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The 20% house - an integrated assessment of options for reducing net carbon emissions from existing UK houses.

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Abstract

This paper takes an integrated analysis approach to explore the options available for a UK homeowner to reduce their domestic emissions to the level advised by the UK governments committee on Climate Change of 20% of those associated with a typical house in 1990. It uses proven thermal models of a typical house and low carbon heating systems to estimate the emissions associated with domestic heating and electricity consumption from a number of combinations of low carbon micro generation technologies. The amount of additional low carbon electricity needed to offset these emissions to the desired level was then calculated. The capacity of photo voltaic panels needed to generate it was then estimated. This has been done over a range of different grid carbon intensities and the resulting configurations have been subjected to energy analysis and financial appraisal. An environmental life cycle assessment was also undertaken to see if there were any unacceptable environmental consequences of an owner adopting any of the options. The research shows that in all cases operational GHG target can be met, but that emissions associated with the production of the systems is variable, meaning that with current technology a 25% house is more likely. It has also been shown that given current subsidies the installation of some of the proposed systems should be financially attractive to the home owner.

Keywords

net domestic carbon emissions reduction, micro generation, thermal modelling, life cycle assessment, PV systems, Financial appraisal

Abbreviations

ASHP	Air Source Heat Pump
CCGT	Combined Cycle Gas Turbine
CEF	Carbon Emission Factor
COP	Coefficient of Performance
DHW	Domestic Hot Water
FIT	Feed In Tariff
GHG	Green House Gas

ICE	Internal Combustion Engine
LCA	Life Cycle Assessment
mCHP	micro Combined Heat and Power
NRPER	non- renewable primary energy requirement
NPC	net present cost
PV	Photo Voltaic
SE	Stirling Engine
SOFC	Solid Oxide Fuel Cell
SHW	Solar Hot Water

1 Introduction

The need to cut greenhouse gas emission to avoid excessive climate change is now generally accepted [1-4]. The UK government's Committee on Climate Change [3] recommends that there should be an 80% reduction in green-house gas (GHG) emission by 2050. Concerned individuals may choose to reduce on their own emissions. This paper considers the options for a householder to reduce the emissions associated with their domestic energy consumption to this target level. To be viable an option must provide acceptable space heating, hot water services and domestic electricity, and not be prohibitively expensive or have unacceptable environmental consequences. In order to access each of these separate criteria it was decided to carry out energy modelling to establish workable options, environmental life cycle assessment to identify the environmental consequences of the option and financial analysis to investigate the economic cost to the homeowner. This multi criteria approach has been used in other similar studies [5-8, 76,77]

There is extensive literature on the application of micro generation to domestic properties including several integrated appraisal papers [5-8, 17-19]. Most of the previous studies have concentrated on the carbon savings which are likely to result from the use of a particular micro generation technology. This paper expands upon the literature by considering the potential use of combinations of micro generation technologies used in conjunction with mains gas and electricity to meet a net emission target.

This study concentrates on those technologies that can be widely applied in a urban area i.e. air source heat pumps (ASHP), natural gas fired micro combined heat and power units (mCHP), solar water heaters (SWH) and photo voltaic cells (PV). These technologies tend to have high capital cost consequently it is common practice to undersize the heating system with respect to the peak load and use a low cost gas boiler to boost the heat output in cold weather [9]. The use of biomass for heating was excluded from this study as there is limited scope to increase its use in the UK[10]. Domestic wind turbines were not considered as their performance has been shown to be poor in urban areas [11].

The aim of the study is to consider options for emission reduction, not energy self-sufficiency. The UK has a feed in tariff (FIT) scheme which allows small scale renewable electricity generators to feed power into the local electricity distribution network and pays them an enhanced rate for the electricity

[12]. This means that it is not necessary to consider battery storage with its inherent cycle losses, additional capital cost and environmental concerns [13]. The ability to export power to the supply grid gives the householder the option of generating more low carbon electricity than they consume in a year. This will contribute to lowering of the carbon intensity of the grid. This reduction in grid carbon emissions can offset the domestic carbon emissions associated with the energy used in the house.

Life Cycle Assessment (LCA) was conducted to assess relative environmental impacts of the competing technologies. LCA considers a range of potential environmental impacts over the life of the product or system, not just operational CO_2 emissions.

2 Background to micro generation technologies being considered

There are many reviews of micro generation in the literature and it is not intended to review them in this paper. This short overview is intended to summarise the operational feature of the technologies that are relevant to this analysis.

2.1 Air source heat pumps

ASHP are thermal engines that take heat from a low temperature source (the outside air) and deliver it to a high temperature sink. They require energy to do this. The ratio of the energy they use to the energy they deliver is called the coefficient of performance (COP). For them to achieve a reduction in emissions the emissions associated with the electricity they use must be less than those associated with the heating system they replace.

The COP is a function of the temperature difference between the heat source and sink. This can be minimised by operating the ASHP all of the time and controlling its output by modulating the output temperature such that the heat delivered from the heat emitters just supplies the net thermal losses from the building [22]. Under this proportional control strategy the heat pump output temperatures continually changes so it cannot provide Domestic Hot Water (DHW) at the same time as space heating. DHW can be provided by diverting the ASHP's output to heat a hot water tank to the required temperature.

2.2 Combined heat and power

The use of reject heat from electricity generation for heating is a proven way of improving energy utilisation and hence lowering emissions. The fuel utilisation of a gas condensing boiler is relatively high (>80%) [23] so a CHP scheme is unlikely to reduce the emissions associated with heating. Consequently any improvements in fuel utilisation in a CHP plant will come from the electrical output. It follows that to give significant savings in emission a gas fired CHP system should have high energy utilisation and low heat to power ratio.

There are three technologies that can be used for domestic scale micro CHP systems.

2.2.1 Internal Combustion engines

The use of gas fired internal combustion engines (ICE) is an established way to generate electricity. Utilisable heat can be recovered from the engine's cooling jacket and an exhaust gas heat recovery unit. Micro CHP IC units typically have electrical efficiencies of 24-30% and heat to power ratios of 2.5-2.0 [18]. An IC engine generates electricity as soon as it is up to speed but takes some time to heat up to a temperature where useful heat can be extracted. These engines are usually run at their most efficient output. They are switched on and off to maintain a thermal store within acceptable temperature limits. It follows that if the engine has been stopped because the thermal store is at temperature the heat stored in the engine cannot be used and is likely to be dissipated into its surroundings; consequently a large thermal store should be used to avoid frequent load cycling.

2.2.2 Stirling Engines

Stirling engines (SE) are heat engines that use external combustion to provide a hot source and cooling water to provide a cold sink. Useful heat can be extracted from the exhaust gases and the coolant. The engines are quieter and vibrate less that IC engines making them suitable for installations in occupied areas. Although their energy utilisation can be over 90%, commercially available units typically have high heat to power ratios. SE units only generate when their hot source is up to temperature consequently they need to be run for periods of over 1 hour to generate reasonable amounts of electricity [23]. A large thermal store is needed to achieve this in the summer if they are only used for DHW.

2.2.3 Fuel cells

There are a number of different fuel cell systems but in essence they all consist of a fuel processing unit, a fuel cell and a DC to AC inverter [24]. There are a number of opportunities to extract reject heat from the process which are dependent on the exact arrangement of the system. Fuel cells can have electrical efficiencies up to 60% and heat to power ratios of 0.3-2.

2.3 Solar Climate

The amount of solar energy available varies with the seasons and weather patterns. From analysis of typical solar year data for UK cities taken the Exeter University's PROMETHEUS database [28] it was found that standard deviation in annual irradiation of cities across the UK is only 7%. Consequently it was decided to carry out this analysis for a single city, Cardiff which has close to the average number of heating degree days for UK cities.

2.4 Solar hot water

The amount of solar energy harvested is a function of the collector area and thermal store size [25]. In this paper it was decided to use the same area of solar collector in all applications to avoid distorting the results.

3 Methodology

3.1 Configurations Modelled

Not all of the micro generation units being considered could satisfy the heating requirement of a household throughout the year so different combinations of equipment were assessed. Twenty configurations that were found to satisfy the heating requirements are given in Table 1.

Table1 : Configurations analysed

Case number	Primary heating System	Secondary heating system	Buffer size / kg	Solar thermal used?
1	Boiler	0	0	0
2	Boiler	0	80	0

3	Boiler	0	300	1
4	ASHP	Boiler	0	0
5	ASHP	0	0	0
6	ASHP	0	80	0
7	ASHP	0	300	1
8	High performance ASHP	0	0	0
9	Large ICE CHP	0	750	0
10	Large ICE CHP	0	750	1
11	Small ICE CHP	Boiler	750	0
12	Small ICE CHP	Boiler	750	1
13	Small ICE CHP	ASHP	750	0
14	Small ICE CHP	ASHP	750	1
15	SOFC	Boiler	80	0
16	SOFC	ASHP	80	0
17	SOFC	ASHP	750	0
18	SOFC	ASHP	750	1
19	SE CHP	0	750	0
20	SE CHP	0	750	1

An 80 kg domestic hot water (DHW) tank is used. It is replaced by a 300kg thermal store when solar water heaters are fitted to allow decoupling of DHW draw off and heating cycles. Larger 750 kg thermal stores are used with the CHP systems following manufacturers recommendations to avoid frequent load cycles.

The characteristic performance of each micro-generation system is summarised in Table 1.

Table 1: Characteristic performance of micro-generators

Equipment	Model	Heat rating kW	Electricity rating kW	Heat efficiency	Electrical efficiency / COP
Boiler	Generic Condensing	9.0		90%	
ASHP	Ecodan W8.5	8.5			2.7
ASHP	High Peformance				4.6
Large ICE CHP	Dachs HK5.5	12.3	5.5	59.5%	24.3%
Small ICE CHP	Ecowill (Freewatt)	2.8	1.0	56.8%	20.3%
SOFC	CFCL Bluegen	0.3 - 0.54	0.5 - 1.5	25%	60%
SE CHP	Whispergen	7.0	1.0	87.4%	8.4%

The heat pump COP values are for an air temperature of 2°C and water temperature of 35°C. ASHP are a rapidly developing technology so a hypothetical high performance ASHP with a COP which is 10% higher than the best currently available model [39] it has been considered. It has been priced at 10% higher than an average ASHP. All the other units are commercially available.

The control algorithms applied to the cases are discussed in section 3.3.3

3.2 Offsetting carbon emissions

In each configuration, the net CO_2 emissions associated with the operation of the heating and electrical loads of a typical house were calculated from the modelled energy flows assuming fixed carbon emissions factors (CEF). Operational emission factors have been used for the carbon offsetting calculation to be consistent with the climate change act [3]. The more comprehensive full cycle emissions and embodied energy requirements are discussed in section (3.4).

The working fluids in ASHP have high global warming potentials so any leakage needs to be considered as a GHG emission. An allowance based on 6% leakage a year of R410A refrigerant [40] has been included in this study.

