Supplementary Information

Forecasting how residential urban form affects the regional carbon savings and costs of retrofitting and decentralized energy supply

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# Appendix A. Technology scenarios for decentralised energy supply

## Table A1. The selection of decentralised heat and power technologies

These were selected for combinations of development type and area type as shown below.

| Scenario | Heat | Power | Scenario | Heat | Power |
|----------|------|-------|----------|------|-------|
| 1        | Low-CO<sub>2</sub> |       | 2        | Low-cost |       |
| Existing |       |       | Intensification |       |       |
| Central  | Micro-CHP & gas | Micro-CHP | Central  | Large Gas CHP & NG DH Boiler | Large gas CHP |
| Urban    | Biomass & Gas  | PV & Grid | Urban    | NG DH Boiler | PV & Grid |
| Suburban | Biomass & Gas  | PV & Grid | Suburban | Biomass DH Boiler | PV & Grid |
| Rural    | Biomass & Gas  | PV & Grid | Rural    | Biomass DH Boiler | PV & Grid |
| Central  | Small Gas CHP & NG DH Boiler | Small gas CHP | Central  | Large Gas CHP & NG DH Boiler | Large gas CHP |
| Urban    | Biomass DH Boiler | PV & Grid | Urban    | NG DH Boiler | PV & Grid |
| Suburban | Biomass DH Boiler | PV & Grid | Suburban | Biomass DH Boiler | PV & Grid |
| Rural    | Biomass DH Boiler | PV & Grid | Rural    | Biomass DH Boiler | Grid |
| Central  | Micro-CHP & gas | Micro-CHP | Central  | Large Gas CHP & NG DH Boiler | Large gas CHP |
| Urban    | Biomass & Gas  | Grid    | Urban    | NG DH Boiler | Grid    |
| Suburban | Biomass & Gas  | Grid    | Suburban | Biomass DH Boiler | Grid    |
| Rural    | Biomass & Gas  | Grid    | Rural    | Biomass DH Boiler | Grid    |
| Central  | Small Gas CHP & NG DH Boiler | Small gas CHP | Central  | Large Gas CHP & NG DH Boiler | Large gas CHP |
| Urban    | GSHP           | Grid    | Urban    | GSHP         | Grid    |
| Suburban | GSHP           | Grid    | Suburban | GSHP         | Grid    |
| Rural    | GSHP           | Grid    | Rural    | GSHP         | Grid    |
| Central  | Small Gas CHP & NG DH Boiler | Small gas CHP | Central  | Large Gas CHP & NG DH Boiler | Large gas CHP |
| Urban    | Resistive Heater | CHP   | Urban    | Resistive Heater | Grid    |
| Suburban | Resistive Heater | Grid   | Suburban | Resistive Heater | Grid    |
| Rural    | Resistive Heater | Grid   | Rural    | Resistive Heater | Grid    |

### Key:
- **CHP** Combined heat and power
- **DH** District heating
- **GSHP** Ground source heat pumps
- **NG** Natural gas
- **PV** Photovoltaic
Table A2. Typical percentages of decentralised supply per area type
The percentages shown are indicative and differed between tile types and area types

| Scenario          | Low densities Heat (%) | Low densities Electricity (%) | High densities Heat (%) | High densities Electricity (%) |
|-------------------|-------------------------|-------------------------------|-------------------------|-------------------------------|
|                   | Central areas | Other areas | Central areas | Other areas | Central areas | Other areas | Central areas | Other areas |
| Existing          |             |             |             |             |             |             |             |             |
| Low-CO₂           | 24          | 23          | 30          | 15          | 50          | 22          | 30          | 11          |
| Low-cost          | 24          | 23          | 30          | 0           | 50          | 22          | 30          | 0           |
| Highly-electric   | 24          | 24          | 30          | 0           | 40          | 23          | 30          | 0           |
| New-build         |             |             |             |             |             |             |             |             |
| Low-CO₂           | 30          | 30          | 30          | 22          | 30          | 30          | 30          | 10          |
| Low-cost          | 30          | 30          | 30          | 0           | 30          | 30          | 30          | 0           |
| Highly-electric D.H. | 30        | 100         | 30          | 0           | 30          | 95          | 30          | 0           |
| Resistive heating | 30          | 0           | 30          | 0           | 30          | 0           | 30          | 0           |

