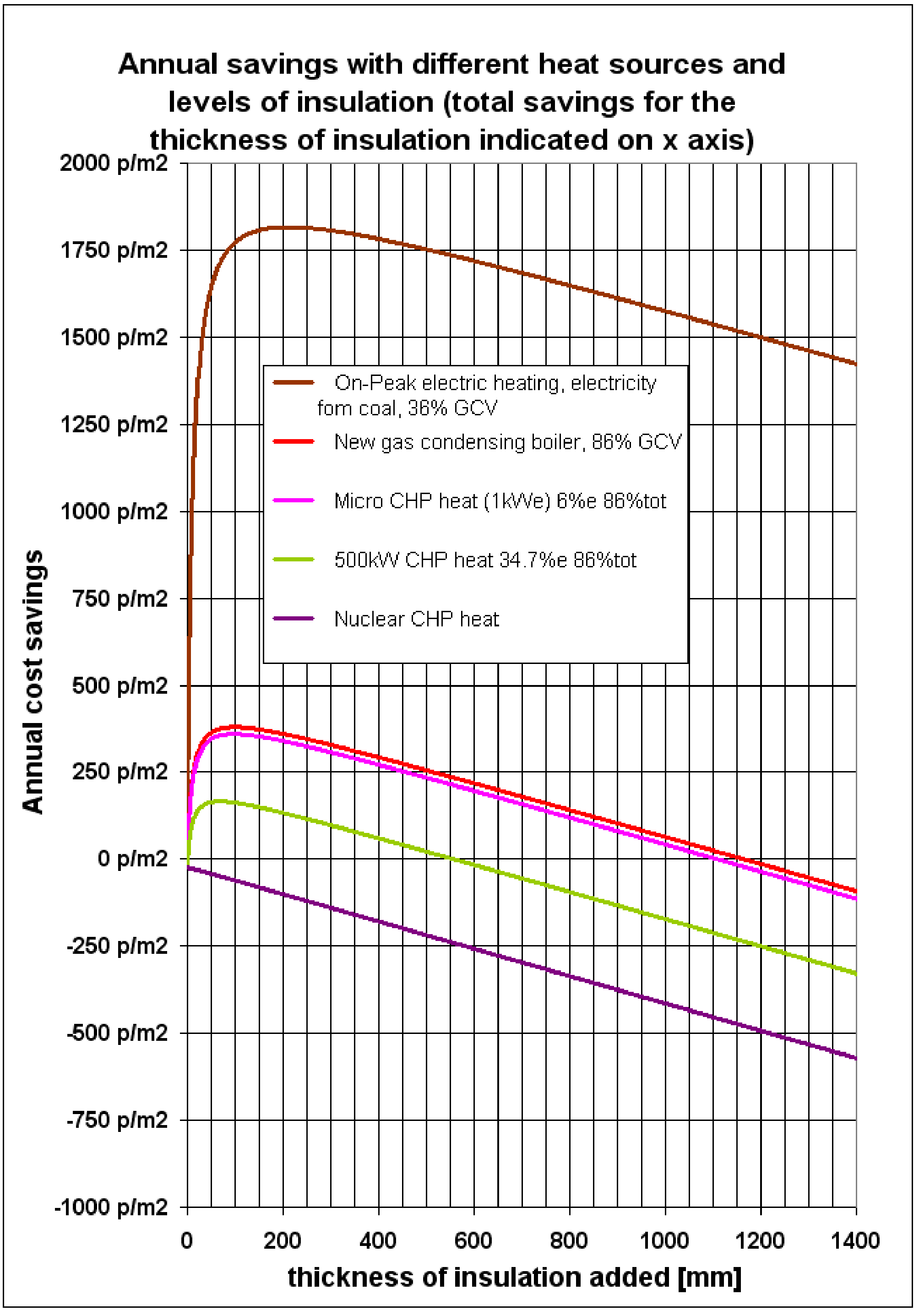

Figure 5: Annual savings with different heat sources and levels of insulation (total savings for the thickness of insulation indicated on x-axis)

This chart shows the annual savings minus the annual costs for different heat sources.

The point where the lines peak reflects an optimal level of insulation. This most economic insulation thickness can be much better seen on a chart using a marginal analysis shown in the following chart.

