# AN APPROACH TO VISUALISING THE OPERATIONAL MIX OF RENEWABLE GENERATION TECHNOLOGIES NEEDED TO ACHIEVE ZERO-CARBON EMISSIONS FROM COMPACT URBAN DWELLINGS

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## ABSTRACT

There is an increasing demand for housing in the UK and the trend towards urban living is resulting in the redevelopment of inner city areas. Often sites are constrained by existing buildings and infrastructure and hence the choices over orientation and layout are limited, the roof area in particular. In addition, the living space is maximised to provide the greatest return on the initial investment and hence the area required for plant and equipment is at a premium. The drive towards producing dwellings that produce net zero-carbon emissions during operation places further constraints on the design of these buildings and results in a challenging web of interdependencies between the architectural layout of the building, the building fabric itself, the systems and their control, the renewable energy generation equipment and occupant demand for electricity and heat. Based on a case study, this paper presents an approach to break down these interdependencies into manageable stages and suggests a way to visualise the zero carbon performance as part of the overall design process.

**Keywords**: Dynamic building simulation, Zero carbon (ZC) housing, Compact urban dwelling, energy demand profiles, on-site energy generation.

## INTRODUCTION

The trend towards inward migration is resulting in new homes being built on brown-field sites in towns and cities in the UK, where space is limited (Banfill and Peacock, 2007). In the UK, apartment based living is less common than the single family house on its own plot of land, however, to maximise the space available, these urban sites are having apartment based dwellings constructed on them. These are being termed ‘compact urban dwellings’ and often have a living space of around 50 m$^2$ in either one or two stories with a likely occupation of one or two people.

From 2016 all new build UK homes must meet the highest criteria of the government’s Code for Sustainable Homes (CSH) as stated in greener homes for the future. (Department for Communities and Local Government, 2006). The CSH (DCLG, 2006) states that code level 6 can be achieved by: “*using low and zero carbon technologies such as solar thermal, biomass boilers, wind turbines and combined heat and power systems (CHP). It would mean that for example energy taken from the national grid has to be replaced by low or zero carbon generated energy, so that over a year the net emissions were zero*”.

The lack of control over building orientation, building volume and roof space available in these buildings presents a major challenge to both the architect and engineer in the pursuit of an appropriate design that will deliver zero carbon operation when in service. There is little, if any, literature focused discussion of the engineering constraints, control considerations and other factors that affect the selection of the mix of renewable energy technologies during the design of these types of buildings.

The work presented here is based on a study of the design of the energy systems for a recently constructed net zero-carbon housing development in Derby, UK. This paper presents a simulation-based approach that could be applied to the design of other similar buildings, to help unpick the critical interdependences between the design of the engineering systems, system inputs and control assumptions in order to establish some confidence that a selected mix of renewables has a high chance of delivering zero-carbon performance when in use, before embarking on a more detailed analysis to determine the precise capacities, configurations and control strategies that would be developed into a working design for the real building.

## FORMULATING THE APPROACH

The design of the energy systems for a net zero-carbon compact urban dwelling can be split into three principle components: the demand through the occupants and their influence on the consumption of electricity and heat; the building systems that deliver ventilation and heat recovery, space heating and domestic hot water (DHW) supply; and the supply/generation of heat and electricity to those systems. Ideally, it would be possible to decouple the generation systems from the building in order to explore which mix of renewables is most appropriate for a particular building.

Combined Heat and Power (CHP) plant does run largely independently of environmental conditions, and as long as there is a sufficiently large thermal store, the relatively high temperature of the heating water being produced means that it is possible to make a reasonable evaluation of performance without coupling it to a model of a building and its systems.

Although driven by the availability of solar radiation, Photovoltaic (PV) systems can also be treated in isolation to assess performance when connected to the national electricity supply grid. The Grid in this case can be treated as electrical storage with infinite capacity, where a 100% of the demand can be met and 100% of the generated power can be exported.

Systems such as Solar Thermal (ST) arrays and Heat Pumps (HP) are affected by the supply temperature of the heating water they produce and this water supply is affected by the operating conditions of the system the equipment is connected to as well as the environmental or ground conditions, depending whether you have an air sourced or ground sourced heat pump. Any intermittent generation must also be buffered by storage to maintain the supply of the demand at the appropriate time. The capacity, volume and configuration of this store are critical to the operation of the systems that might be connected to it such as CHP, HP and Solar Thermal arrays.