A CEF for natural gas as delivered on a gross calorific value basis of 202gCO_2e/kWh was used [21]. The CEF for the electricity grid will depend on the mix of power plant running at any one time. A lower grid electrical CEF will reduce the emissions associated with an ASHP and decrease the emissions offset by a mCHP unit (increasing its total net emissions). The capacity of PV panels required in each configuration is therefore dependent on the CEF. It was decided to use a range of fixed CEFs for grid supplied electricity to allow comparisons of the different configurations to be made independently of any assumptions about the short term grid mixes. CEFs of 600, 400 and 200 gCO_{2e}/kWh were used. These represent recent grid CEFs and possible stages of grid decarbonisation. For each configuration the required capacity of solar PV panels was then determined such that the total net operational CO_2 emissions of the dwelling were 1558kgCO_2e/yr. This is 20% of the emissions associated with satisfying the same electrical and thermal demands using CEFs representative of 1990 [29].

The PVGIS web site [27] was used to produce an estimate of for the annual yield for a well-positioned system in Cardiff using mono-crystalline silicon cells with a rated efficiency of 16% (927 kWh/kW installed). It was assumed that the same CEF applies to electrical imports and exports throughout the year.

3.3 Energy analysis

3.3.1 Overall approach

It is possible to use steady state models to investigate the annual energy demands of a building or heating systems [74,75]. However these technique cannot be used to see if a proposed arrangement can cope during the coldest periods on the year or if you want to assess the running hours of auxiliary heating systems this requires a dynamic model with a short time period and thermal storage. Previous work on micro CHP systems [17] indicated that time periods around 1 minute are needed to account for the operational cycles of IC based systems consequently it was decided to use this time period for our models.

The energy flows associated with each configuration were analysed. The main metric used to compare the energy requirements of the systems was the Non-Renewable Primary Energy Requirement (NRPER). NRPER ratios of 1.02 for natural gas and 2.05 for grid-supplied electricity were used; this reflects work carried out for the realising transition pathway project [66].

A simplified thermal model of the house and heating systems was used reflecting , the control system appropriate for each case and a secondary model to provide time series data on thermal gains and active occupancy.

A modelling approach was used that integrated data taken from the outputs of a number of existing models. The structure of the interlinked models is shown in Appendix 1 .The models were implemented using VBA.

The gross calorific value of fuel and alternating current electrical flows (net of inverter losses) were used throughout.

3.3.2 Modelling energy flows

The heat transfers which were simulated are illustrated in Figure 1. This is a development of work presented by Cooper [30] such that it includes solar hot water systems and secondary heaters. The simplified structure of the building model is justified on the basis that it is the comparison between results which is of interest here rather than absolute energy demands (which are, in any case, highly sensitive to uncontrolled factors such as occupant behaviour).

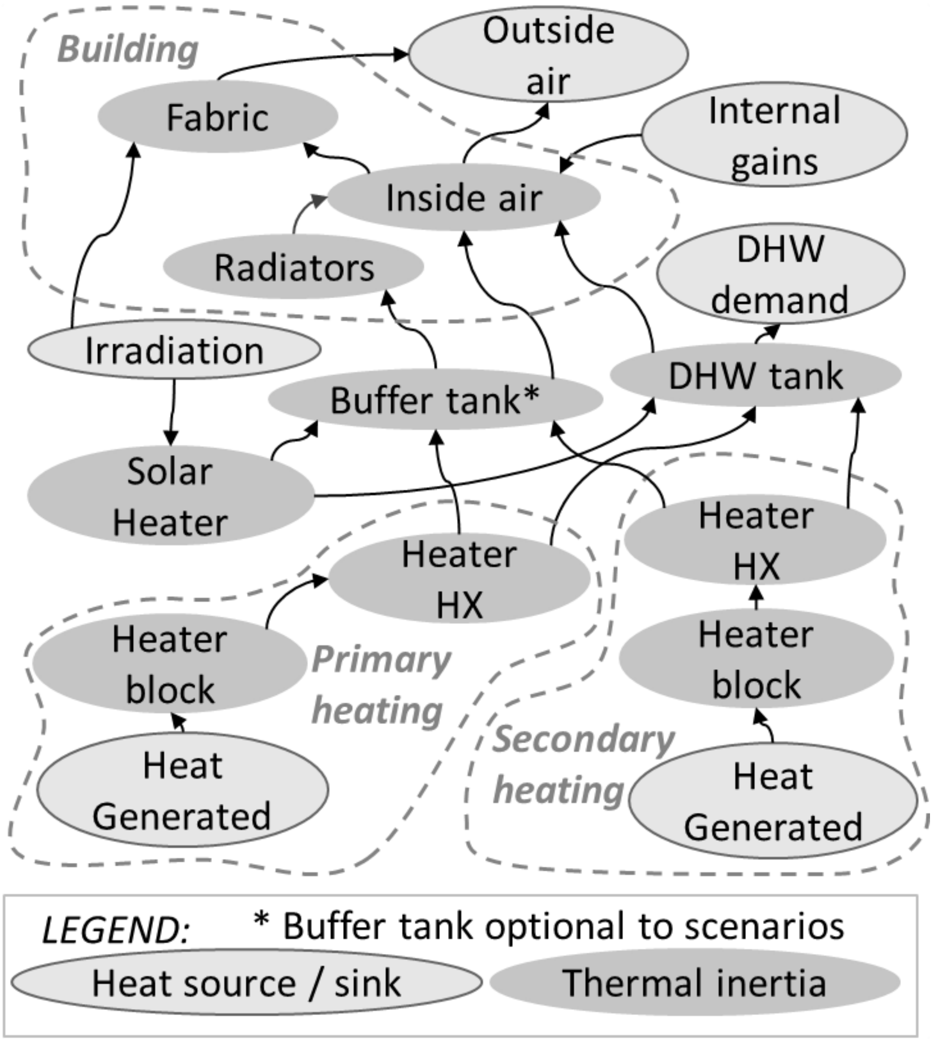

Figure 1: Heat flows

The heat transfer from the heat emitter system was assumed to be buoyancy-driven convection [36], scaled such that a flow temperature of 50°C was required to balance heat losses when the outside temperature was 0°C. The main thermal parameters are given in Table 3.
Parameters for the building model were calibrated against temperature and heating profiles generated by a simulation of a typical semi-detached house, modelled using ESP-r by Dr. N. Kelly and Dr. J. Hong [34]. Simplified models of buildings have been shown to be capable of producing heat demand profiles with acceptable fidelity [35] and in this case a root-mean-squared temperature difference of less than 0.5°C was achieved between the two air temperature profiles.

Table 3: Thermal parameters of building

Parameter	Value
Outer heat transfer coefficient	386 W/K
Inner heat transfer coefficient	339 W/K
Overall effective thermal inertia of mass	16.6 MJ/K
Air infiltration rate	0.5 ACH
Effective solar gains area	13m^2
Heat emitter coefficient (at 50°C)	231 W/K

Note that these parameters were determined by calibration against the thermal lag and heat demand of the more detailed thermal model, not using a bottom-up approach based upon the properties of the building materials. These figures are consistent with a typical UK two story semi-detached (Duplex) house built before 2000 which has undergone common insulation upgrades resulting in the following construction:

- cavity walls consisting of brick outer skin, 60 mm insulation and light weight block internal skin,
- studwork and plaster board internal walls,
- 20% glassed area fitted with UPVC double glassing units (these have been retrofitted to a large proportion of the UK housing stock),
- suspended wooden floors which have fitted carpets on them,
- pitched tiled roof with 100mm glass fibre insulation,
- total floor area 85m^2.

From the Prometheus project [28] the City with a total heating degree day requirement closes to the UK average is Cardiff. Consequently time series of air temperature and solar irradiation data that Cardiff may experience in a typical year was used for the thermal modelling.

Thermal and performance models of the SE-mCHP and large ICE-mCHP unit have been developed and calibrated by the IEA ECBCS Annex 42 and are used here [16, 17]. Thermal parameters for the small ICE-mCHP unit were estimated by scaling from the large unit and efficiency data was gathered from [31]. The same model structure was used for the ASHP and SOFC-mCHP units. however the dynamics of the SOFC-mCHP unit are dominated by technological constraints rather than the heat transfers constraints.

Interpolation methods were used to determine the efficiencies of the units under different operating conditions. In the case of the ASHP units, it was the exergy efficiency at known test conditions [32] which was interpolated (rather than COP) in order to improve accuracy. Efficiency data for the SOFC-mCHP unit was taken from [33].

In configurations with buffer tanks, heat transfers into the tank were modelled as having a 5°C temperature difference between the flow and return temperature. When more than one heating unit was used with a buffer tank, these heat transfers were arranged in parallel (i.e. independent of each other). When more than one heating unit was used in configurations without buffer tanks (i.e. direct heat transfers to emitter system), the heat inputs were arranged in series with the flow rate adjusted to maintain a 5°C difference across the primary heater's heat exchanger and the temperature difference across the secondary system determined by the corresponding heat transfer rates. In these configurations, the arrangement was such that the ASHPs supplied heat at the lower temperature position in order to maximise overall performance.

Heat input to the solar hot water system was taken to be a function of its internal fluid temperature and the radiation intensity. Irradiation intensity was modelled as a function of the geometry and location of the collector and of the weather. Further details of these functions are available in [25]. The collector was modelled as a 4m2 unit, facing south at an angle of 35° to the horizontal, at the latitude of Cardiff, UK (51.1°N). The output from the solar hot water system was not actively controlled and was assumed to be fed to the buffer and domestic hot water (DHW) tanks through a heat exchanger.

Dynamic appliance and lighting demands were modelled using the "CREST active occupancy and appliance model" [37], resulting in a total annual electrical demand of 3760kWh. The profile from this model was also used to provide internal gains for the dwelling, assuming standard metabolic rates (ISO 2005) and three residents in each house. Daily hot water demand was taken from empirical studies [38] and distributed according to the active occupancy [37].

3.3.3 Control system

The space heating was controlled to aim for a temperature of 20°C between 07:00 and 22:00 and 16°C at other times.

In configurations without buffer tanks, the space heating control system used a proportional control strategy. That is, the system requested a heat flow proportional to the difference in temperature between the program and the inside air temperature. The gain was set such that the losses consistent with an outside air temperature of -1°C would cause a 1°C offset from the profile temperature.

In configurations with a buffer tank, a single on-off control (equivalent to a thermostat with a deadband of +/-1°C) was used to manage heat flows to the heat emitter system. The control system aimed to maintain the buffer tank at a temperature which varied with the outside air temperature. That is, the target temperature for the buffer tank decreased linearly from 55°C to 25°C as the outside air temperature increased from -2°C to 15°C. This is equivalent to the "weather compensated" control arrangement used with some ASHP systems. The heat generation requested by the control system was calculated using a proportional control strategy based upon the difference between the buffer tank temperature and its target temperature.

The heating units have finite capacities and varied ability to modulate their output. The heat actually generated by the primary heating unit in response to the signal from the control system did not necessarily matchthe demand. When a secondary heating unit was available, a signal requesting the net unmet demand was sent to the secondary unit. A deadband of 500W was used when the secondary system was an ASHP. Because the gas boiler secondary units were modelled with very high capacity and low thermal inertia, the deadband used with them was increased to avoid unstable behaviour. In real installations this duty may be performed by a secondary thermostat or manual intervention by the occupier.

The ramp rate of the SOFC units was limited to the equivalent of a 10 hour start to full capacity time. They were therefore run continuously with their outputs maintained in the range 75% to 100% electrical capacity.