Table A3. Low carbon technologies tested and their requirements

| Technology          | Requirements                        | Comments                                                                 | Typical cost of one unit | Typical size in kW |
|---------------------|-------------------------------------|--------------------------------------------------------------------------|--------------------------|-------------------|
| Photo-voltaic       | Roof or space facing SE/SW          | Can export electricity if connected to grid, more cost effective if high on-site demand | £5k to £25k upwards     | 1 to 4 upwards    |
| Ground source heat pump | Land area for ground collector or a water source | Building with a space heating (and possibly cooling) demand and low temperature heating system (e.g. under-floor) | £5k to £25k upwards     | 3.5 kW to 15 kW upwards |
| Micro-CHP           | Domestic or communal space          | Proportional heat and electricity demand, scope for heat network          | £500 to 800 /kWe and £660/kWe | kW to MW       |
| Resistive heater    | Open floor space                    | Building with minimum heating demand, highly-electric future              | £30 to 50 /kW           | W to kW         |
| CHP & District Heating | Communal space                     | Higher concentration of heat and electricity demand and their proportionality, scope for networking | £650 to 850 /kWe        | kW to MW       |
| Biomass & gas       | Domestic space                      | Fuel supply network                                                       | £500/kW                  | kW               |

¹ These systems were sized to the on-site requirements by selecting the nearest available manufactured size.
**Fig. A1.** Schematic illustration of the tiles

**Table A4:** A subset of the built form data per tile type

Table A4a. Tile data per house (Figure A1 illustrates the tile types)

| Dwelling type     | Tile Type | Tile Density (dph) | Floor space (sq.m) | Total garden (sq.m.) | Rear garden (sq.m.) | Rear garden soft surface | Top floor roof (sq.m.) | Roads & paths % of tile |
|-------------------|-----------|--------------------|--------------------|----------------------|---------------------|--------------------------|------------------------|--------------------------|
| **Detached**      | D1        | 7                  | 234                | 1131                 | 633                 | 80%                      | 117                    | 14%                      |
|                   | D2        | 12                 | 191                | 610                  | 362                 | 80%                      | 87                     | 14%                      |
|                   | D3        | 23                 | 133                | 258                  | 140                 | 70%                      | 58                     | 22%                      |
|                   | D4        | 30                 | 120                | 184                  | 103                 | 60%                      | 54                     | 24%                      |
| **Semi-detached** | S1        | 13                 | 126                | 562                  | 407                 | 75%                      | 63                     | 16%                      |
|                   | S2        | 23                 | 105                | 299                  | 198                 | 70%                      | 47                     | 19%                      |
|                   | S3        | 31                 | 95                 | 196                  | 124                 | 65%                      | 41                     | 22%                      |
|                   | S4        | 42                 | 85                 | 119                  | 69                  | 60%                      | 37                     | 30%                      |
| **Terraced**      | T1        | 22                 | 106                | 280                  | 215                 | 65%                      | 53                     | 25%                      |
|                   | T2        | 68                 | 86                 | 57                   | 42                  | 30%                      | 43                     | 32%                      |
|                   | T3        | 90                 | 68                 | 25                   | 21                  | 15%                      | 30                     | 43%                      |
|                   | T4        | 109                | 62                 | 14                   | 5                   | 5%                       | 31                     | 51%                      |
Table A4b. Tile data for apartments (Figure A1 illustrates the tile types)