One of the conflicts that arise with the thermal store is the volume required. Increasing the volume of the tank increase construction costs and reduced the saleable/letable floor area of the building and hence the operation of the system is at odds with the commercial drivers. In addition, whether to have single or multiple tanks is an important consideration that can have effects on the performance (Grondzik et al. 2010).

The heat losses are minimised in these buildings in order that the demand for space heating, and hence the required onsite generation capacity, is minimised. This does mean, however, that the internal heat gains from the occupants and through the consumption of electricity through appliance use noticeably affects the heating demand in winter. Establishing the occupancy profiles and range of expected appliance use therefore becomes important to evaluate those generation systems connected to the thermal store that is part of the system used for the provision of heat.

Occupants also have control over the DHW draw-off, although principally for hygiene and food preparation is likely to dominate over the provision of heating since the high insulation levels in the fabric and MHVR minimise that required for space heating.

The dependencies between the generation and consumption of heat and electricity, the likely variation in occupation, the use of heat and electricity and the interdependencies of plant characteristics suggest that the analysis should use dynamic thermal simulation. As part of the commercial design of such buildings the challenge here is to minimise the effort expended in establishing a workable mix of renewable technologies relatively early on in the design of the engineering systems. This generates confidence that a particular scheme will produce net zero-carbon performance, before embarking on a more detailed analysis to fine tune the capacities of the each component and establish the most affective control strategy, involving further simulation work.

## The Approach

The approach it to establish some bounds, or an envelope of annual heat and electricity demand in which there is some confidence that the real building will operate once occupied. This can be estimated in any thermal simulation tool, or even using simple, steady-state methods. The second stage is to estimate some generation plant capacities based on conventional design-day loads for the specified building such that each generation option is able to supply 100% of the power and/or heat demand. The exceptions are the determination of the generation capacities of ST and PV which are constrained by the area available for installation. The third stage is to model the building and its systems in a dynamic simulation (TRNSYS was used here) to evaluate the overall building heat/power consumption/generation in hourly time steps and aggregating these figures over a typical year and various load conditions. The initial steps are to establish the:

1. architectural design/building dimensions;
2. available area for the collection of solar energy;
3. heating and ventilation delivery methods;
4. volume available for heat storage;
5. range of generation methods available;
6. dynamic performance estimates of the loads and generation methods;
7. principle space gain/demand characteristics; and,
8. constraints on the systems and components.

Establishing items 1 through 5 are straightforward and should be identifiable for any given project. The environmental conditions are given by historical weather data for the specified location. The principle demand characteristics describe things like the occupancy profile, space heating use, hot water consumption and use of electrical appliances. Internal gains from occupants and solar gains through the windows should be accounted for. These can be generated from rules of thumb, or by simulation which will depend on the time available for analysis and for the level of detail required. What is important is to establish the bounds for the annual heat and electricity consumption within which it can be reasonably expected the building will perform; and this is termed here, the ‘demand envelope’.

Using the architectural information, a knowledge of the heat and electricity demand and simulation results

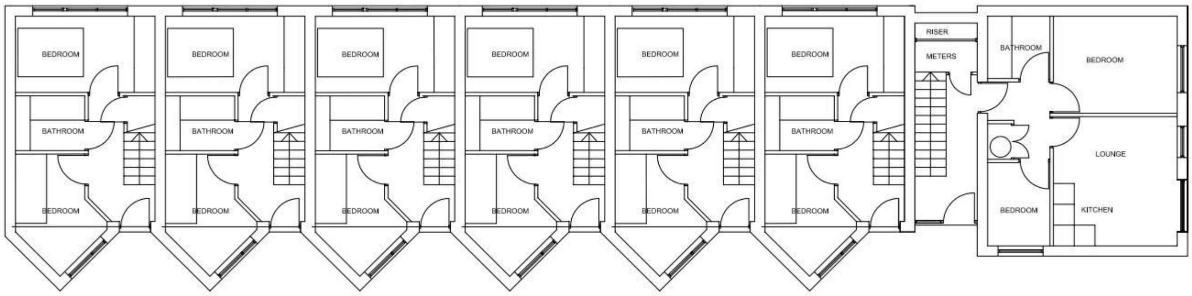


***Figure 1, the ground floor plan of the building. The upper floors to the 6 identical flats are an open plan living space with kitchen. The flat to the right is the first storey of three identical units. The building dimensions are approximately 36m by 8m and 9 m at the highest point.***

it is possible to estimate the size/capacity of the key components of the energy generation systems:

1. roof area for solar thermal and/or PV;
2. CHP, HP, etc. for a design heating day; and,
3. thermal store based on volume and medium.