Daily domestic hot water (DHW) demand was taken from empirical studies [38] and distributed according to the active occupancy [37]. This demand was drawn from the DHW tank and did not directly affect control of the heating units. Heat transfers to the DHW tank occurred in parallel with the other heat transfers (i.e. independently of flows to the buffer tank or heat emitter system) whenever the temperature of the DHW tank was below its maximum and the flow temperature from the heating system was sufficiently high to supply heat. If the temperature of the DHW tank dropped below its minimum, the heating system was operated at maximum capacity, without transfers to the space heating system, until the DHW tank temperature was restored (deadband of 10°C).

3.4 Environmental analysis –life cycle assessment

The Life Cycle Assessment (LCA) environmental management tool was developed in order to identify and evaluate the environmental impacts of a product or system that result from each stage of its complete life cycle. . The system configurations analysed here, were modelled using the software package SimaPro v7.3 [43] , allowing the manipulation and examination of the system input-output data in accordance with the ISO LCA Standards [71,72]. SimaPro is a product system modelling and assessment program developed in 1990 at the Institute of Environmental Sciences (CML), Leiden University, The Netherlands [73], and is now widely used by both academic and industrial researchers. A consequential LCA was conducted using the impact assessment methodology ReCiPe (midpoint H v10.1) [67].

The LCA considered the following 11 environmental criteria:

- green house gas emissions
- fossil fuel depletion
- human toxicity
- photochemical oxidant formation
- particulate matter formation
- ionising radiation

- agricultural land occupation
- urban land occupation
- natural land transformation
- water depletion
- metal depletion

The system boundaries consider the impacts of material and fuel extraction and system manufacture, transportation, installation, operation and maintenance. As only the operational and environmental performance of the listed technologies was analysed the impact associated with any existing infrastructure (radiators, for example, or any resource demands by the building or its occupants) is not considered in this study.

For each of the technologies considered, the data has been sourced from the ecoinvent 2.0 database [44] (which was customised where appropriate to represent UK specific installations), publicly available technical manuals from system manufacturers [16, 17, 55, 68, 69, 70], published literature, and existing LCA models [41]. The impacts resulting from decommissioning and recycling are omitted from the system boundaries of the study due to inconsistent availability of appropriate empirical data for some of the technologies analysed.

The configurations considered would benefit from the reduction in environmental impact associated with the displaced grid electricity. It was decided to consider a relatively environmental benign grid mix in order to produce a conservative estimate of these benefits. Consequently the electricity generation was accounted for by using the Transition Pathways 2020 dataset for the Thousand Flowers (TF) scenario [14], this has an estimated grid carbon intensity of 390 g/kWh. This dataset was modelled as part of a full LCA evaluation of the three pathways for a low carbon UK energy future developed by the Transition Pathways Consortium [66]. This analysis examined and accounted for all upstream and operational activities right through to the point of delivery to the consumer. The 2020 Thousand Flowers future is based on an electricity system transitioning to a civic led energy sector where more electricity is generated by means of distributed generation; making up 28% of total generation in 2020 and rising to over 55% in 2050. Traditional large scale generation is replaces with both Natural Gas CHP and renewable fuel CHP (predominately Biogas). A high growth in both onshore and offshore wind is witnessed, while nuclear capacity is greatly reduced. The dependency of the UK on imports is seen to grow while overall demand reduces due to energy efficiency measures, and more responsive and engaged consumers. The Thousand flowers scenario produced the highest overall reduction in GHG emissions of all three pathways, both in terms of the overall system, and per kWh of electricity produced [14] .

3.5 Financial appraisal

3.5.1 Assessment Criteria

A financial appraisal considers the economic viability of a project from the owner's perspective. It excludes consequential external costs and benefits with the exception of government subsidies. The broader external consequences are discussed in the life cycle assessment analysis. Some of the options considered qualify for payments under the renewable heat incentive (RHI) [45] which is payable over 7 years and some qualify for FIT payments which are payable over 20 years[46] Consequently it was decided to use the net present value (NPV) to compare the different cases where:

$$NPV = -Capital_{cost} + \sum_{Y=1}^{Y=20} \frac{annual_{income} - annual_{cost}}{(1+discount_{rate})^{Y}} \qquad \text{equation 1}$$

Where Y is the year

The UK FIT scheme is designed to give the owner a real rate of return of 3% (i.e. rate of return after inflation) [47]. The RHI assumes that the owner will have to pay 7.5% interest on the capital used for the installation, if inflation is kept at the Bank of England Target of 2% this equates to a real rate of interest of 5.5%. Both of these real rates of returns (3% and 5.5%) have been used as discount rates to illustrate the sensitivity of the analysis to changes in discount rates.

As the installations provide a service rather than a product the NPVs are likely to be negative so they are more accurately considered as Net Present Cost (NPC). The FIT and RHI schemes are political instruments that bias the true economic viability of the options. A subsidy free NPC has also been calculated to see the impact of subsides. In the subsidy free case it has been assumed that the "market" value of the electricity generated can still be realised.

3.5.2 Capital Cost

Capital costs for all technologies other than PV were taken from sources listed in table 4. They are either online list prices, estimated cost from consumer advice web sites or taken from published papers. The cost from published papers have been converted to Stirling at the average spot market exchange rate for the year of publication and inflated with the UK Producer price index (excluding tobacco, beverages and petrol) to 2012 prices.

Table 4 capital cost of installed equipment

Equipment	cost	Source references
Condensing boiler	£1673	49,49,50
Ecodan W8.5 ASHP	£4233	51
Dachs IC mCHP	£15,000	23,52,53,54
High performance ASHP	£4656	Authors estimate
Ecowill (Freewatt) IC mCHP	£6,000	52,53
Bluegen SOFC mCHP	£23,724	55,56,57
Whispergen	£4,046	23,52
Solar water heating	£4,000	58
300l thermal store	£1,455	59
750l thermal store	£1,989	59

The ASHP costs include a £500 allowance for installation cost. The other sources gave estimates for installed cost.

PV costs were calculated using the formula derived from estimates contained in the UK 2012 PV FIT review [60]:

$$cost = 1967 + 2.014Q \qquad \text{equation 2}$$

Where Q is the installed system rating in Watts.

Equation 2 was used to calculate the cost of the PV systems that would be needed to provide the required CO_2 offsetting for each case at different grid carbon intensities. The installed capital cost of the heating systems and associated PV systems are shown in Table 5.

Table 5 capital cost of installed equipment excluding

Case number	Installed capital cost of heating systems	PV system installed capital cost for 600g/kWh grid	PV system installed capital cost for 400g/kWh grid	PV system installed capital cost for 200g/kWh grid
1	£1,683	£17,123	£20,635	£30,843
2	£2,443	£18,491	£22,704	£35,016
3	£7,138	£17,737	£21,559	£32,697
4	£5,916	£14,823	£13,192	£7,973
5	£4,233	£14,681	£11,969	£3,507
6	£4,993	£18,474	£15,762	£7,300
7	£9,688	£17,764	£15,052	£6,590
8	£4,656	£12,070	£9,358	£0
9	£16,989	£11,107	£19,891	£45,919
10	£16,989	£10,565	£18,399	£41,574
11	£9,672	£15,997	£22,842	£43,053
12	£13,672	£15,138	£21,304	£39,476
13	£12,222	£15,849	£18,985	£28,070
14	£16,222	£14,898	£17,696	£25,762
15	£27,396	£0	£14,229	£55,924
16	£27,957	£0	£8,894	£38,037
17	£29,946	£0	£10,357	£39,529
18	£33,946	£0	£10,031	£39,198
19	£6,035	£18,035	£23,763	£40,621
20	£10,035	£16,552	£21,428	£35,730

3.5.3 Operating cost

Average UK retail price for gas in 2012 of 0.044 £/kWh and 0.1331 £/kWh for mains electricity were used to calculate the fuel costs [61].

An annual allowance of £100 was made for routine maintenance of the boiler and ASHP systems, the micro CHP maintenance cost were estimated using the formula:

$$maintenance = 100 + 0.01 generation\,£ \qquad \text{equation 3}$$

Where generation is the annual gross electricity generation in kWh. Equation 3 is based on estimations in [52,54].

3.5.4 Income

Income comes from FIT subsidy payments, savings in electricity purchased from the public supply, export payments for sales to the public supply and payments for heat production under the RHI scheme.

The FIT payments for PV systems vary with the size of installation and were set at the following rates in 2012 (levels set following a review [60]):

Under 4kW 0.1544 £/kWh,

4kW to 10kW 0.1399 £/kWh

Over 10 kW 0.1300 £/kWh

Micro CHP plants with under 2kW output qualify for FIT payment of 0.1289 £/kWh, this rate has been assumed for all the micro CHP units.

Export payments of 0.045 £/kWh [46] are be made on metered exports or 50% of generations in situations without export metering. The rest is assumed to be used on site and so has an assumed value equal to the retail price. This effectively gives a market value to the generation of 0.088 £/kWh.

The RHI payments subsidise renewable heat generation; they are made for 7 years at the following rate [45]:

Air source heat pumps 0.073 £/kWh

Solar water heaters 0.19 £/kWh

4 Results

4.1 Energy Analysis

Figure compares the magnitude of the non-renewable primary energy requirements (NRPER) associated with the different configurations. Electricity generated by mCHP units is shown in terms of the reduction in the NRPER of the grid.