| Dwelling type | Tile Number | Tile Density (dph) | Floor space per dwelling (sq.m.) | Garden area per block (sq.m.) | Roof area per block (sq.m.) | Pitched roof (%) | Green space (%) of tile | Roads & paths % of tile |
|---------------|-------------|--------------------|----------------------------------|------------------------------|-----------------------------|------------------|------------------------|------------------------|
| Purpose built | F1          | 77                 | 69                               | 686                          | 549                         | 100%             | 30%                    | 23%                    |
|               | F2          | 101                | 66                               | 568                          | 662                         | 90%              | 23%                    | 27%                    |
|               | F3          | 164                | 53                               | 61                           | 259                         | 75%              | 13%                    | 28%                    |
|               | F4          | 216                | 51                               | 0                            | 2350                        | 55%              | 27%                    | 21%                    |
|               | F5          | 330                | 62                               | 0                            | 587                         | 0%               | 29%                    | 26%                    |
| Converted     | C1          | 162                | 70                               | 69                           | 74                          | 100%             | 0%                     | 23%                    |
|               | C2          | 277                | 57                               | 25                           | 58                          | 100%             | 0%                     | 38%                    |
|               | C3          | 374                | 59                               | 11                           | 61                          | 100%             | 0%                     | 35%                    |

Table A5. Suitability of the technologies tested for the tile types

Table A5a. Suitability Table for Existing houses

| Area Type     | Technology                  | Tile Types | D1 | D2 | D3 | D4 | S1 | S2 | S3 | S4 | T1 | T2 | T3 | T4 |
|---------------|-----------------------------|------------|----|----|----|----|----|----|----|----|----|----|----|----|
| Central       | Micro-CHP & gas             | √           |    |    |    |    |    |    |    |    |    |    |    |    |
|               | Micro-CHP & biomass         | √           |    |    |    |    |    |    |    |    |    |    |    |    |
| Urban, Sub-urban & Rural | Biomass & gas       | √           |    |    |    |    |    |    |    |    |    |    |    |    |
|               | GSHP                        | √(H)       |    |    |    |    |    |    |    |    |    |    |    |    |
|               | PV                          | √           |    |    |    |    |    |    |    |    |    |    |    |    |

Table A5b. Suitability Table for Existing apartments

| Area Type     | Technology                  | Tile Types | F1 | F2 | F3 | F4 | F5 | C1 | C2 | C3 |
|---------------|-----------------------------|------------|----|----|----|----|----|----|----|----|
| Central       | Micro-CHP & gas             | √           |    |    |    |    |    |    |    |    |
|               | Micro-CHP & biomass         | √           |    |    |    |    |    |    |    |    |
| Urban, Sub-urban & Rural | Biomass & gas   | √           |    |    | x  |    |    |    |    |    |
|               | GSHP                        | √(H)       |    |    |    |    | x(V) |    |    |    |
|               | PV                          | √           |    |    |    |    |    |    |    |    |

Key: √ The technology outputs are suitable for this tile type
x The technology outputs are unsuitable for this tile type
√(H) Suitable for the horizontal GSHP systems tested
x(V) Unsuitable because only vertical GSHP would be feasible (not tested for this case study)
Table A5c. Suitability Table for New-build houses

| Area Type       | Technology                                      | Tile types |
|-----------------|-------------------------------------------------|------------|
|                 |                                                 | D1  D2  D3  D4  S1  S2  S3  S4  T1  T2  T3  T4 |
| Central         | Gas CHP & NG DH boiler                          | x    x    x    x    x    x    x    x    x    √    √    √ |
|                 | Gas CHP & resistive heating                     | x    x    x    x    x    x    x    x    x    √    √    √ |
| Urban           | NG DH boiler                                    | x    x    x    x    x    x    x    x    x    √    √    √ |
| Urban, Suburban & Rural | Biomass DH boiler                         | √(H) √(H) √(H) √(H) √(H)      x(V)  √(H) x(V) x(V) x(V) |
|                 | GSHP DH Resistive heating                      | √    √    √    √    √    √    √    √    √    √    √    √ |
|                 | PV                                              | √    √    √    √    √    √    √    √    √    √    √    √ |