This will allow the determination of the renewable mix required to deliver a zero-carbon evaluation energy supply together with an indicator of the risk of under/over delivery of electricity or heat, which will lead to non zero-carbon performance. To generate this indicator of risk, simulation can be used to estimate:

1. the likely annual electrical and thermal energy demand envelope, and,
2. the annual production/consumption by each of the heat and electricity generation systems.

The simulation output can be used to calculate power/heat consumption/production characteristics for each item of generation equipment. These characteristics can be overlaid on the demand envelope and used to establish the annual over/under generation for given systems combinations. The plot can be used to evaluate the in-operation balance of renewables to inform further simulation work to establish the optimum plant capacities and control strategies and set points.

The next sections of the paper introduce the case study building and work through these stages for this building, presenting the results and describing the analysis method in more detail.

## THE CASE STUDY BUILDING

The SHINE-ZC building in Derby (Figure 1) is north facing and comprises nine dwellings; six, two-storey houses and one three-storey block containing three flats. Each dwelling has a living space of approximately 50m$^2$. The architectural layout of the building meant that it was challenging to make the space available for large thermal storage, which would have made solar thermal panels in particular, more effective. Instead the design was based around each dwelling having sufficient space to house a 315 litre thermal store which is large enough to supply the estimated space heating and hot water demand to each flat 99% of the time under standard conditions CIBSE (1986).

The roof area is split in two levels; usable roof area for solar collection is ~160m$^2$ over the 6 houses and ~70m$^2$ over the right hand flats. Ideally the roof would have been constructed with a 40º pitch to maximise the yield from any solar thermal or Photovoltaic (PV) systems installed (Energy Saving Trust, 2004), however, planning consent restricted the pitch to 6º, leading to an estimated loss per year of direct solar radiation in the order of 20% (CIBSE Guide 1986).

Key to minimising the heat required for space heating, is a highly insulated fabric, minimal infiltration and to employ heat recovery on the ventilation air. An Insulating Concrete Formwork (ICF) system was used for the structure in combination with triple glazed windows with U-values of 0.123W/m$^2$K and 1.0W/m$^2$K respectively. Ventilation is provided by mechanical ventilation with heat recovery (MVHR), with an air exchange rate in each dwelling of 17l/s (Building regulations part F, 2006). The heat recovery capacity of the specified system has a stated manufacturerôs efficiency of 90 % (Segen, 2006).

The properties are heated with radiators with thermostatic radiator values (TRVs) for the control of individual rooms and the heating in each dwelling is controlled through a central thermostat located in the hallway of each unit.

## ENERGY GENERATION OPTIONS

Solar thermal collectors, photovoltaic panels, air-source heat pumps and a bio-fuelled, micro combined heat and power generator where considered in this analysis. Watson et al (2008) stated that wind generation has a very limited yield in an urban setting and bio-mass boilers were not considered in this particular case. Ground source heat pumps were also not considered because the available area for horizontal evaporator coil was limited and the commercial viability of installing vertically drilled systems was prohibitive.

If the most common type of PV array (crystalline silicon) is used, Bayod-Rújula et al (2010) show that around 9m$^2$ of roof space is required to install 1kWp of PV panels. With 230m$^2$ of roof space, a maximum installation of approximately 25kW$_p$ can be installed.

The variation of the heat output of ST collector is not only dependant on area, but also on inlet temperature. Brinkworth (2001) derived a set of graphics using as parameters the storage capacity and the collector area. If the size of the panels is small compared to the storage capacity, the limiting case is the area of the collectors. If, however, the collector area is large compared to the storage capacity, the reverse is true. In this installation, the ST collectors would be mounted on the roof at 6° and hence the yield will be reduced. In addition, the capacity of the thermal storage is likely to limit their effective deployment and so they were not considered as an option in this study.

## DEMAND CHARACTERISTICS

The demand characteristics are determined here to vary the inputs to the simulation in order to calculate the annual electrical and heat demand for the building. These figures are then used to estimate the likely demand envelope.