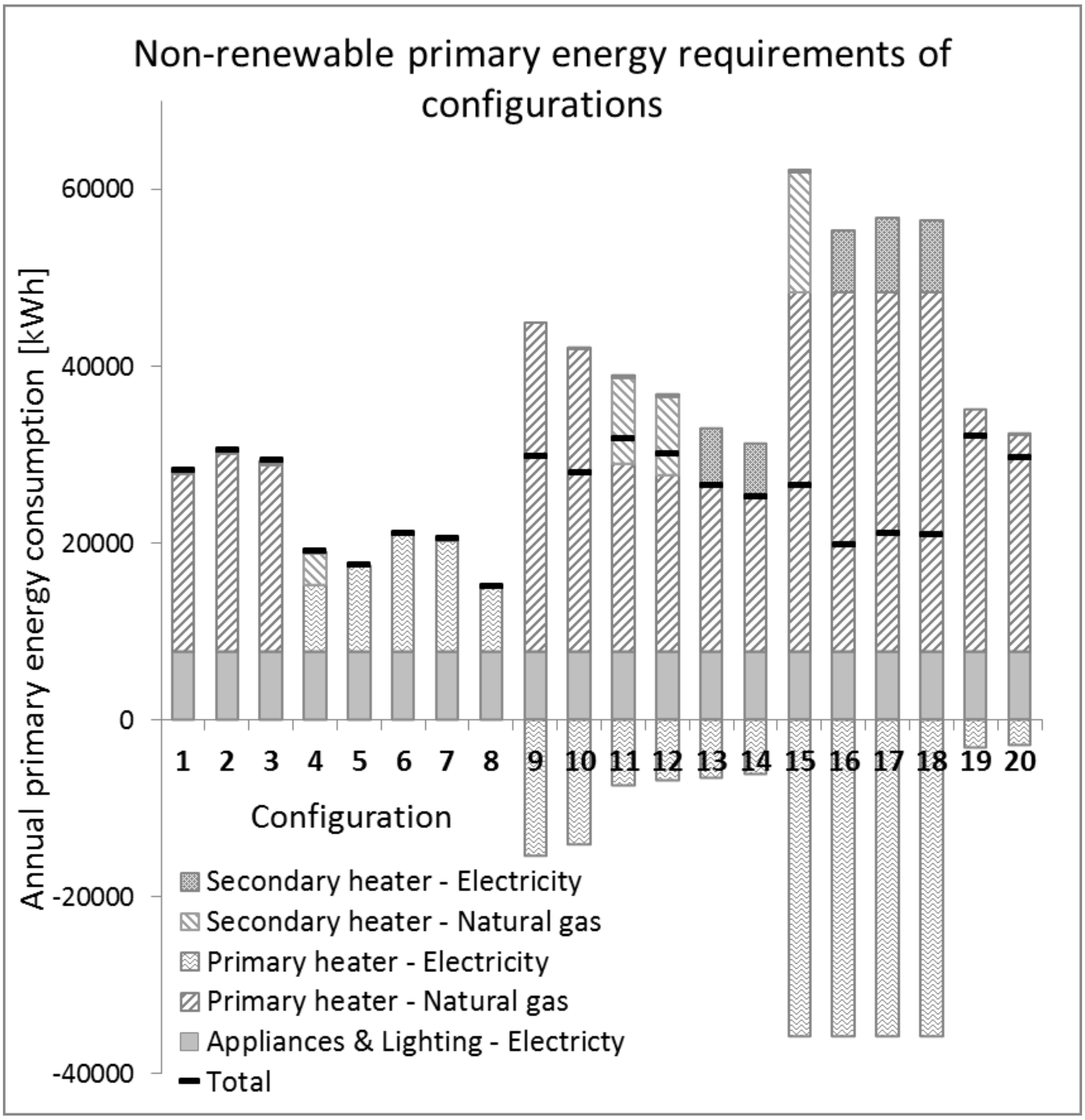

Figure 2: Non-renewable primary energy requirements

In the cases with mCHP (9 to 20) the house has been credited with the primary fuel equivalent of the grid electricity that the onsite generation has displaced.

The SE-mCHP and large ICE-mCHP based systems achieve annual electrical efficiencies of around 7% and 24%, respectively, consistent with other studies [16,17,23]. The use of gas in the secondary heater means that the electrical efficiency of the configurations based upon the SOFC-mCHP and the small ICE-mCHP are lower than the published efficiencies for the mCHP units(from 51% to around 39% for the SOFC and from 20% to around 13% for the small ICE).

Figure 2 relates to the primary energy flows associated with the heating systems and domestic electricity consumption. Figure3 shows the solar energy (in terms of thermal and electrical energy) delivered in each scenario. The solar PV capacities are selected to achieve the target net operational emissions with a grid CEF of 400 gCO_{2e}/kWh.

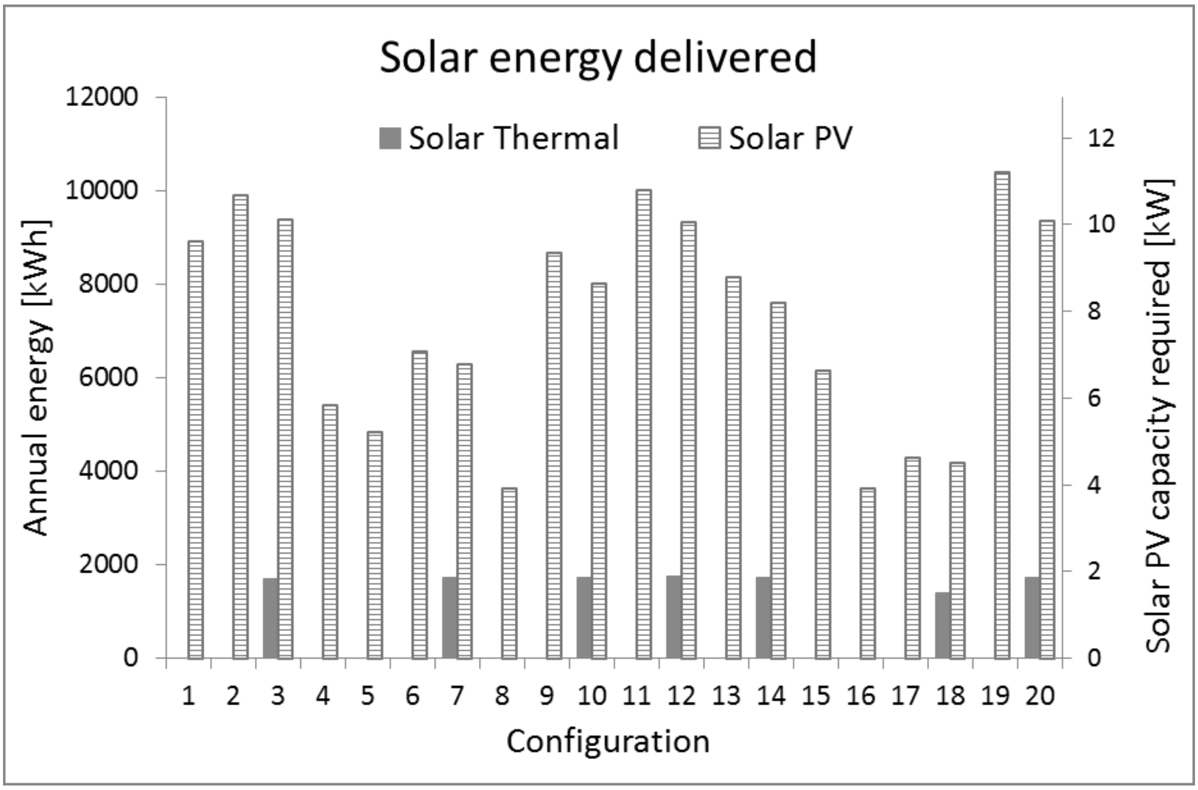

Figure 3 : Solar energy delivered

The heat delivered by the solar thermal system decreases slightly when combined with the SOFC-mCHP unit due to the higher tank temperatures that result from continuous operation of the SOFC. There is no inherent linkage between hot water demand and the availability of solar hot water consequently some of the collected solar energy is in excess of the daily demand. This raises the thermal store temperature and increases the thermal losses consequently the heat required from the main heating system is only reduced by 80% of the heat collected by the solar systems. In the case of an ASHP system, the reduction in heat demand associated with the use of a solar thermal system is similar to the performance penalty associated with the use of a thermal store.

The impact of changes in grid CEF on the required size of PV installation is shown in Figure 4.

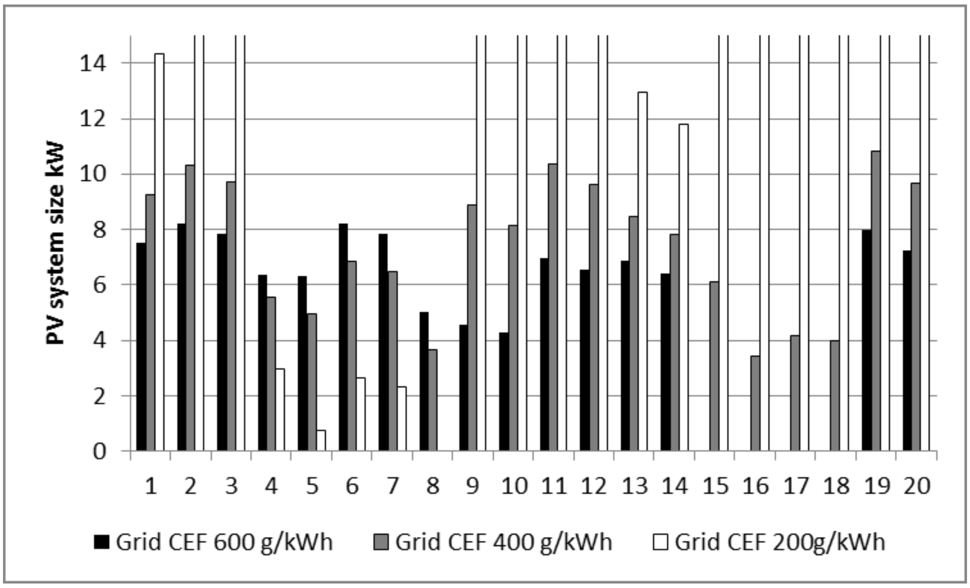

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Figure 4 PV installation size of different grid carbon emission factors

The maximum system size required was 27kW but it is unlikely that a system this size could be installed on a domestic site. The maximum size of PV systems that can be installed on a property will vary between properties. It has been assumed that properties will have no more than 100m^2 of surface area where PV panels could be mounted (this could be split between roof space and outbuilding or space frames above car parking area) this would give a maximum installation capacity around 15 kW consequently the scale of figure 4 has been truncated at 15kW to remove unrealisable installation. It is worth noting that a typical domestic PV system in the UK is rated around 4kW and an 8kW limit may be more realistic in most cases.

In the case of the grid with a CEF of 600 gCO_{2e}/KWh the SOFC units generate sufficient reduced carbon electricity to offset the emission from the gas and grid electricity consumed by the household without the need for any PV generation. Likewise the emission from using grid electricity and the high performance heat pump with the 200 gCO_{2e}/KWh grid are under the target value so no PV generation is required.

4.2 Environmental Analysis

4.2.1 Green house gas emission

The LCA produced estimates of the GHG emissions during the operational life time including those associated with fuel extraction and supply. There is another source of emission associated with the equipment that is those emissions which were the result of the energy used during their construction (including material production) this is known as embodied emission (embodied climate change). Figure 5 shows the annual operational GHG emissions for the configurations, annualised GHG emissions (total embodied GHG divided by operational life) for both the heating systems and PV systems and GHG emissions associated with coolant leakage from the ASHP.