Key:
- √: The technology outputs are suitable for this tile type
- x: The technology outputs are unsuitable for this tile type
- √(H): Suitable for the horizontal GSHP systems tested
- x(V): Unsuitable because only vertical GSHP would be feasible (not tested for this case study)

Table A5d. Suitability Table for New-build apartments

| Area Type       | Technology                                      | Tile types |
|-----------------|-------------------------------------------------|------------|
|                 |                                                 | F1  F2  F3  F4  F5  C1  C2  C3 |
| Central         | Gas CHP & NG DH Boiler                          | √    √    √    √    √    √    √    √    |
|                 | Gas CHP & resistive heating                     | √    √    √    √    √    √    √    √    |
| Urban           | NG DH Boiler                                    | √    √    √    √    √    √    √    √    |
| Urban, Suburban & Rural | Biomass DH boiler                       | √(H) √(H) x(V) x(V) x(V) x(V) x(V) x(V) |
|                 | GSHP DH Resistive heating                      | √    √    √    √    √    √    √    √    |
|                 | PV                                              | √    √    √    √    √    √    √    √    |

Key:
- √: The technology outputs are suitable for this tile type
- x: The technology outputs are unsuitable for this tile type
- √(H): Suitable for the horizontal GSHP systems tested
- x(V): Unsuitable because only vertical GSHP would be feasible (not tested for this case study)
Appendix B. Further details of the tiles method

B1. Regional spatial planning forecasts
There were planning projections available from TEMPro [1] which was based on the land use transport interaction modelling for the National Transport Model of the UK Department for Transport. These projections included households, jobs and population that were spatially disaggregated into TEMPro zones and produced in consultation with the local authorities (each local authority district consists of several TEMPro zones). The local planning authorities produce local development frameworks with policies on densities for future development in different parts of their District. This information was combined with the planning projections to deduce the local authority expectations of housing capacity and densities per electoral ward to thereby derive an estimate of the future residential land available within urban areas. (Estimating future land and housing capacities outside urban areas is less problematic due to fewer constraints.)

The total future residential land $a_i$ per ward $i$ included the Existing-areas $a_{ei}$ and the estimates of New-land $a_{ni}$. The increase in households $h_i$ over the forecast period to year 2031 was allocated to this New-land based on density targets of local authority planning policies. Surplus households were accommodated by the intensification of Existing-areas, so that:

$$a_i = a_{fi} + a_{gi} + a_{hi}$$

Where:
- $a_{fi}$ = Estimate of Existing residential land remaining in year 2031
- $a_{gi}$ = The Existing residential land that would be redeveloped by Intensification
- $a_{fi} + a_{gi} \equiv a_{ei}$

Hence there were three development types $j$ that consisted of Existing, Intensification and New-land.

A LUTI model could be used to test alternative spatial planning policies by changing the inputs of the constraints on land available per area. The rate of intensification per ward was constrained within the LUTI model so that this did not exceed the empirically evidence of what would be achievable and acceptable in practice. This depended on the planning policy and area type. Any remaining surplus was allocated within the model to other nearby areas.

B2. Generating the tiles to represent the future dwelling stock

The forecast of average density $d_{ij}$ was converted into a representation of the future dwelling stock $h_{ij}$ by systematically selecting from a set of one-hectare tiles (Section 2.2) using the tiles method [2], where:

$$h_{ij} = d_{ij}.a_{ij}$$

We considered that having just 20 tile types was sufficient to demonstrate the method with our limited time and resources. More tile types could be added to increase the accuracy of approximating the distribution of dwelling plot densities. However, this would have increased the amount of time needed for the building-scale modelling of energy consumption and supply for the various combinations of technology scenario, area type and development type per tile type.

