Simulation of a 4\textsuperscript{th} generation district heating network operating with renewable heat sources and TES technologies

LoT-NET project

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Low Temperature Heat recovery and Distribution Network Technologies (LoT-NET)

Main objectives:

✓ To develop a spatial and temporal simulation tool that can be used to simulate a smart thermal network interacting with storage and thermal transformation technologies, which will allow the adoption of 4th generation district heating concept based on low/zero carbon heat sources.

i. Determine and geographically map the heat demand and available heat resources and how they vary in time within an area. Obtain heat demand time resolved data (for different areas) and heat production time resolved data (for different heat resources, focusing in low carbon heat resources).

ii. Develop a model for a heat network based on low carbon heat sources.

iii. Apply the developed model to 3 selected regions: Loughborough, Bunhill and Coleraine.

✓ Prototype a range of alternative systems utilising chemical, phase change material or sensible heat for both the distribution and storage of energy.
Simplified framework for the model

Stage 1

WEATHER at hour i

Heat demand at hour i

Heat production by renewable sources at hour i (kWh)

Heat losses in pipes (kWh)

Stage 2

Heat production > Heat demand + Heat losses?

Scenario 1

Additional heat input needed to meet demands, supplied by TES.

Scenario 2

Surplus heat produced, to be stored in TES.
Simplified framework for the model

Stage 1

Obtained with on-line tool Renewables.ninja developed by Staffell and Pfenninger\(^1\)\(^-\)\(^2\). The tool allows to obtain different historic hourly weather data for a given location:

i. temperature (°C),
ii. precipitation (mm/h),
iii. snowfall (mm/h),
iv. snow mass (amount of snow per land area, kg/m\(^2\)),
v. ground-level solar irradiance (W/m\(^2\)),
vi. top of atmosphere solar irradiance (W/m\(^2\)),
vii. cloud cover fraction and air density (kg/m\(^3\)).

The data are taken from the MERRA-2 reanalysis.

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The on-line tool **Renewables.ninja** can be used to directly estimate the hypothetical **hourly capacity factor** that could be achieved in a given location by using **Solar Photovoltaic (SPV) panels and Wind turbines**. Some variables can be modified also, such as:

i. System loss fraction  
ii. Tilt  
iii. Azimuth angle

For the SPV panels and:

i. Hub height  
ii. Turbine model

For the Wind.

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Simplified framework for the model

Stage 1

\[ HD_i = \sum_{j=1}^{4} HL_{ij} + H_{hw_i} + HL_{v_i} - H_{Gi} \]

*\( HL_{ij} \) are the hourly heat losses through fabric at \( t = i \) of the part of the dwelling \( j \) (where \( j = 1...4 \), being 1 = walls, 2 = floor, 3 = ceiling and 4 = glazing) (kWh)

*\( H_{hw_i} \) is the hourly heat demand originated from tap water heating (kWh)

*\( HL_{v_i} \) are the hourly heat losses due to ventilation (kWh)

*\( H_{Gi} \) are the hourly heat gains due to:

1. Occupancy
2. Solar heat gains
Hourly heat losses through fabric

\[ HL_{ij} = U_j \cdot A_j \cdot (T_{in} - T_{out_i}) \]

Hourly heat losses due to ventilation

\[ HL_{vi} = \frac{\rho_{air} \cdot C_{p\text{air}} \cdot HV \cdot (T_{in} - T_{out_i}) \cdot N_{air}}{3600} \]

*HL_{ij}* are the heat losses at \( t = i \) of the part of the dwelling \( j \) (where \( j = 1...4 \), being 1 = walls, 2 = floor, 3 = ceiling and 4 = glazing) (kWh)

- \( U_j \) is the U-value or thermal transmittance of the part of the dwelling \( j \) (W/m\(^2\) K)
- \( A_j \) is the area of the part of the dwelling \( j \) (m\(^2\))
- \( T_{in} \) is the desired temperature inside the dwelling or the space heating control set point, and was assumed to be 21 °C (typical of that seen in UK housing [7])
- \( T_{out_i} \) is the outdoors temperature at \( t = i \) (obtained with the on-line tool *Renewables.ninja* )
- \( \rho_{air} \) is the density of the air inside the house (1.225 kg/m\(^3\) at 20°C),
- \( C_{p\text{air}} \) is the specific heat capacity of the air (1 kJ/kg K),
- \( HV \) is heated volume of the dwelling (which is obtained from the dimensions showed in Table 2 for every type of dwelling, m\(^3\))
- \( N_{air} \) is the number of air changes per hour, which is taken from Table 1 for every type of dwelling.
Heat demand calculation. Heat losses through fabric and due to ventilation: Assumptions