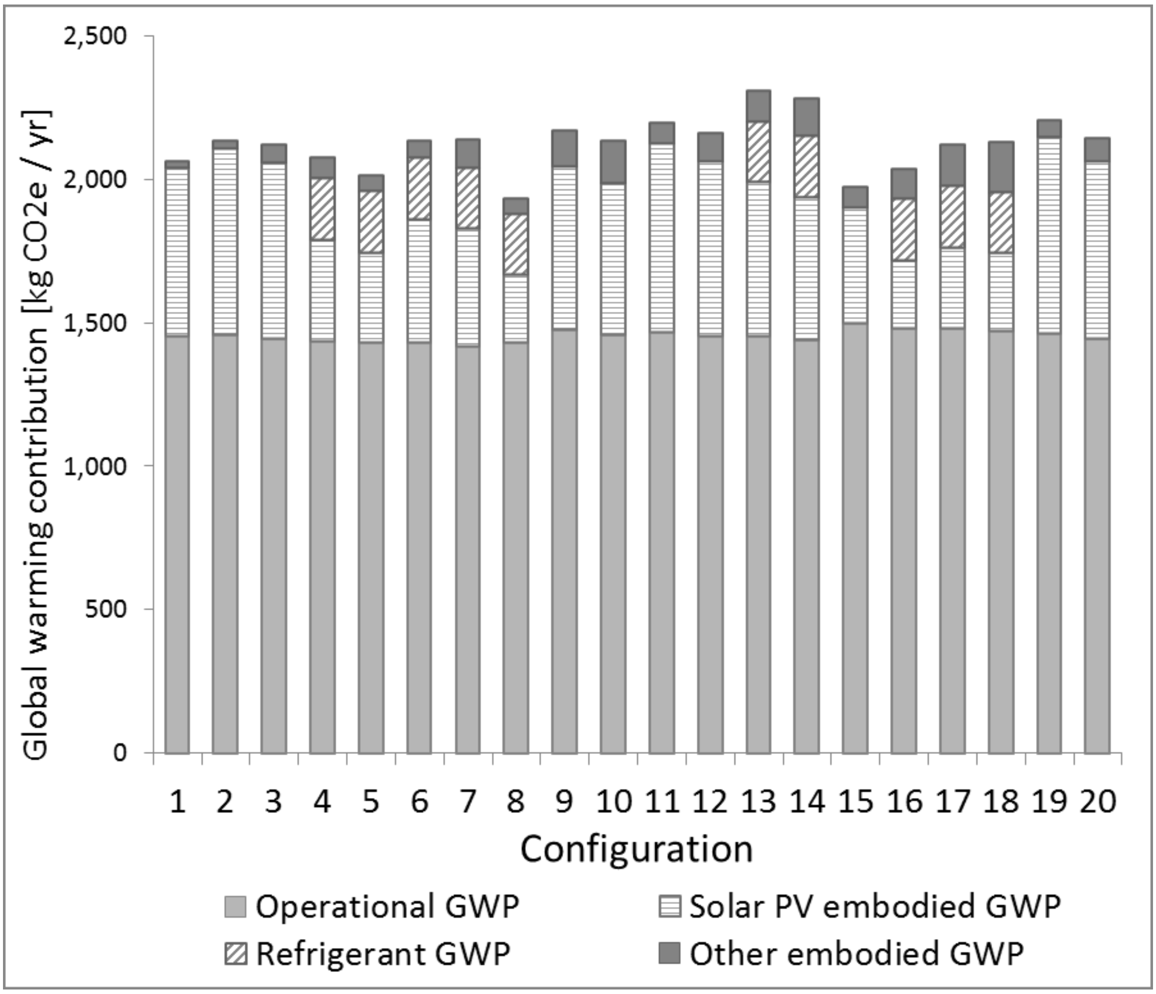

Figure 5 Green house gas emissions for configuration considered

4.2.2 Fossil fuel depletion

The total of the embodied and operational annualised fossil fuel depletion and GHG emission are shown in Figure 6. The values have been normalised by those associated with the base case of a condensing boiler. The fossil fuel depletion varies over a wider range than the GHG emissions. This is because the systems have been designed such that the operational emissions from burning gas are offset by emissions savings made by displacing grid electricity with low carbon electricity. To offset the GHG emissions associated with 1kWh of gas requires the generation of 0.52 kWh of renewable electricity which will only offset 0.87 kWh of fossil fuel use so although the GHG emissions are fully offset the fossil fuel use is not.

The situation in the heat pump cases is different as the high electricity consumption is offset by renewable electricity as such the GHG emissions and fossil fuel use will be offset by the same proportion. However they also have GHG emissions associated with refrigerant leakage.

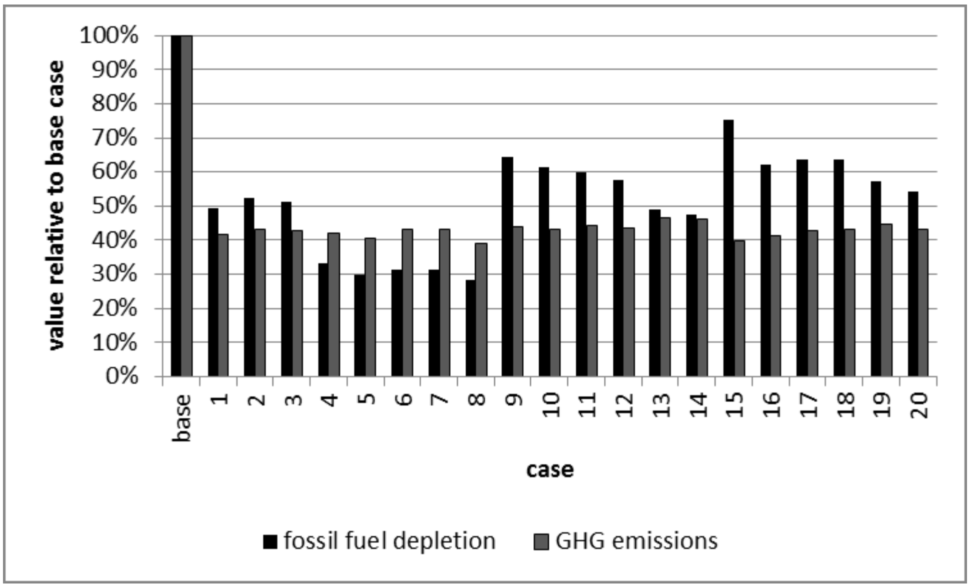

Figure 6 fossil fuel depletion and green house gas emissions

The base case in Figure 6 actually represents a 35% GHG saving on 1990 levels (mainly resulting from lowering in grid carbon intensity) consequently all the options produce significant GHG emission savings and a reduction in fossil fuel depletion.

4.2.3 Water and Metal depletions

Figure 7 shows that the use of heat pumps in configurations 4 to 8, 13,14 and 16 to 18 increases the metal and water depletion although in cases 16 to 18 this is outweighed by the reductions which are associated with the use of SOFCs to replace grid electricity. This would indicate that the use of grid electricity is the main factor influencing water and metal depletion.

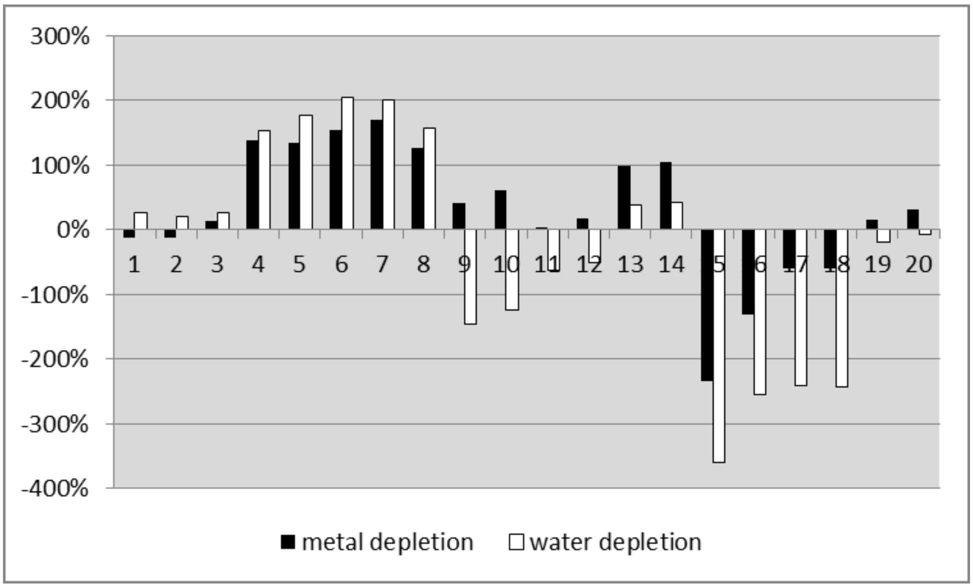

Figure 7 water and metal depletion levels

4.2.4 Other LCA impact factors

The results for LCA for the other impact factors for each of the 20 cases have been plotted against the net grid electricity consumption for each case in Figures 8, this show that many of the impact categories can be approximated to linear functions of the net grid electricity used. Consequently it can be deduced that these impacts derive from the operations of the electricity grid rather than the micro generation systems themselves.

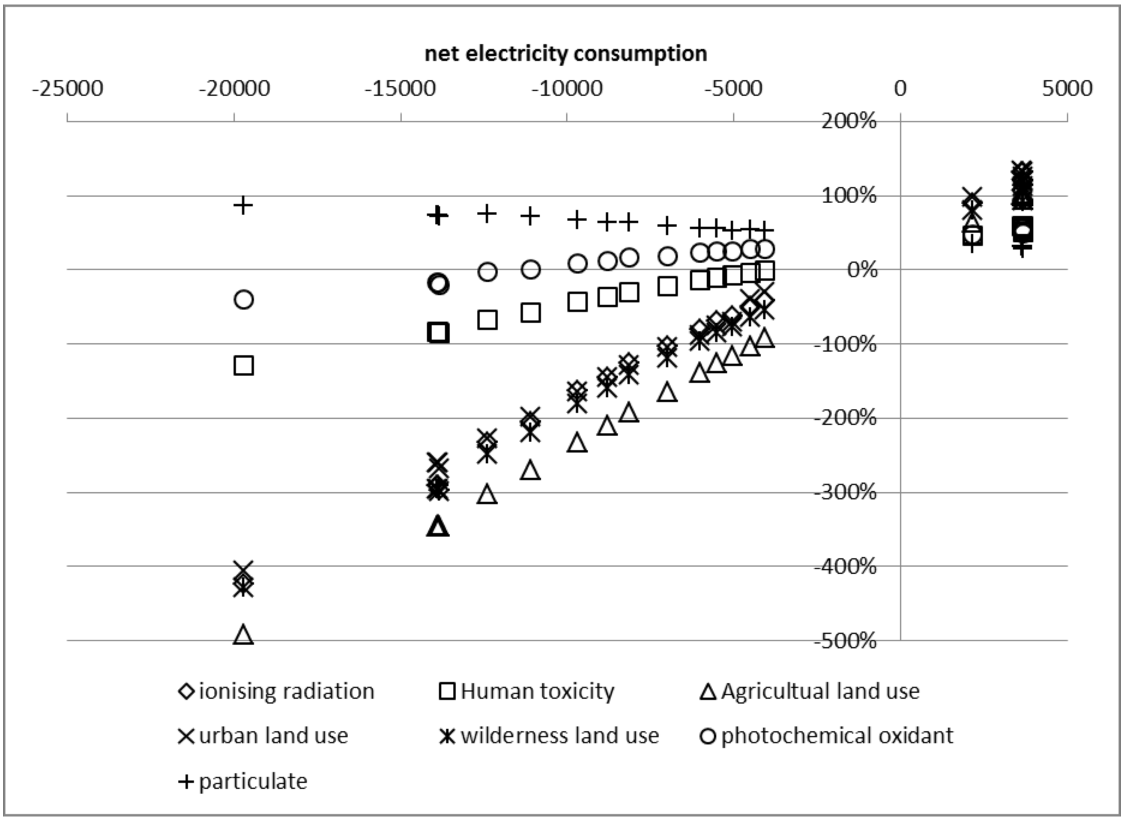

Figure 8 impact of net electricity demand on LCA criteria

The particulate emissions fall as the net electricity consumption increases, this is because the particulate emission rate per unit of GHG is higher for gas (2.75 g/kg$_{CO2e}$) than for the offseting electricity (1.5 g/kg$_{CO2e}$). Consequently the particulate emissions associated with the gas only being partially offset by the export of electricity. However all the configuration have lower particulate emissions than the base case. All the other parameters shown in Figure 8 have much higher values for electricity than gas and so their values increase with net electricity use.