The number of tiles $n_t$ selected of each tile type $t$ can be any rational positive number (e.g. fractions of one-hectare). The tiles were systematically selected to represent the dwellings forecast and land constraints:
where:

\[ B3. \text{Modelling the energy demands and consumption per tile} \]

The application of the building energy model [3] is described in Section 2.3. There were four energy demand scenarios per tile type for year 2031; one for New-build and three for Existing dwellings i.e., without retrofitting, ‘low CO}_2\) retrofitting and ‘low cost’ retrofitting. Outputs included the fuel mix of gas, oil, solid fuel, biomass and electric for space heating, water heating, cooking and electrical power per tile type. The monthly heat and electricity demands were aggregated to annual Kw/hr per dwelling and the demands per tile calculated based on the tile density \(z_t\). The energy demands for Existing dwellings were converted into energy consumption per fuel type using the heating efficiency factors in SAP 2005 [4]. It was assumed that there would be on average a 10% improvement in the efficiency of conventional boiler heating systems over the forecast period.

\[ B4. \text{Energy supply outputs per tile} \]

The method of modelling the energy supply per tile is outlined in Section 2.4 and Appendix C. There were four energy supply scenarios for Existing dwellings i.e.: conventional supply only; or with the three technology scenarios shown in Table A1. There were five energy supply scenarios for New-build dwellings i.e.: conventional supply only, or the four technology scenarios shown in Table A1. These technologies for New-build differed depended on the development type \(j\) (Intensification or New-land). The energy scenarios per development type were modelled as a combination of the energy demand scenarios \(e\) and the energy supply scenarios \(s\) (there were therefore 3x4= 12 combinations for Existing dwellings, and 5 for Intensification and 5 for New-land). The selection of the energy supply technologies differed depending on the ‘area type’ \(k\) (4 types) and development type \(j\) (3 types). The outputs per tile included CO}_2\) emissions, capital & operating costs, overall supply cost, and land take (not presented). Therefore, each was produced as ‘lookup’ tables of outputs \(x\) for the forecast year as an array: \(x_{tesjk}\).

\[ B5. \text{Taking into account the uptake assumptions} \]

For energy supply, the technology uptake assumptions were taken into account when designing the system sizes per tile type as explained in Section 2.4. Examples of the percentages of decentralised supply are shown in Table A2. However, energy demands were modelled per dwelling either with, or without the retrofitting for energy efficiency.

The uptakes per tile for the demand and supply were therefore combined as follows:

\[ x = (1 - u)x_1 + u.x_2 \]

Where:

\(x_1 = \text{energy supply outputs for unretrofitted dwellings}\)
\(x_2 = \text{energy supply outputs for retrofitted dwellings}\)
\(u = \text{proportion of retrofitted dwellings}\)

For this case study, \(u=0.4\) for Existing dwellings and \(u=\text{zero}\) for New-build.
B6. Outputs per area

The outputs per tile $t$ for the required scenario were aggregated per electoral ward $i$. The tile outputs could easily be aggregated to a larger spatial area and, or by development type $j$ or area type $k$.

$$x_{iesj} = \sum_{t=1}^{20} n_{tj} \cdot x_{tesjk}$$  \hspace{1cm} (6)

The output per capita $= \frac{x_{iesj}}{p_{ij}}$

Where: $p_{ij} = \text{population forecast for development type } j \text{ in ward } i$

B7. Assessment of cost effectiveness

The reference case for the assessment was the tiles with conventional supply only, and the alternative case was the tiles with the decentralised technologies included. The cost effectiveness was calculated as the cost of a one tonne reduction of CO$_2$ emissions, as follows:

$$\text{Cost effectiveness} = \frac{(\text{Cost}_{\text{alt}} - \text{Cost}_{\text{ref}})}{(\text{CO}_2\text{emissions}_{\text{ref}} - \text{CO}_2\text{emissions}_{\text{alt}})}$$  \hspace{1cm} (7)

Where:

Cost$_{\text{alt}}$ = overall supply cost of the technology scenario (£/yr)
Cost$_{\text{ref}}$ = overall supply cost of the reference case (£/yr)
CO$_2$$_{\text{alt}}$ = CO$_2$ emissions of the technology scenario (tonnes/yr)
CO$_2$$_{\text{ref}}$ = CO$_2$ emissions of the reference case (tonnes/yr)

If any scenario would increase CO$_2$ emissions compared to conventional supply it was excluded from this cost effectiveness assessment.
Appendix C: Further details of the energy supply method and assumptions

C1. The energy supply technology options

The choice of the energy supply technologies depended on various factors: such as suitability, sustainability, and adoptability of decentralised technology to a particular dwelling type. The feasibility of these technologies would also depend on patterns of development which are density dependent; and the availability and scope of resources; the technological limitations of scale and advancements; and the temporal energy demands [5, 6, 7]. In view of these factors, the supply technologies were explored for various housing types in Table C1 and whether they would be for Existing housing, Intensification or on New-land and the scale of development. These considerations were taken into account when deciding on the suitability of these technologies shown in Table A5.

Table C1. Decentralised energy technologies – their suitability for different types of housing

| Technology       | Heat | Power | High-density urban housing | Low-density urban housing | Distributed suburban housing | Rural housing |
|------------------|------|-------|-----------------------------|---------------------------|------------------------------|---------------|
| CHP              | ✓    | ✓     | Very suitable (due to higher concentrated demand) | Not suitable              | Not suitable                  | Not suitable  |
| Micro-CHP        | ✓    | ✓     | Not suitable (due to higher demand) | Sometimes suitable        | Very suitable                | Very suitable |
| Solar water heating | ✓   |       | Very suitable with communal heating or CHP | Very suitable             | Very suitable                | Very suitable |
| PV electricity   | ✓    |       | Sometimes suitable (due to less exposed area) | Very suitable             | Very suitable                | Very suitable |
| Wood fuel boilers | ✓   |       | Generally suitable with communal heating (local availability) | Sometimes suitable        | Sometimes suitable           | Very suitable |
| Ground source heat pumps | ✓     |       | Suitable (if in vertical form) | Sometimes suitable for groups of dwellings | Very suitable (in horizontal form) | Very suitable (in horizontal form) |

1 Only horizontal GSHP were tested by this case study

The suitability of decentralised energy technologies as per the above patterns of development were also explored with respect to the settlement size as shown below in Table C2.

Table C2. Decentralised energy technologies - their suitability for different settlement sizes

| Settlement Size Bands (No. of dwellings) | Density | 1-10 | 10-100 | 100-1,000 | 1,000-10,000 |
|-----------------------------------------|---------|------|--------|-----------|-------------|
| High                                    | Micro-CHP¹, PV³ | CHP, PV⁴ | CHP, PV⁴ | CHP, PV⁴ | CHP, PV⁴ |
|                                        | GSHP², Biomass Boilers (BB³) | GSHP², BB³ | GSHP², BB³ | GSHP², BB³ | GSHP², BB³ |
| Medium                                  | Micro-CHP¹, PV, GSHP, BB³ | CHP, PV, GSHP, BB³ | CHP, PV, GSHP, BB³ | CHP, PV, GSHP, BB³ | CHP, PV, GSHP, BB³ |
| Low                                     | Micro-CHP¹, PV, GSHP, BB | Micro-CHP¹, PV, GSHP, BB | Micro-CHP¹, PV, GSHP, BB | Micro-CHP¹, PV, GSHP, BB | Micro-CHP¹, PV, GSHP, BB |

¹ If gas grid connections/extension would be possible.
² Vertical systems would be needed.
³ Subject to the suitability of a community heating system and is constrained by the biomass resource and space.
⁴ Constrained by solar radiations, roof area, shadow of the neighbouring buildings, etc.
In view of above constraints, different energy supply technologies were tested for heat and electricity supply for the three types of development (i.e. Existing, Intensification and New-land) and for three different scenarios (i.e. Low-cost, Low-carbon and Highly-electric), and for each one a possible supply solution is shown in Appendix A, Table A1.