<table>
<thead>
<tr>
<th>Detached</th>
<th>Semi-detached</th>
<th>Teraced</th>
<th>Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area (m²)&lt;sup&gt;[1]&lt;/sup&gt;</td>
<td>Heated volume (m³)&lt;sup&gt;[1]&lt;/sup&gt;</td>
<td>Total windows area (m²)&lt;sup&gt;[1]&lt;/sup&gt;</td>
<td>Width (m)&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>136</td>
<td>286</td>
<td>34.00</td>
<td>10</td>
</tr>
<tr>
<td>87</td>
<td>186</td>
<td>21.75</td>
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</tr>
<tr>
<td>57</td>
<td>142</td>
<td>14.25</td>
<td>10</td>
</tr>
<tr>
<td>56</td>
<td>140</td>
<td>14.00</td>
<td>10</td>
</tr>
</tbody>
</table>

<sup>1</sup> Assumed as a 25% of the floor area, according to [2]

<sup>2</sup> Assumed values.

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<table>
<thead>
<tr>
<th>fabrics</th>
<th>Basic U-value (W/m² K)&lt;sup&gt;[1]&lt;/sup&gt;</th>
<th>Improved U-value (W/m² K)&lt;sup&gt;[1]&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>0.45</td>
<td>0.11</td>
</tr>
<tr>
<td>Floor</td>
<td>0.60</td>
<td>0.10</td>
</tr>
<tr>
<td>Ceiling</td>
<td>0.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Glazing</td>
<td>2.94</td>
<td>0.70</td>
</tr>
<tr>
<td>Infiltration (air changes per hour</td>
<td>0.50</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Heat demand calculation. Heat demand originated from tap water heating

\[
H_{\text{hw}_i} = \frac{V_{\text{hw}_i} \rho_{\text{water}} C_{\text{p,water}} (T_{\text{supply}} - T_{\text{return}}) N_{\text{occ}}}{3600 \cdot 1000}
\]

\( V_{\text{hw}_i} \) is the volume of hot water consumed per 4 person and per hour at \( t = i \) (l/h per 4 person),

\( \rho_{\text{water}} \) is the density of water (kg/m\(^3\)),

\( C_{\text{p,water}} \) is the specific heat of water (kJ/kg K),

\( T_{\text{supply}} \) temperature of the water in the supply pipe (°C),

\( T_{\text{return}} \) temperature of the water in the return pipe (°C) and

\( N_{\text{occ}} \) is the number of occupants.

Heat demand calculation. Solar heat gains

\[ H_{G,i} = A_w \alpha F_c \left( \bar{f}_i \tau_b I_{b,i} \bar{R}_b + \tau_d F_{rs} I_{d,i} + \frac{\rho}{2} \tau_g I_{T,i} \right) \]

<table>
<thead>
<tr>
<th>Dwelling orientation</th>
<th>South-facing windows (50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loughborough latitude</td>
<td>52.8°</td>
</tr>
<tr>
<td>Ground reflectance ((\rho))</td>
<td>0.20</td>
</tr>
<tr>
<td>Control function ((F_c))</td>
<td>1</td>
</tr>
<tr>
<td>Reflectance of the room surfaces ((\tau_R))</td>
<td>0.60</td>
</tr>
<tr>
<td>Transmittance for beam radiation ((\tau_b))</td>
<td>0.71</td>
</tr>
<tr>
<td>Transmittance for diffuse and ground-reflected ((\tau_d) and (\tau_g))</td>
<td>0.64</td>
</tr>
<tr>
<td>Radiation view factor between receiver and sky ((F_{rs}))</td>
<td>Calculated from the dimensions of the window and overhang (using Tables at Duffie and Beckman, 1980)</td>
</tr>
<tr>
<td>Ratio of total beam radiation on a vertical surface during a month to that on a horizontal surface during the same month ((\bar{R}_b))</td>
<td>Estimated for every month as a function of latitude from Figures at Duffie and Beckman, 1980.</td>
</tr>
<tr>
<td>Ratio of total beam radiation on the shaded receiver during a month to that on the unshaded receiver in same month ((\bar{f}_i))</td>
<td>Calculated from dimensions of window and overhang (using Tables at Duffie and Beckman, 1980)</td>
</tr>
</tbody>
</table>