The level of detail used in the demand profiles are important and will affect the estimation of thermal and electrical generation. There are a number of inputs to vary:

- the occupancy profile, affecting internal heat gains, DHW use and switching of appliances;
- heating schedule, affecting the space heating demand;

The approach reported here can be easily expanded to incorporate more sophisticated models of occupancy and electrical demand (Richardson et al, 2010), DHW draw (Jordan et al, 2000) for example. The approach could be extended to include future weather scenarios also (TM36, 2005). However to demonstrate the approach, simpler models have been used and are described below.

**Occupancy and Activity:** Each dwelling is treated the same. The dwellings are occupied from 16:00 to 09:00 the following day. Occupants are regarded as sleeping between 23:00 and 07:00. No differentiation for weekend activity has been made in this analysis. Anderson et al, 2001)

**Electrical Consumption:** Three levels of electrical consumption are applied. 75W is assumed to be the unoccupied, or sleeping base load, accounting for white goods and the MHVR system. During the awake occupied hours a constant load of 496W is applied. The annual electrical consumption is therefore 2288kWh, as given in the BREDEM model (Anderson et al, 2001).

**Heating Schedule:** The temperature of the space is controlled to 21ºC during occupied hours in the heating season and 15ºC during unoccupied/sleeping hours. The heating season is taken to be from November until the end of March. The space heating requirement is only 20% of the total thermal requirement.

**DHW draw:** The CSH requires that the DHW water consumption must be less than 80 litres per day per dwelling (DCLG, 2006). There is no DHW consumption pattern given in the code and so for the purposes of this analysis it has been assumed that half of the volume is used in the morning between 07:00 and 08:00 and half in the evening between 18:00 and 19:00.

**Treatment of internal heat gains:** During occupancy the internal heat gains from the occupants is taken as 115 W (CIBSE, 1985). The solar heat gains are negligible as most of the windows are north facing and the south facing windows are shaded. The gain from the use of electrical appliances and lighting is assumed to heat the spaces, with the exception of the load for cooking, where only 90% of the heat generated enters the space (Anderson et al, 2001). The power used by the extract fans does not enter the space.

## CONSTRAINTS AND ASSUMPTIONS

**Thermal Stores:** The thermal stores are taken to be charged to capacity when the water in the bottom of the store reaches a temperature of 90ºC; and for the purposes of control, taken to be able to supply no useful heat if the bulk water temperature drops below 50ºC. The assumption is made here that the majority of this water is used for personal hygiene and therefore has a temperature of 40ºC at the draw-off points. The cold water supply is assumed to be 10ºC and mixed with the water from the tank to supply at 40ºC at the required flow rate.

**Air movement and ventilation:** High construction quality is assumed and so the infiltration rate is assumed to be low. There is no air movement modelled between the different zones, except the ventilation air through the heat recovery unit. The electrical consumption and the heat generated by the heat recovery are added to the internal gains according to the BREDEM method (Anderson, 2001).

**Air Source Heat Pumps:** The heat pump switches on if the average store temperature is less than 50 ºC. The maximum temperature the heat pump can deliver is 65ºC, hence the control system will prevent the HP running when the water in the bottom of the thermal store reaches this temperature. The electrical load to the heat pumps is assumed constant, however the heat output is dependant on the operating conditions.

**CHP:** The micro-CHP is modelled as a constant power output with an electrical power estimated at

10kW. This micro-CHP plant has twice the capacity to provide all the thermal needs for all the dwellings for 99% of the days, (CIBSE, 1986). The CHP switches on once a day. If the thermal stores are at 90ºC and the electrical demand has been satisfied, the CHP switches off.

## SIMULATION MODEL

The building and systems were simulated in TRNSYS software (Klein et al, 2007). The six houses were divided up in two zones per house, one upstairs and one downstairs. The flats and the staircase were modelled as one zone. Figure 2 details the renewable generation options, energy storage and energy inputs to the system. The occupants have some influence on the heating set points, DHW supply, lighting and appliance use. Two-way flows of heat are shown for the heating, solar thermal, HP and CHP systems. DHW is a draw-off where the heat flows from the store to the mains cold water supply. The CHP and PV both supply electricity, where as the HP consume it in exchange for heat.