4.3 Financial Analysis

Although the NPC gives an assessment of the life time costs its absolute value is not particularly meaningful to the reader. To allow the cases to be easily compared, their NPCs have been normalised with the NPC of a gas condensing boiler and grid electricity so any value less than 100% represents an economically favourable option for the owner. The owner will be entitled to subsidies so these have been included in the calculation. However this is an artificial situation that will vary between countries. Consequently the NPCs excluding subsidies have been included to get an indication of the true costs. Figure 5 shows that different sized PV systems are required to achieve the target emission for differing grid CEF consequently the NPC for each case also changes with grid CEF. The values for the different CEFs are shown in Figures 9-11

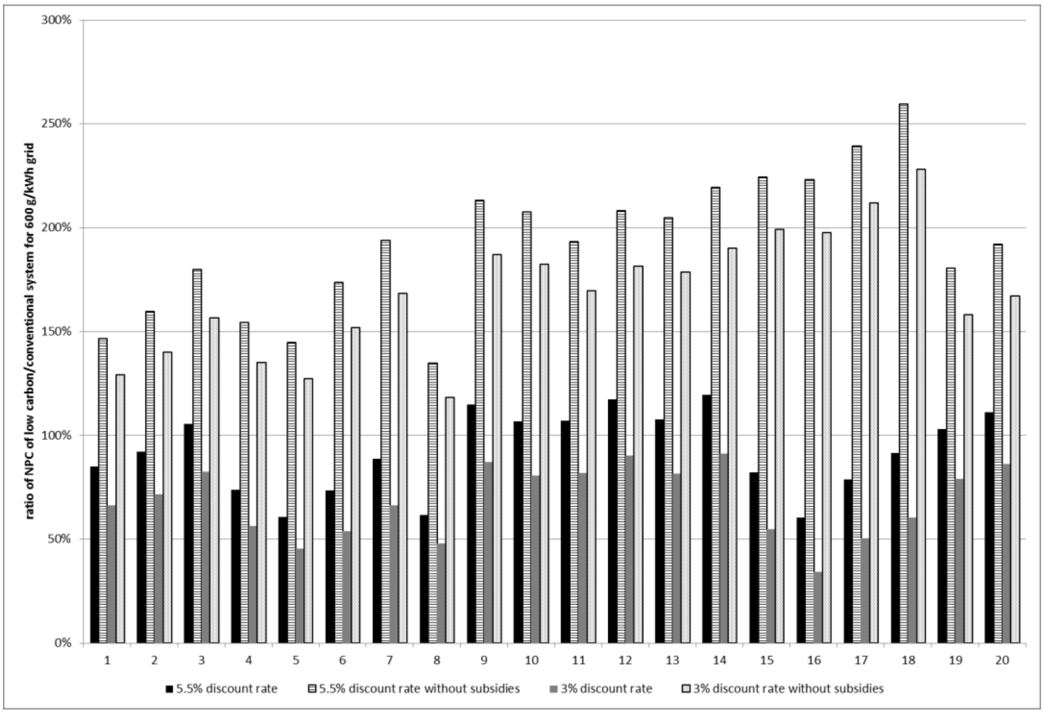

Figure 9 ratio of NPC for low carbon system to standard system with grid intensity of 600g/kWh

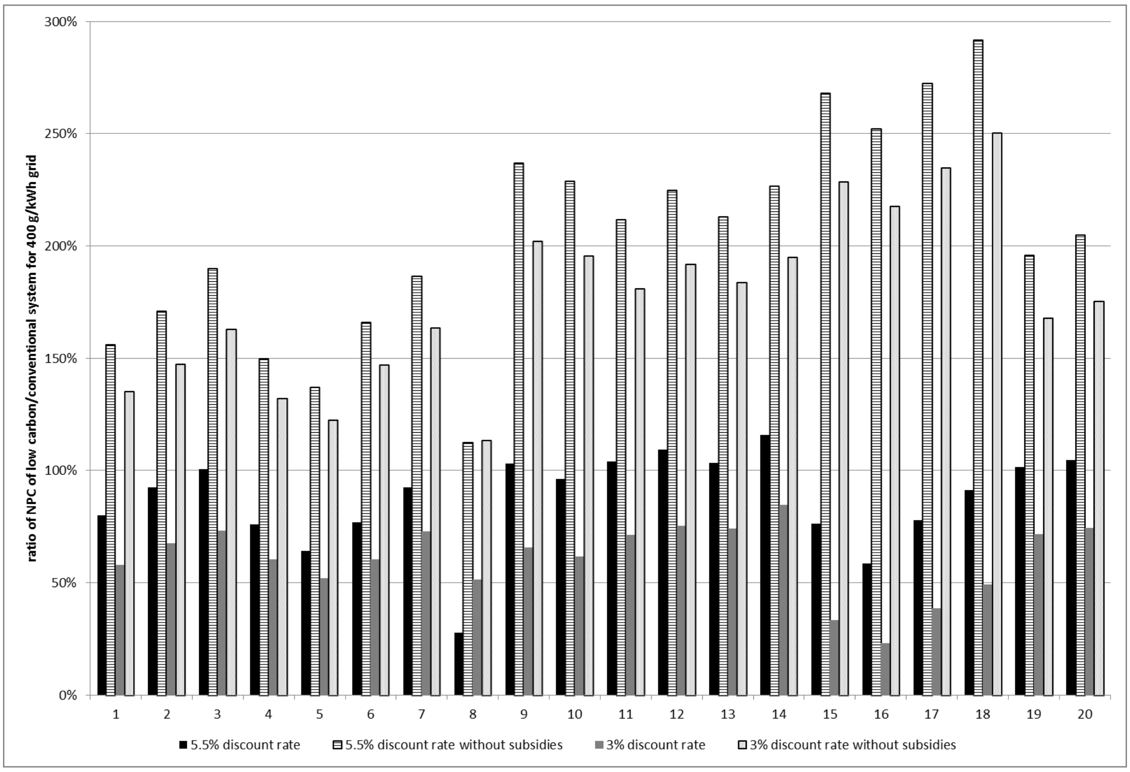

Figure 10 ratio of NPC for low carbon system to standard system with grid intensity of 400g/kWh

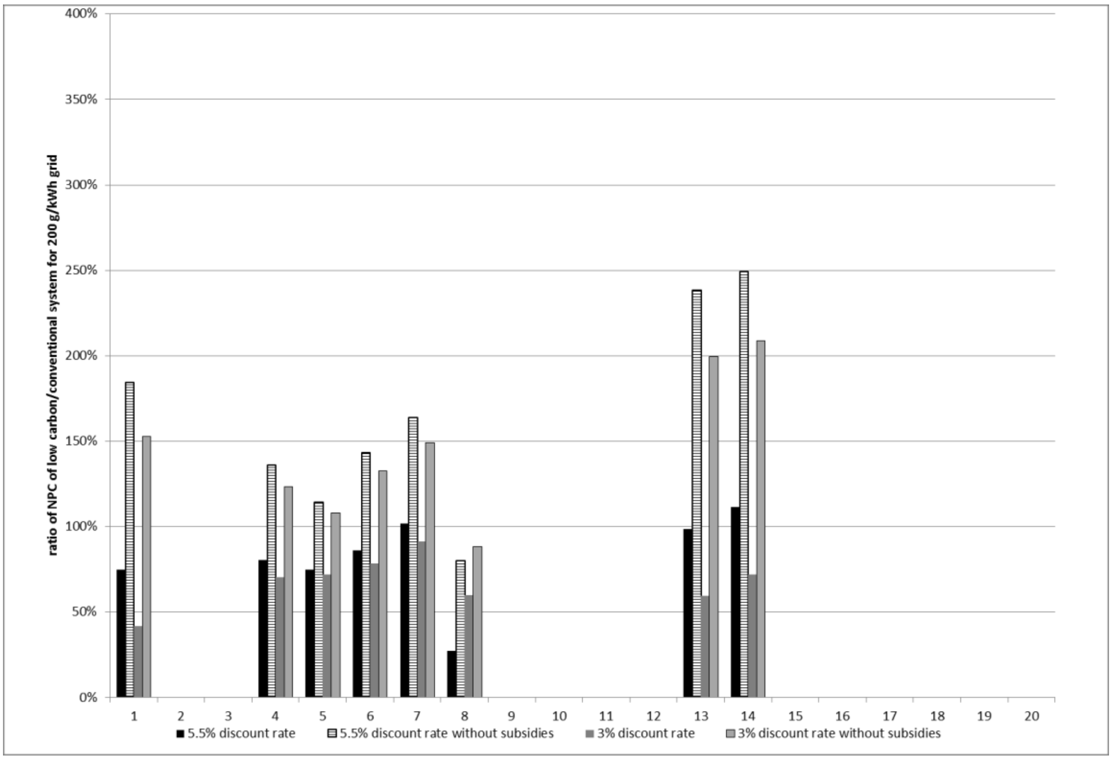

Figure 11 ratio of NPC for low carbon system to standard system with grid intensity of 200g/kWh

Figure 11 only shows those configurations with realisable PV installation (see Figure 4).

The estimated NPC may be one of the deciding factors for selecting a project to invest in but it assumes that sufficient funds are available to make the investment. Another criteria that is significant for a home owner is the initial capital cost this is shown as multiples of the cost of a condensing boiler in Figure 12.

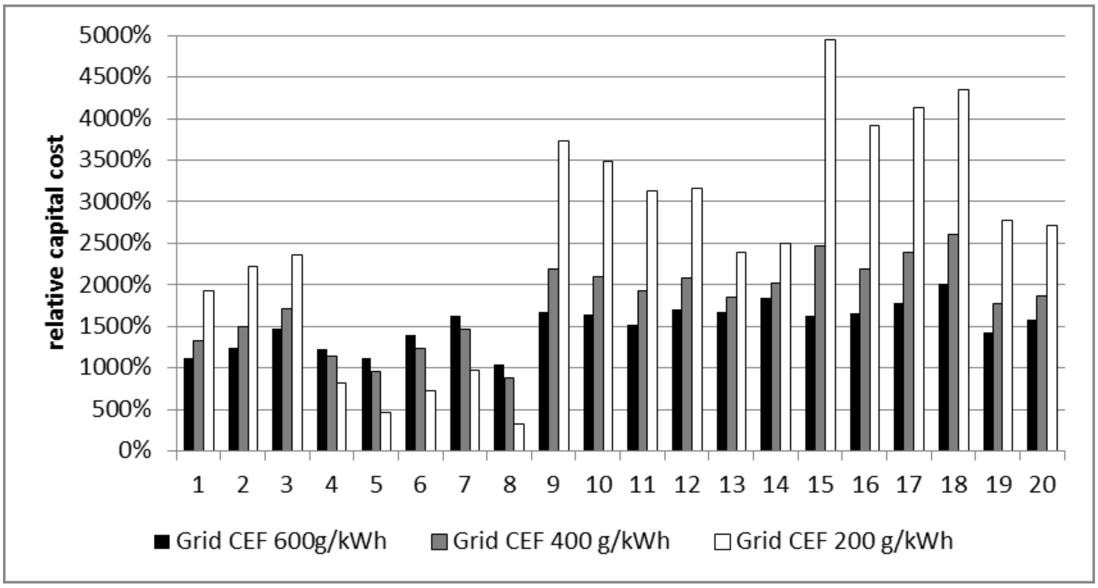

Figure 12 capital costs as % of cost of gas condensing boiler

Figure 12 shows that all the options are considerable more expensive than a simple condensing boiler. Figure 12 only show the capital cost expended by the owner. The installation of micro generation technology will have an impact on the capacity requirement of the electricity supply system. Although these changes in system costs will be reflected in the electricity price their impact has not been considered in this analysis as it will depend on the total amount and type of micro generators installed.