\(I_{b,i}, I_{d,i}\) and \(I_{T,i}\) are, respectively, the hourly daily beam, diffuse and total solar radiation per unit area on a horizontal surface (W/m²)

Obtained by [renewables.ninja](https://renewables.ninja)
Heat demand calculation. Solar heat gains

\[
H_{G,i} = A_w \alpha F_c \left( \overline{f}_i \tau_b I_{b,i} \overline{R}_b + \tau_d F_{rs} I_{d,i} + \frac{\rho}{2} \tau_g I_i \right)
\]

<table>
<thead>
<tr>
<th></th>
<th>Detached</th>
<th>Semi-detached</th>
<th>Terraced</th>
<th>Flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative width of window</td>
<td>≈4,0</td>
<td>≈4,0</td>
<td>≈4,0</td>
<td>≈4,0</td>
</tr>
<tr>
<td>(width/height)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative projection of</td>
<td>≈0,5</td>
<td>≈0,5</td>
<td>≈0,5</td>
<td>≈0,5</td>
</tr>
<tr>
<td>overhang (projection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>overhang/height window)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overhang: position above</td>
<td>0,4</td>
<td>0,4</td>
<td>0,4</td>
<td>0,4</td>
</tr>
<tr>
<td>the window (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extensions (m)</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
</tr>
</tbody>
</table>

\(\alpha\) is the effective absorptance of the window/room combination, calculated as

\[
\alpha = 1 - \left[ \frac{\tau_b t_R A_w}{1 - t_R \left( 1 - \frac{A_w}{A_R} \right)} \right] [\text{where } t_R \text{ is the reflectance of the room surfaces, assumed as 0.6 (0.9 can be used for clean white surfaces, 0 for black surfaces) and } A_R \text{ is the room surface area (walls, floor, ceiling)}]
\]

\[
\alpha = 1 - \left[ \frac{\tau_b t_R A_w}{1 - t_R \left( 1 - \frac{A_w}{A_R} \right)} \right]
\]
Heat demand calculation. Solar heat gains

I. Solar heat gains higher in the winter due to a lower sun position in the sky and therefore lower incidence angle of the sun on south-facing windows.

II. Solar heat gains higher in detached houses due to a bigger windows area in these dwellings.
Heat demand calculation. Heat gains due to occupancy

Table 6.1 Heat emission (W) from an adult male body (of surface area 2 m²) and average heat emission per person for a mixture of men, women and children typical of the stated application