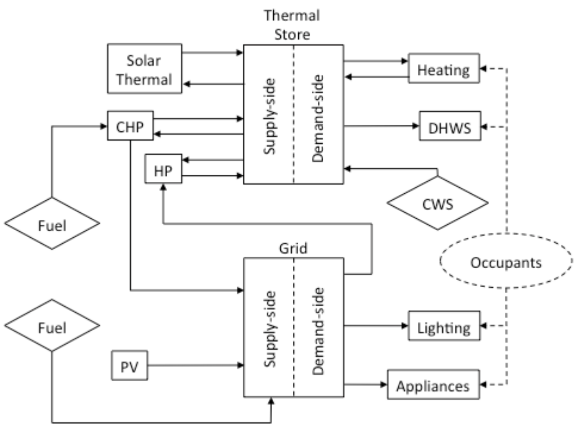


***Figure 2, Block schema of the heat and electricity generation, storage and demand system.***

The systems were modelled using the TRNSYS library with a few exceptions. Those to note:

- TRNSYS type 194b with inverter is used to determine the yield of the photo-voltaic array.
- TRNSYS type 4a, with 9 nodes of 0.2 meters high, which corresponds with the 1.8-meter high thermal stores in the dwellings.
- ASHP was modelled by the approach described by (Steijger et al, 2010) as the installed heat pump was completely characterized by this model.
- MHVR system was simulated using the approach described by Taylor et al (2010). This model was used because for the ease of control.
- Space heating input is calculated from the radiator models described by Knoll and Wagenaar (1994).
- There is a range of heat:power ratios for CHP from 10:1 (Whispergen 2010) to 2:1 (Baxi Dachs mini CHP, 2010). A small Diesel CHP can reach a 1.5:1 heat to electricity ratio (Tipkoetter BioGenio, 2010). Additional thermal losses with the operation of these small CHP can be high and hence a limiting case of 1:1 heat to electricity has been taken and used to illustrate the approach.

## RESULTS AND ANALYSIS

Using the BREDAM levels of energy consumption (DHW 80 l/day/dwelling, 2.3MWh/dwelling) the simulation demonstrated electrical energy demand for the whole building is 20.6MWh/year, the DHW energy is 15.3MWh and the space heating demand is 3.8MWh/year. This gives an estimate of a central operating condition. To develop the performance envelope, a number of other simulations were carried out to vary DHW draw and electrical load. Since the space heating represented such a small proportion of the overall consumption, varying the heating schedule and internal air temperatures was neglected.

To generate the limiting cases the CSH DHW water consumption of 80 litres/day was used as a central estimate. Measured data from the Energy Saving Trust (2008) showed a mean hot water consumption of 122 litres a day with a 95% confidence interval of ±18 litres a day. The data was taken from a study of 124 homes over a year. The mean number of occupants was 2-3 and hence taken to be at the upper limit of what might be expected from these homes since the expected occupancy is 1-2. The minimum DHW usage was estimated by mirroring the difference between the upper bound and the central case, to yield a lower boundary condition 42 litres/day. Figure 3 shows the resultant annual thermal energy requirement as a function of a variation in electrical load (20.6MWh/year is approximately central on the *x* axis).

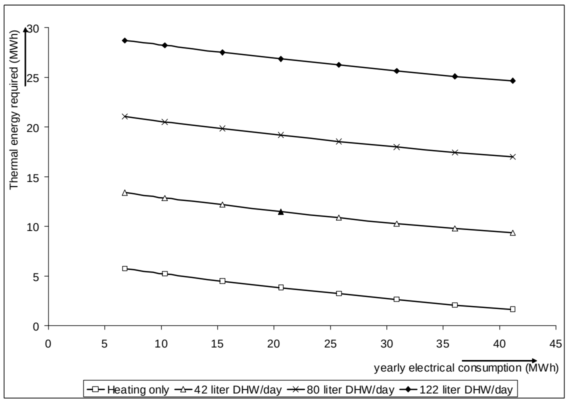


***Figure 3, total thermal energy demands in relation to the average electrical use for the whole building.***

The lower of the four lines represent the base heating demand. As the electrical appliance use goes up, the internal gains increase, offsetting the heat losses from the space and hence there is a reduction in the heating requirement. Second from the top is the BREDEM case for a range of electricity consumption (BREDEM electricity consumption is highlighted with a black triangle). The lines either side of that represent the upper and lower limits of the likely thermal energy consumption and as such are two sides of the likely performance envelope.