The other reason for high capital cost is the inclusion of relatively large PV systems. The fraction of the capital cost represented by the PV system is shown in Figure 13.

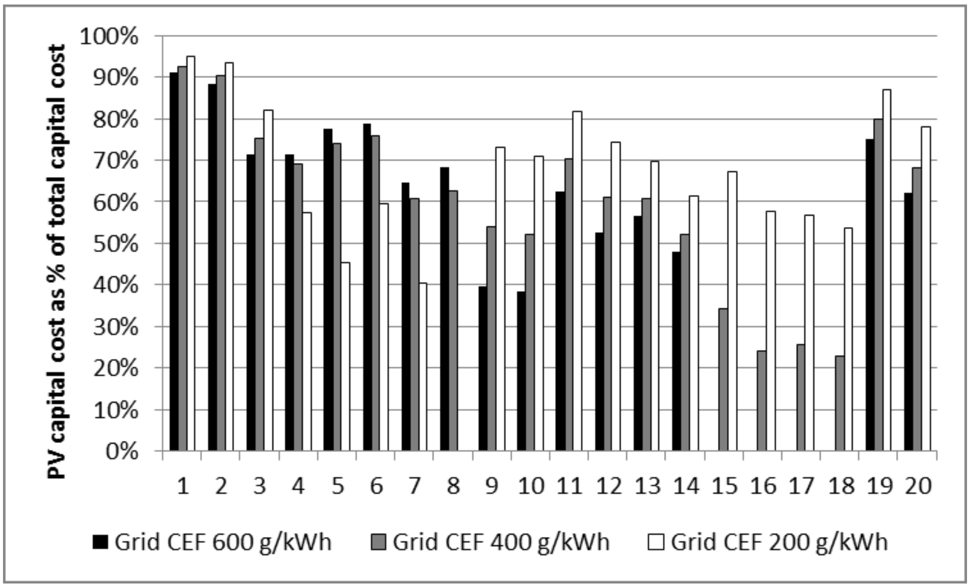

Figure 13 PV costs as % of total capital costs

5 Discussion

5.1 Technically available option

Figure 4 indicates that in principal all the systems should produce the desired operational emission level. However this may require unrealistically large PV systems if the grid CEF fall to a level close to the CEF for gas combustion. If this happens the electricity generated by the mCHP systems will have a higher CEF than the grid consequently their electricity generation will not help offset the emissions from the gas they consume so a very large PV system will be required to offset their emissions. In this situation only the ASHP options are implementable.

The ASHP configurations have the lowest NRPERs, followed by those based upon the SOFC unit. For these configurations, the inclusion of buffer tanks and the associated control systems, increases the NRPER. The NRPERs for the configurations based upon the other mCHP units are similar to those required by the condensing boiler configurations, with minor savings achieved by the larger ICE-mCHP units.

5.2 Financially viable options

From Figures 9 to 11 it can be seen that the NPC including subsidies for the configurations using ASHP and SOFC mCHP systems are less than the cost of using a condensing boiler and grid electricity. However the SOFC options cannot be realised with a low carbon electricity grid. It is noticeable that the systems become more financially viable for the owner as the grid CEF reduces. This is a consequence of the FIT payment being set at a level where PV generation is profitable and the PV elements increasing in size as the grid CEF fall.

This profitability is dependent on subsidies. Configuration 8 is the least cost option if subsidies are not considered but it is a hypothetical system where as the equipment used in cases 4&5 is already on the market. Case 4 includes a back-up boiler where case 5 relies solely on the ASHP. The need for the back-up boiler will change with the level of insulation, climate and orientation of the property.

NPV is only one tool for assessing the viability of projects and it assumes that the investor is able to finance all the options being considered. It is clear from Figure 12 that all of the options are much more expensive than a condensing boiler. The capital investment required for mCHP options are considerably higher than that for the heat pump options.

5.3 Environmental performance

5.3.1 Green house gas emissions

The operational Green House Gas emissions (GHG) for all the systems are below the 1,558 kg CO_{2e} target. If the annualised embodied GHG is also considered the emissions are considerably higher for all cases.

The emissions associated with production of the systems varies considerable between the cases. However the following points need to be considered when interpreting these results;

The GHG emissions associated with leakage from the heat pumps is an allowance which is based on a particular refrigerant and leakage rate. It follows that this is an indication of the order of impact that leakage may have, not a measure of the actual impact.

The embodied emissions from the manufacture of the PV systems makes up a significant part of the total embodied emissions. This is dependent on the technology used to make the PV panels which is still under development. The Inventory of Carbon and Energy ICE [63] gives a range of 132 to 440 $kgCO_2/m^2$ for the embodied carbon for monocrystalline PV modules which reflects the diversity of production plants (the EcoInvent value used in the LCA was 194.88 $kgCO_{2e}/m^2$) so the embodied GHG emissions of PV panels may be significantly different from those quoted. Thin film PV panels which are starting to compete with monocrystalline panels have about half of the GHG emissions associated with their construction.

The embodied emissions will all have been emitted at the time of manufacture and will be included as industrial sector emissions (much of which will occur in the country of origin of the equipment) so if they are added to the operational emissions there is a danger of double counting them in any global GHG inventory.

The grid mix used as a basis for this analysis was the Thousand flowers 2020 generation mix which embodied GHG emissions are specific to that particular combination of electricity generators for this scenario. The TF 2020 system is significant different from the current UK electricity system and its underlining assumptions should also be taken into consideration when interpreting the GHG emissions of the consider cases.

5.3.2 Other LCA criteria

The outputs of the LCA need to be treated with some caution as they trade off the emissions which would have been made if the electricity was produced by the grid against the emissions associated with onsite generation. This is valid for operational emissions but it is only valid for embodied emissions if the displaced power plant is not built. A large number of consumers owning mCHP units may reduce the electrical peak demand which reduce the need to build more power stations, but PV generation in the UK does not occur at times of peak generation so will not reduce the need for new power stations. This may mean that some of the benefits shown in Figures 9 and 10 will not be realised. However it is clear from Figure 9 and 10 that the options considered are unlikely to have a disproportional detrimental impact on the environment.

5.4 Impact of solar water heating

From Figures 2 and 4 it can be seen that the energy collected by the solar water heaters is less than 10% of the total primary energy consumption of the house. This is consistent with the performance of this size collector in earlier studies [65]. The reduction in the NRPER which is achieved by the use of the SHW heaters is often outweighed by the performance penalty associated with the requirement that the primary heat system feeds into thermal store. Consequently the inclusion of solar water heating only produces a relatively small reduction in the size of the PV systems required to bring the emissions down to the desired level. It is noticeable that the SHW options all have a higher NPC than the equivalent non SHW options. It is possible that with seasonal control algorithms and larger SHW systems the proportion of primary energy supplied by the SHW could rise to 20% [20] but this is unlikely to produce a significant change to the viability of any of the options.

6. Conclusions

It is both practical and economically feasible for a homeowner to reduce their net operational GHG emissions by 80% of the 1990 values by using combinations of micro generation equipment to supply their heat and electricity demands. However when LCA analysis is considered it was found that the true GHG emissions would be nearer to 25% once embodied GHG emissions are considered.

On further investigation it was found that the majority of the embodied GHG was in the PV panels and that it may be possible to select panels with lower embedded GHG emissions if this data were generally available. If/when thin film systems become competitive they will provide an option to lower the embodied GHG emissions.

The number of options available depends on the grid CEF. As the grid becomes less carbon intensive the amount of grid electricity that needs to be displaced by PV generation to balance onsite use of natural gas becomes excessive.

It would appear that the solution that are future proved against falling grid CEF are the heat pump configurations 4 and 5 these also seem to be the best credible finical option. It is likely that the ongoing developments of heat pumps will further improve their viability as demonstrated by case 8. They are also the lowest cost choice if the effects of subsidies are ignored.

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References

1, UN, Kyoto Protocol To The United Nations Framework Convention On Climate Change, 1998 downloaded from http://unfccc.int/kyoto_protocol/items/2830.php Aug 2013

2, European Commission, Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions A Roadmap for moving to a competitive low carbon economy in 2050,ref 52011DC0112,2011 downloaded from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0112:EN:NOT Aug 2013

3, HMG, Climate Change Act 2008, HMSO 12/2008 415435 19585,2008

4,UN, Report of the Conference of the Parties on its eighteenth session, held in Doha from 26 November to 8 December 2012, FCCC/CP/2012/8,2012 downloaded from http://unfccc.int/resource/docs/2012/cop18/eng/08.pdf Aug 2013

5, Allen, S.R., G.P. Hammond, H. Harajli, C.I. Jones, M.C. McManus and A.B. Winnett, 2008. 'Integrated appraisal of micro-generators: methods and applications', Proc. Instn Civil Engrs: Energy, 161 (2):73-86. [DOI:10.1680/ener.2008.1 61.2.73]

6,Allen, S.R., G.P. Hammond, H. Harajli, M.C. McManus and A.B. Winnett (2010). Integrated Appraisal of a Solar Hot Water System, Energy 35, (3), 1351-1362

7,Allen, S.R., G.P. Hammond and M.C. McManus, 2008. 'Energy analysis and environmental life cycle assessment of a micro-wind turbine',Proc. Instn Mech. Engrs Part A: Journal of Power and Energy,222 (7): 669-684. [DOI:10.1243/09576509JPE538]

8, Allen S.R.,and Hammond, G. P., 2010. Thermodynamic and carbon analyses of micro-generators for UK households. Energy, 35 (5), pp. 2223-2234.

9, O.A. Shaneb∗, G. Coates, P.C. Taylor, Sizing of residential CHP systems, Energy and Buildings 43 (2011) 1991–2001

10 Royal Commission on Environmental Pollution, Biomass as a renewable energy source, ISBN 0-95441 86-1-1,2004

11, Energy Saving Trust, Location, location, location Domestic small-scale wind field trial report, www.energysavingtrust.org.uk CO1711 © Energy Saving Trust July 2009.

12, Courture T.D., Cory K., Kreycik C., Williams E.: A Policymaker's Guide to Feed-in Tariff Policy Design, Technical Report NREL/TP-6A2-44849, July 2010.

13, McKenna, E. et al., 2013. Economic and environmental impact of lead-acid batteries in grid-connected domestic PV systems. Applied Energy, 104, pp.239–249. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0306261912008094 [Accessed January 7, 2013].

14 Foxton T J, Transition pathways for a UK low carbon electricity future, Energy Policy52(2013)10–24

15 , Dan T. Ton, Charles J. Hanley, Georgianne H. Peek, and John D. Boyes, Solar Energy Grid Integration Systems–Energy Storage (SEGIS-ES), National Technical Information Service,5285 Port Royal Rd.Springfield, VA 22161 Online order: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

16, Beausoleil-Morrison I, Kelly N,. Specifications for Modelling Fuel Cell and Combustion-Based Residential Cogeneration Device within Whole-Building Simulation Programs. A Report of Subtask B of FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme, 2007.