Chart number 8: Annual savings with different heat sources and levels of insulation on a marginal basis (amounts saved for each 1mm increase of insulation)

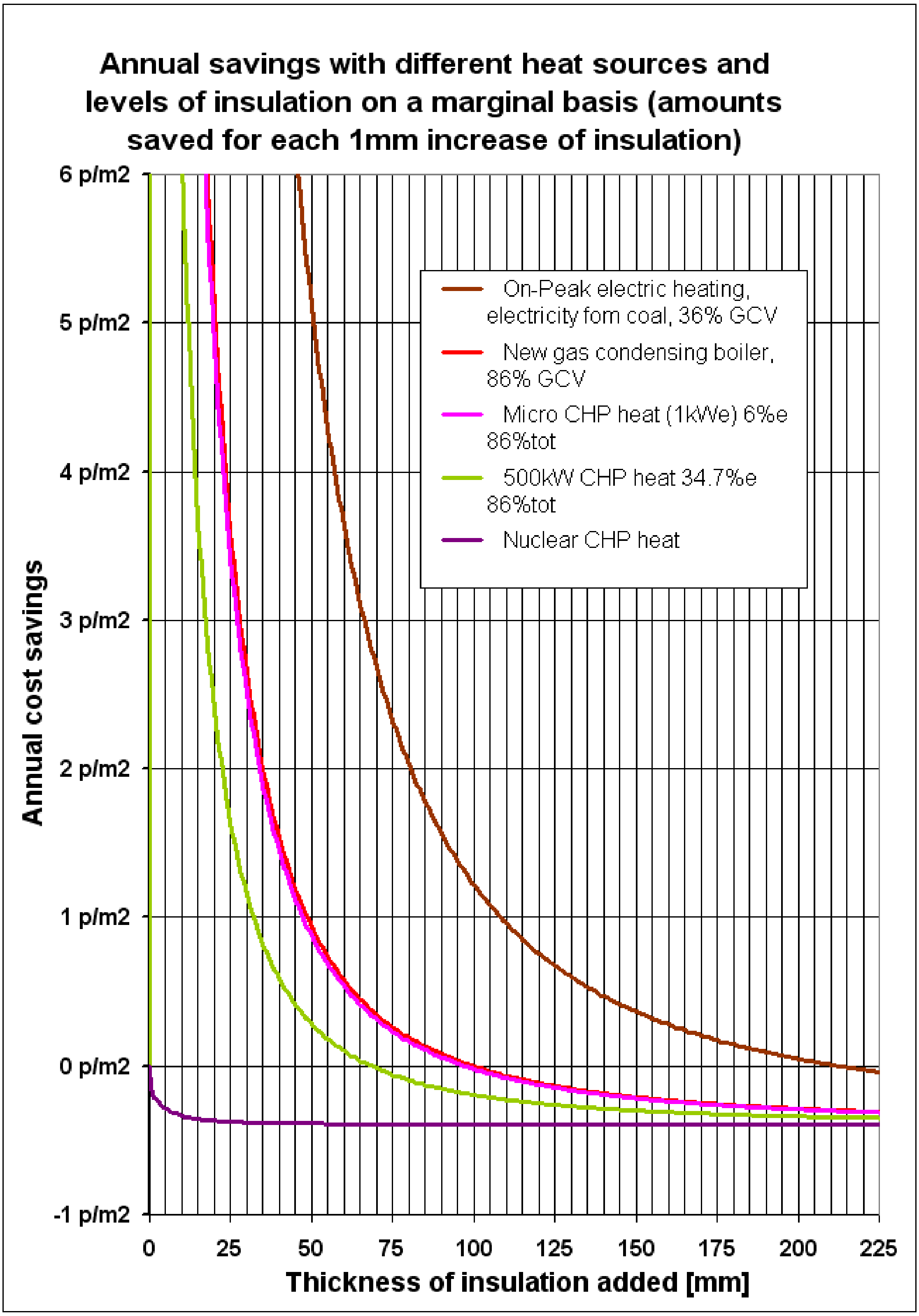

Figure 6: Annual savings with different heat sources and levels of insulation on a marginal basis (amounts saved for each 1mm increase of insulation)

This chart shows, from which point of insulation thickness the cost of an extra one-millimetre layer of insulation gets greater than the savings from it. This occurs, where curves cross the zero-line. A thicker insulation will give small extra savings but a negative return on the investment for the selected real rate of return.