Determining the upper and lower expected levels of electrical consumption is also challenging. A recent study by Richardson et al (2010) reported a 10 fold difference in electrical consumption between similar housing with a mean consumption higher then the BREDEM value. The variation in distribution in the work was shown to be Gaussian and if the mean is multiplied by 9 to get a likely value for the consumption of the whole building, the variation in this value likely to be less than 10 fold. For the purposes of this paper, we have judged that this would be closer to a variation of 4 by averaging over 9 dwellings, but further work is needed to generate a more robust limit. The electrical consumption limits can be plotted on to Figure 3 with the limits associated with the heat demand. The building demand envelope can be shown as the grey area in Figure 4.

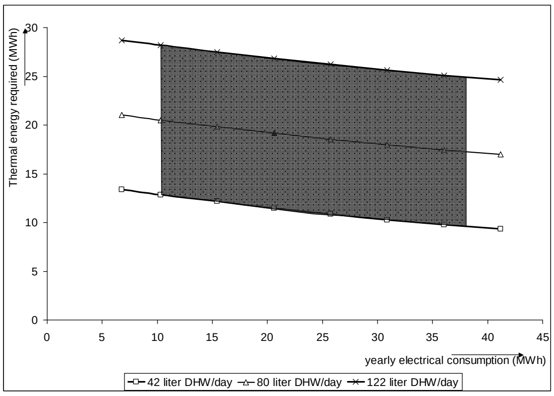


***Figure 4, the likely demand envelope for the building.***

The characteristics of the generation equipment can also described by their relationship between the annual electrical power and heat generated. Figure 5 depicts these characteristics, where the generation of heat/power is considered to be positive and the consumption of heat/power by the generation equipment is considered to be negative, i.e. it must be generated by another system.

For this building the ST collectors were not considered and hence the roof is covered with 100% PV. The simulation shows an annual generation of 18.5MWh. Since the PV does not interact with the building thermally, the heat/power relationship is zero. This characteristic is represented in Figure 5 by the positive horizontal line on the *x* axis, from zero to 18.5MWh.

The electricity production/consumption and heat production of the CHP and HP are not independent. The CHP generates a net positive contribution to the heat and electricity supply, whereas the HP generates heat, but uses electricity to do so, hence makes a positive contribution to the heat demand, but a negative contribution to satisfying the power demand. In more detail:

**Heat pump:** A heat pump transfers heat from a lower to a higher temperature by consuming electrical energy. This seasonal performance over a given period can be calculated from results from the simulation by:

$$SPF = \frac{\sum E_{thermal}}{T_{running} P_{in}} \qquad (1)$$

| | | |
|---|---|---|
| SPF | Seasonal performance factor | ( ) |
| $E_{thermal}$ | Generated thermal energy | (kWh) |
| $T_{running}$ | Time that the heat pump is running | (hrs) |
| $P_{in}$ | Electrical input power | (kW) |

As part of the analysis a number of HP scenarios were run and the lowest calculated SPF was 1.64, with a standard heat pump, running the whole year and with a water supply temperature control set point of 65 ºC. The highest SPF was 3.82, using a high performance heat pump, running during the summer and a water supply temperature control set point of 55 ºC. ***Figure 5*** plots these two cases, shown with the negative gradient on the left hand side.

The length of the vector defines how much energy is converted from electricity to heat and is linear with the number of running hours. The value on the *x* axis in the electricity consumed and the value on the *y* axis, the amount of thermal energy generated. The limiting case is resistive heating where the heat generated to power consumed in 1:1.

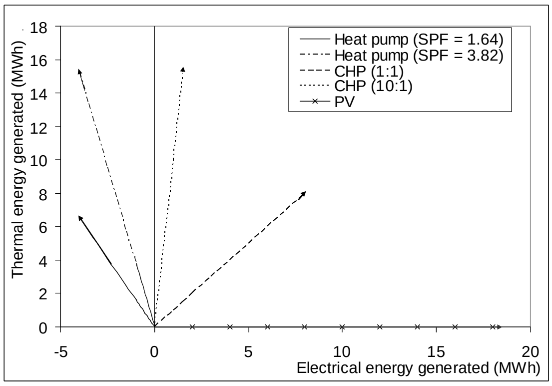


*Figure 5 thermal generation as a function of electrical power consumption/production with different type of generation plant.*

**CHP:** The CHP converts (in this case) vegetable oil into both thermal and electrical energy. The ratio of this is determined by the plant, and in this case assumed to be 1:1. Again the length of the vector is equivalent to the number of running hours. The upper case where a CHP with a 10:1 heat to electricity ratio is plotted for comparison.