C2. Energy supply cost calculations

Tables C3 and C4 show the capital and operating costs of various decentralised supply technologies along with the district heating costs considered for the case study.

Table C3.
Domestic and communal heat technologies [8, 9]

| Technology                        | Cost Capital     | Operation and maintenance | Lifetime |
|-----------------------------------|------------------|----------------------------|----------|
| Individual Domestic Gas Boilers   | £2500/dwelling   | £200/year                  | 15 years |
| Electric Heating                  | £175/kW          | £17/kW                     | 15 years |
| Biomass Boiler                    | £528/kW          | £18/kW                     | 15 years |
| Ground Source Heat Pumps          | £1200/kW         | £9/kW                      | 20 years |
| Air Source Heat Pumps             | £600/kW          | £9/kW                      | 20 years |
| PV Panels                         | £4000/kW         | £40/kW                     | 20 years |
| Micro-CHP                         | £850/kW          | £125/kW                    | 20 years |
| Small Gas CHP                     | £850/kW          | £80/kW                     | 20 years |
| Large Gas CHP                     | £650/kW          | £50/kW                     | 20 years |

Table C4.
District heating costs per dwelling type [8]

| Dwelling type                  | Total costs ¹         |
|-------------------------------|-----------------------|
| Small Terrace                 | £6,347                |
| Medium/Large Terrace          | £6,690                |
| Semi-detached Dense           | £7,617                |
| Semi-detached less Dense      | £8,217                |
| Converted Flat                | £3,764                |
| Low Rise Flat                 | £5,300                |
| High Rise Flat                | £4,800                |

¹ Total Cost included DHN infrastructure costs, DHN branch Costs, HIU and heat meter costs

The total cost of energy supply per tile type was estimated by accounting for the decentralised and centralised cost of energy supply. The decentralised cost of energy supply was calculated on the basis of assumed up-take of decentralised technologies. The percentage of decentralized supply was assumed based on our view of the achievable energy supply share in 2031, which would also be constrained by economic viability, scope for building integration, etc. In this case, the initial up-take assumption of the decentralised technologies was 30% (which we considered to be realistic) i.e., around 30% of the total energy demand that would be met through building integrated or community scale technologies for the component of conventional supply (heat or power) relevant to that chosen technology, subject to what would then be achievable after taking into account the factors affecting suitability and system size.

The energy supply systems were sized with respect to their connected energy demand, technical efficiencies, availability of space, operating hours, etc. For example, in case of sizing PV systems, the constraints such as south facing roof area, size of the panel, capacity factor, average sunshine hour, etc. were used to estimate the system size and its annual output. Similarly, in case of ground source heat pumps, the constraints such as garden area, seasonal coefficient of performance, capacity factor, hours of operation, etc. were used.
The unit cost of heat and electricity supply per tile, $C_t$, for different decentralised energy technologies was estimated in 2009 prices based on the net present value of the capital, operation and maintenance costs over the lifetime of the technology; the expected energy output over the lifetime of the technology; and the assumed discount rate of 3.5%. This was used to calculate the decentralised energy supply cost $C_d$:

\[ C_d = x_t \times D_t \times C_t \times z_t \]  \hspace{1cm} (8)

Where,
- $x_t = \text{Assumed uptake of decentralised supply technologies}$
- $D_t = \text{Annual heat/electricity demand for tile type } t \text{ in kWh/yr per dwelling}$
- $C_t = \text{Unit cost of decentralised heat/electricity supply for tile type } t \text{ in £/kWh}$
- $z_t = \text{density of tile type } t$

For calculating the overall cost including the centralised energy supply, it was assumed that the remaining energy demand would be met through the use of existing grid and gas networks. The cost of conventional grid and gas supply was assumed to be 0.1397 £/Kwh and 0.0398 £/kWh, respectively in 2009 prices [10].