Note the large difference in optimal insulation levels for very high CO_2 emitters such as electricity compared to the use of reject heat from electricity generation for decarbonisation of the heat sector.

The insulation that is optimal for the waste heat from thermal generation from nuclear fuel is lower than the insulation value of the solid wall using CO_2 as the sole basis for the analysis.

Other CHP options fall between the nuclear line and the 500kW gas fired CHP.

These can be readily plotted by substituting the lower CO_2 footprint for heat from coal fired CHP instead of that for the 500 kW gas fired CHP.

Spreadsheet history

The spreadsheet was originally developed to analyse the building stock in the Ukraine by Orchard's working as sub consultants to AEA for an EU national energy strategy led by Dr Roger Price. The most recent version has been developed with Max Fette who worked on previous versions for Orchard Partners London Ltd.

We trust it will assist the Zero Carbon Hub in its work to assess the practicality and costs associated with modifications to Part L of the building regulations.

We look forward to working with the Hub and their objective to produce cost effective solutions towards lowering the CO_2 footprint of new buildings and the existing building stock

Recommendation that SAP signals actual CO_2 emissions from biomass when burnt, as well as the amount removed from the biosphere

We recommend that the building regulations in some way signal the actual CO_2 emissions from biomass to optimise its use as a sustainable source of energy.

We suggest that SAP modifies its cost basis for its supply side options to a basis that signals the CO_2 tax that would apply on actual CO_2 emissions. Typical figures for use might be those calculated in the table in this paper.

This would effectively signal the likely marginal CO_2 overhead for the different options to add to marginal cost or tariff signals for the respective products.

We suggest that the appropriate signal for electricity, due to the large variation in CO_2 footprint for this product depending on its source, should be the same CO2 signal given to encourage investment in renewable electricity.

This in terms of ROCs at £80 per tonne of CO_2, equates to 8p per kWh of electricity from coal with a CO_2 footprint of 1kg CO_2 per kWh.

Renewable electricity is justified and subsidised on the basis that it displaces coal-fired plant. There are economic advantages in giving the same signal in principle to all consumers on the demand side to encourage them to invest in lower CO_2 energy supply options and to reduce their demand in parallel with investment in renewables. This will accelerate the decarbonisation of the electricity sector, which in many countries is the major CO_2 emitter from the residential and commercial sector buildings.

Such a signal will accelerate the rate that the electricity network will be decarbonised with renewable generation and increase the rate at which electrical good products improve their electrical efficiency.

Recommendation for renewable heat for Part L: CHP, electrically driven and engine driven heat pumps

We recommend that heat from CHP and fossil fired engine driven heat pumps should be accorded the same status as heat from electric heat pumps, that of renewable energy.

We recommend that reject heat from power generation be defined as renewable, as the process for upgrading the heat from 30°C to 95°C is no different to that of an electrically driven heat pump.

The CO_2 footprint of heat from CHP and fossil-fired engine driven heat pumps is in most cases lower than heat from electric heat pumps. Use of such heat also does not result in an increase in demand for electricity, a further reason for its renewable classification.

The heat from both sources is at a higher temperature, making it more suited to retrofit existing heating systems thus officering greater penetration of the heat sector than is possible with electric heat pumps due to their incompatibility with existing heating installations.

A further feature is that heat from CHP is at temperature that can supplement and raise the temperature of heat from electric heat pumps.

Currently in many applications, such as heating domestic hot water, electric heat pump applications switch to direct electric heating to reach the 60C temperature required for the water heating.

Electric heat pumps may have an important part to play in upgrading heat from geothermal sources where the source of the heat is closer to the source of environmental heat available for large scale CHP of 30°C. Such heat pumps will have much higher COPs than ground or air sources where the heat they are attempting to upgrade is at much lower temperatures.

We recommend that all forms of energy, feeding piped heat supply systems should be included in any plans for the encouragement of the use of renewable heat and the development of clean heat supply systems.

Actual CO_2 emissions from fossil-fired CHP are significantly lower than actual CO_2 emissions from biomass boilers, because the heat is a waste product that has to be rejected to an environmental sink.

Some mechanism to signal the actual emissions from biomass and the CO_2 emitted in its conversion to different forms of energy appears to be essential if Biomass is to maximise its potential as a CO_2 displacer in the heat and electricity sectors.

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