17, Beausoleil-Morrison I, Kelly N, 2007b, Experimental Investigation of Residential Cogeneration Devices and Calibration of Annex 42 Models. A Report of Subtask B of FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme, 2007

18 I. Staffell , P. Baker , J. P. Barton, , N. Bergman , R. Blanchard ,N. P. Brandon , D. J. L. Brett , A. Hawkes , D. Infield , C. N. Jardine,, N. Kelly , M. Leach , M. Matian , A. D. Peacock,S. Sudtharalingam B. Woodman , UK microgeneration. Part II: technology overviews, Energy 163, November 2010 Issue EN4,Pages 143–165,doi: 10.1680/ener.2010.163.4.143,2010

19 BERGMAN, N., JARDINE, C., 2009. Power from the people: domestic microgeneration and the low carbon buildings programme, Oxford: Environmental Change Institute, University of Oxford, www.eci.ox.ac.uk.

20 Cooper, S. J. G., Hammond, G. P. and Mcmanus, M. C., 2013. Thermodynamic efficiency of low-carbon domestic heating systems: heat pumps and micro-cogeneration. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 227 (1), pp. 18-29.

21 J AEA,2011 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. 2011downloaded from http://www.defra.gov.uk/environment/economy/business-efficiency/reporting Aug 2013

22 Cooper, Samuel J G, 2013. Thermodynamic Analysis of Air Source Heat Pumps & Micro Combined Heat & Power Units Participating in a Distributed Energy Future. Thesis (PhD): University of Bath. Available at: opus.bath.ac.uk.

23 J21, Carbon Trust, Micro-CHP Accelerator Interim report November, 2007, Carbon Trust report CTC726,2007

24 J22, A D Hawkes, D J L Brett, and N P Brandon, Role of fuel cell based micro-cogenerationin low carbon heating, Proc. IMechE Vol. 225 Part A: J. Power and Energy,2010

25 Rogers, J.G., McManus, M.C. & Cooper, S.J.G., 2013. Potential for reliance on solar water heating throughout the summer in northern cloudy climates. Energy and Buildings, 66, pp.128–135. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813004192 [Accessed August 20, 2013].

26 ŠÚRI M., HULD T. A., DUNLOP E. D., PV-GIS: a web-based solar radiation database for the calculation of PV potential in Europe, International Journal of Sustainable Energy Vol. 24, No. 2, June 2005, 55–67, 2005

27 European Commission: Photovoltaic Geographical Information System –Interactive Maps, http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=europe, accessed December 2013

28, Eames, M., Kershaw, T. & Coley, D.A., 2010. On the creation of future probabilistic design weather years from UKCP09. Building Services Engineering Research and Technology, 32(2), pp.127–142. Available at: http://bse.sagepub.com/cgi/doi/10.1177/0143624410379934 [Accessed November 8, 2012].

29, Palmer, J. & Cooper, I., *Great Britain's housing energy fact file*, London: DECC,2011.

30, Rogers, J., Cooper, S., Hammond, G. and McManus, M., 2013. Use of micro CHP plants to support the local operation of electric heat pumps. In: 3rd International Conference in Microgeneration and Related Technologies in Buildings: Microgen 3, 2013-04-15 - 2013-04-17, Naples.

31, Roselli, C. et al., 2011. Experimental analysis of microcogenerators based on different prime movers. Energy and Buildings, 43(4), pp.796–804. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778810004184 [Accessed November 6, 2012].

32, Butler, D. & Hyde, K., 2007. Ecodan PUHZ-W90VHA air to water heat pump tests, Garston: Building Research Establishment Ltd.33, Payne, R., Love, J. & Kah, M., 2009. Generating Electricity at 60% Electrical Efficiency from 1 - 2 kWe SOFC Products. In ECS Transactions. ECS, pp. 231–239. Available at: http://link.aip.org/link/ECSTF8/v25/i2/p231/s1&Agg=doi [Accessed May 17, 2013].

34, Hong J, Kelly N J, Thomson M, Richardson I. Assessing heat pumps as flexible load. Proc. of the IMECHE Part A: Journal of Power and Energy. 2013: v227;1; pp 30-42.

35, Ramallo-González, A.P., Eames, M.E. & Coley, D.A., 2013. Lumped parameter models for building thermal modelling: An analytic approach to simplifying complex multi-layered constructions. Energy and Buildings, 60, pp.174–184. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778813000315 [Accessed February 27, 2013].

36, Incropera, F.P. & DeWitt, D., 1985. Fundamentals of heat and mass transfer; 2nd Edition, New York: John Wiley & Sons, Inc.

37, Richardson, I., Thomson, M.J. & Infield, D.G., 2008. A high-resolution domestic building occupancy model for energy demand simulations. *Energy and Buildings*, 40(8), pp.1560–1566. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378778808000467 [Accessed July 16, 2010].

38, Energy Saving Trust, 2008. Measurement of Domestic Hot Water Consumption in Dwellings, London: Energy Saving Trust

39, Warmepumpen-Testzentrum, 2013. Test results of air to water heat pumps based on EN 14511:2011, Buchs, Switzerland: Institut fur Energiesysteme, Interstaatliche Hochschule für Technik.

40, Johnson, E.P., 2010. Air-source heat pump carbon footprints: HFC impacts and comparison to other heat sources. Energy Policy, 39(3), pp.1369-1381.

41, H. A. Udo de Haes and R. Heijungs, "Life-cycle assessment for energy analysis and management", Applied Energy, vol. 84 (7-8), pp. 817-827, 2007.

42, McManus MC, Hammond GP, Burrows CR. Life-cycle assessment of mineral and rapeseed oil in mobile hydraulic systems. Journal of Industrial Ecology 2004;7(3–4):163–77.

43, PRé Consultants. SimaPro 7.3. Netherlands : PRé Consultants, 2010.

44, EMPA. EcoInvent. Switzerland : EcoInvent, 2007.

45, DECC, Domestic Renewable Heat Incentive A Government Response to 'Proposals for a Domestic Scheme' September Consultation, URN 13D/176, 2013 https://www.gov.uk/government/policies/increasing-the-use-of-low-carbon-technologies/supporting-pages/renewable-heat-incentive-rhi Accessed Aug 2013.

46, Energy Saving Trust web site www.energysavingtrust.org.uk/Generating-energy/Getting-money-back/Feed-In-Tariffs-scheme-FITs accessed July 2013

47, Cambridge Economic Policy Associates Ltd and Parsons Brinckerhoff, Updates To The Feed-In Tariffs Model Documentation Of Changes For Solar PV Consultation, 26 October 2011.

48 , http://www.which.co.uk/home-and-garden/heating-water-and-electricity/reviews/boilers/

49, http://new-boiler-cost.co.uk/a-guide-to-gas-boiler-replacement-costs/

50 , http://local.which.co.uk/advice/cost-price-information-boiler-repair-central-heating

51 , www.Airconwharehouse.com

52 , Hollie Orr, Distributed Generation and Storage Technical Portfolio, IMPROSUME report, 2012

53, www.microchp.be accessed July 2013

54, H.I. Onovwiona, V.I. Ugursal, Residential cogeneration systems: review of the current technology, Renewable and Sustainable Energy Reviews10 (2006) 389–431

55, www.bluegen.info

56, Parkinston , Reneweconomy, 30 October 2012, http://reneweconomy.com.au/2012/ceramic-fuel-cells-packs-its-bags-and-moves-to-europe-47229

57,J, Fuelcelltoday, 17 August 2012, BlueGen Domestic Fuel Cell Available for Under £20,000 in the UK - http://www.fuelcelltoday.com/news-events/news-archive/2012/august/bluegen-domestic-fuel-cell-available-for-under-%C2%A320,000-in-the-uk#sthash.AtfzJCxo.dpuf

58, http://www.solar-trade.org.uk/solarHeating/typesOfCollectors.cfm

59, http://www.stovesonline.co.uk/wood_burning_stoves/Akvaterm-Standard-Thermal-Stores.html

60, Parsons Brinckerhoff Solar PV cost update May 2012, prepared for Department of Energy & Climate Change, May 2012

61, DECC, DUKES Table 5.6.2 Domestic electricity prices in the EU for medium consumers including tax, www.decc.gov.uk, 2012

62, Interlink, Household Electricity Survey a study of domestic electrical product usage, R66141 Final Report Issue 4 commissioned by AEA group, The Gemini Building, Fermi Avenue Harwell Oxford Didcot OX11 0QR,2012.

63, Hammond G, P,. Jones C, INventry of Carbon & Energy (ICE) version 2, downloaded from

http://www.circularecology.com/ice-database.html Jan 2014

64, World Nuclear Organisation, Nuclear Radiation and Health Effects website 2012 http://www.world-nuclear.org/info/Safety-and-Security/Radiation-and-Health/Nuclear-Radiation-and-Health-Effects/ accessed Jan 2014

65, Rogers J, G,. Simplified strategy for modelling the performance of a novel multi house heating schemes, Paper presented at SESDE conference Athens 2013

66, Barton J, Davies L, Dooley B, Foxton T J, Galloway S, Hammond G P, O'Grady Á, Robertson E, Thompson M, Transition Pathways for a UK low carbon electricity system: comparing scenarios and technology implications, working paper 2013/5,2013 available from www.realisingtransitionpathways.org.uk

67 PRé Consultants, Radboud Universiteit Nijmegen. ReCiPe web site http://www.Icia-recipe.net

68, Whispergen Tech ltd, Whispergen Mk 5 System design manual, Part No. WP-5037-025-00 UK, 2006

69, SenerTec, Instructions for Installation, assembly, commissioning and assembly of Dachs, Art No 07/4798.232.102

70, Mitsubishi electric, Ecodam Advanced heating technology,2009 web:www.mitsubishielectric.co.uk/heating

71, International Standards Organization [ISO] (2006a) Environmental management – life cycle assessment – principles and framework, [EN ISO 14040.] 2ndedn, ISO, Geneva, Switzerland.

72, International Standards Organization [ISO] (2006b) Environmental management – life cycle assessment – requirements and guidelines, [EN ISO 14044.] ISO, Geneva, Switzerland.

73, Guinée, J.B.; Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M.A.J. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, 692 pp.

74, Jenkins D P, Peacock A D, Banfill P F G, Kane D, Ingram V, Kilpatrick R, Modelling carbon emissions of UK dwellings - The Tarbase Domestic Model, Applied Energy, Volume 93, May 2012, Pages 596-605, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2011.11.084.

75, Rees M T, Wu J, Jenkins N, Abeysekera M, Carbon constrained design of energy infrastructure for new build schemes, Applied Energy, Volume 113, January 2014, Pages 1220-1234, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2013.08.059.

76, Herrando M, Markides C N, Hellgardt K, A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance, Applied Energy, Volume 122, 1 June 2014, Pages 288-309, ISSN 0306-2619,

77, Yao J, A multi-objective (energy, economic and environmental performance) life cycle analysis for better building design, Sustainability 2014, 6, 602-614; doi:10.3390/su6020602

Appendix 1

There are a number of open access or fully described, verified models for domestic energy demand and heating system performance available in the public domain. We have endeavoured to use these where appropriate and use their outputs in our modelling. The basic relationships between the models used is shown in the following diagram.