**C3. The CO₂ savings calculations**

Table C5 and C6 shows the average fuel mix of conventionally supplied dwellings based on their total fuel consumption for space heating, water heating, cooking, appliances, lighting, pumps and fans for dwellings in the base year 2009 and for the forecast year of 2031 [3].

**Table C5. Fuel mix for Existing dwellings in 2009 (Base Year) for a selection of the tile types**

| Tile type | Gas (%) | Oil (%) | Solid (%) | Biomass (%) | Electric for heating (%) | Electric for power (%) |
|-----------|---------|---------|-----------|-------------|--------------------------|------------------------|
| D1        | 42      | 28      | 14        | 1           | 5                        | 11                     |
| D4        | 73      | 4       | 3         | 0           | 7                        | 13                     |
| S1        | 66      | 9       | 7         | 0           | 7                        | 11                     |
| S4        | 74      | 2       | 3         | 0           | 8                        | 14                     |
| T1        | 77      | 1       | 3         | 0           | 6                        | 13                     |
| T4        | 76      | 0       | 2         | 0           | 9                        | 13                     |
| F1        | 68      | 0       | 1         | 0           | 16                       | 15                     |
| F5        | 56      | 0       | 0         | 0           | 27                       | 17                     |
| C1        | 75      | 0       | 4         | 0           | 9                        | 13                     |
| C3        | 66      | 0       | 1         | 0           | 19                       | 14                     |

**Table C6. Fuel mixes of conventionally supplied dwellings (Existing ~ New-build) in 2031**

| Tile type | Gas (%) | Oil (%) | Solid (%) | Biomass (%) | Electric for heating (%) | Electric for power (%) |
|-----------|---------|---------|-----------|-------------|--------------------------|------------------------|
| D1        | 40–33   | 28-22   | 13-11     | 1-0         | 5-5                      | 14-29                  |
| D4        | 72–59   | 4-3     | 3-2       | 0           | 8-7                      | 15-29                  |
| S1        | 64–52   | 9-7     | 6-5       | 0           | 8-7                      | 14-28                  |
| S4        | 71–60   | 2       | 2         | 0           | 9-8                      | 16-28                  |
| T1        | 74–60   | 1       | 2-3       | 0           | 7-6                      | 15-31                  |
| T4        | 73–62   | 0       | 2         | 0           | 10-8                     | 15-28                  |
| F1        | 65–53   | 0       | 1         | 0           | 17-15                    | 18-31                  |
| F5        | 54–38   | 0       | 0         | 0           | 29-29                    | 19-33                  |
| C1        | 74–59   | 0       | 2-3       | 0           | 10-9                     | 15-30                  |
| C3        | 66–50   | 0       | 1         | 0           | 21-18                    | 16-31                  |
The calculations used a generalised seasonal coefficient of performance of 2.5 for GSHP. The heating efficiencies of the decentralised technologies were consistent with SAP 2009 Table 4 [11].

The CO₂ savings (in tonnes/kWh) were estimated on the basis of the amount of decentralised energy supply per tile type along with their emission factors (shown in Table C5) as below:

\[ CO_{2} \text{Savings} = E_c - E_d \]  \hspace{1cm} (9)

Where:
\[ E_c = CO_2 \text{ for the amount of decentralised supply if based on the conventional supply fuel mix} \]
\[ E_d = CO_2 \text{ emissions of the decentralised supply technology} \]

**Table C7. Emission factors [4]**

| Fuel                                                      | Emission Factors (kg/Kwh) |
|-----------------------------------------------------------|---------------------------|
| Gas (e.g. for conventional heating and CHP technologies)  | 0.206                     |
| Biomass (e.g., for biomass boilers)                       | 0.019                     |
| Solar PV                                                  | 0.0                       |
| Oil (e.g. for conventional heating in areas without gas supply) | 0.259                   |
| Solid fuel (e.g. for conventional heating)                | 0.311                     |
| Electricity (e.g. for power, GSHP and resistive heating)  | 0.482 in 2009 & 0.25 in 2031 |

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