Figures 4 and 5 can be overlaid to give a graphical representation of the relationship between the likely demand envelope and the heat/power characteristics of a combination of generation plant, Figure 6.

To generate the diagram, first the demand envelope in plotted. The generation from PV panels is plotted next, which establishes point A, at 18.5MWh.

The CHP will be required to generate the electricity that the PV cannot, hence the CHP characteristic line is rooted at point A. The heat generation required to cover the demand envelope is delivered when the CHP running hours are between point 5 up to point C.

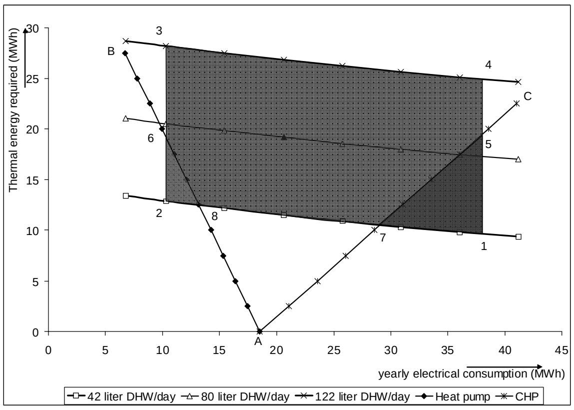


***Figure 6, shows the likely demand envelope and the degree of expected coverage offered by the generation options.***

The CHP is only able to operate along the linear trajectory defined by the heat-power characteristic line A-C in Figure 6. If the annual balance of heat and power consumption happens to fall anywhere to the left of that line, the CHP can only satisfy heat demand by generating a surplus of electricity, and vice-versa, to the right of the line. In order to meet combinations of heat and power requirement, a HP is needed.

If no CHP is used in the year, the HP heat/power characteristic line is also routed at point A. Because it consumes electricity, the line slopes to the left, indicating a reduction in the PV generated electricity available for consumption in the dwellings. To the left of the line the PV will be able to satisfy the electrical demand and the power required to run the heat pump to satisfy the heat demand. To the right of the line additional electricity generation is required hence more PV or where that is not possible, the use of CHP.

The light grey area shows the range of annual heat and electricity demand that can be satisfied by the combination of generation equipment. A complete energy balance can be achieved in the area 3-4-5-7-8-6. Over-production of heat will occur in the area 1-5-7 and would not require the use of the HP. Over production of electricity occurs in area 2-6-8 and the CHP is not required.

The PV, CHP and HP are all needed to have a good chance of achieving net zero-carbon emissions. The coverage risk indicator, *r,* can be calculated by,

$$r = a_{hpp} / a_{lde,} \qquad (2)$$

where $a_{hpp}$ and $a_{lde}$ are the heat/power provision area (3-4-5-7-8-6) and likely demand envelope area (2-3-4-1) respectively. For this building *r >85%.* Especially high electrical demand combined with low thermal demand might result in waste of thermal energy. If the CHP heat/electricity production ratio increases from 1:1, the value of *r* will go down indicating and increased likelihood of the building not performing as a zero-carbon building as waste heat is generated.

## CONCLUSIONS

A case study building was presented and an approach to evaluating the likelihood of generating sufficient heat and power on site for the development to be zero-carbon was introduced.

The approach is a staged and utilises dynamic thermal simulation. It is intended to be used as part of the design process to gain confidence that the selected mix of renewables will deliver the required heat and electricity generation performance.

A number of findings were reported:

- there is a lack of design targets detailed in the CSH and hence values have to be found from elsewhere and their appropriateness justified;
- a óperformance envelopeô was introduced based on annual electrical and heat demand and this was used to evaluate the selected mix of renewable technologies in the intended design;
- issues of likelihood of over and under generation were discussed and a operational coverage measure was introduced.
- It was demonstrated that a mix of PV, CHP and HP could deliver good coverage of the likely building heat/electricity demand for a compact urban dwelling development in the UK, however, an increasing CHP heat/electricity production ratio would impair the zero-carbon performance by wasting heat.

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