<table>
<thead>
<tr>
<th>Activity</th>
<th>Typical application</th>
<th>Occupancy density (m²/person)</th>
<th>Total, sensible and latent heat emission (W) for stated application and dry bulb temperature (°C) for adult male (and average for mixture of men, women and children)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seated, inactive</td>
<td>Theatre, cinema matinee</td>
<td>0.75–1.0²,³</td>
<td>115 (100) 100 (87) 15 (13) 90 (78) 25 (22) 80 (70) 35 (30) 75 (65) 40 (35) 65 (57) 50 (43)</td>
</tr>
<tr>
<td>Seated, inactive</td>
<td>Theatre, cinema evening</td>
<td>0.75–1.0²,³</td>
<td>115 (105) 100 (91) 15 (14) 90 (82) 25 (23) 80 (73) 35 (32) 75 (68) 40 (37) 65 (59) 50 (46)</td>
</tr>
<tr>
<td>Seated, light work</td>
<td>Restaurant</td>
<td>1.0–2.0²,³</td>
<td>140 (126) 110 (99) 30 (27) 100 (90) 40 (36) 90 (81) 50 (45) 80 (72) 60 (54) 70 (63) 70 (63)</td>
</tr>
<tr>
<td>Seated, moderate work</td>
<td>Office</td>
<td>8–30⁴⁴⁶, 14³⁶</td>
<td>140 (130) 110 (102) 30 (28) 100 (93) 40 (37) 90 (84) 50 (46) 80 (74) 60 (56) 70 (65) 70 (65)</td>
</tr>
<tr>
<td>Standing, light work, walking</td>
<td>Department store</td>
<td>1.7–4.3²,³</td>
<td>160 (141) 120 (106) 40 (35) 110 (97) 50 (44) 100 (88) 60 (53) 85 (75) 75 (66) 75 (66) 85 (75)</td>
</tr>
<tr>
<td>Standing, light work, walking</td>
<td>Bank</td>
<td>—</td>
<td>160 (142) 120 (107) 40 (35) 110 (98) 50 (44) 100 (89) 60 (53) 85 (76) 75 (66) 75 (66) 85 (76)</td>
</tr>
<tr>
<td>Light bench work</td>
<td>Factory</td>
<td>—</td>
<td>235 (209) 150 (133) 85 (76) 130 (116) 105 (93) 115 (102) 120 (107) 100 (89) 135 (121) 80 (71) 155 (138)</td>
</tr>
<tr>
<td>Medium bench work</td>
<td>Factory</td>
<td>—</td>
<td>265 (249) 160 (150) 105 (99) 140 (132) 125 (117) 125 (117) 140 (132) 105 (99) 160 (150) 90 (85) 175 (164)</td>
</tr>
<tr>
<td>Heavy work</td>
<td>Factory</td>
<td>—</td>
<td>440 (440) 220 (220) 220 (220) 190 (190) 250 (250) 165 (165) 275 (275) 135 (135) 305 (305) 105 (105) 335 (335)</td>
</tr>
<tr>
<td>Moderate dancing</td>
<td>Dance hall</td>
<td>0.5–1.0</td>
<td>265 (249) 160 (150) 105 (99) 140 (132) 125 (117) 125 (117) 140 (132) 105 (99) 160 (150) 90 (85) 175 (164)</td>
</tr>
</tbody>
</table>

* Recommended
Notes:
(1) Figures in parenthesis are adjusted heat gains based on normal percentage of men, women and children for the applications listed. This is based on the heat gain for women and children of 85% and 75% respectively of that of an adult male.
(2) For restaurant serving hot meals add 10 W sensible and 10 W latent for food per individual.

Simplified framework for the model

Stage 1

Heat demand at hour $i$

Heat production by renewable sources at hour $i$ (kWh)

WEATHER at hour $i$

1. SOLAR PHOTOVOLTAIC
2. WIND ONSHORE
3. SOLAR THERMAL
4. WASTE HEAT
5. BIOMASS

HEAT

POWER

AIR SOURCE HEAT PUMPS (50%)

WATER SOURCE HEAT PUMPS (50%)
Heat output produced by heat pumps powered by SPV and Wind turbines

\[
P_{\text{output}(SPV+W),i} = CF_{(SPV+W),i} \cdot C_{\text{output}(SPV+W)}
\]

Assumed capacity for SPV and Wind (MW)

Hourly power output produced by SPV and Wind (kWh), \( P_{\text{output}(SPV+W),i} \)

\[
COP = a_0 + a_1 \Delta T + a_2 \Delta T^2
\]

Hourly heat output produced by SPV and Wind (kWh)

\[
CoP_i = \frac{H_{\text{output HP},i}}{P_{\text{output (SPV+W),i}}}
\]

Data supplied by manufacturers (\( a_0, a_1 \) and \( a_2 \))

Hourly power output produced by SPV and Wind (kWh), \( P_{\text{output}(SPV+W),i} \)

Assumed capacity for SPV and Wind (MW)

\[
T_{\text{air},i} \ (\degree C)
\]

\[
T_{\text{water},i} \ (\degree C)
\]

\[
T_{\text{water \ in \ pipes}} = 35 \degree C
\]

\[
T_{\text{air, home}} = 21 \degree C
\]

\[
\text{Renewables.ninja}
\]

\[
\text{Hourly capacity factor for SPV and Wind (\%)}
\]
Heat output produced by Solar thermal Collectors

**Renewables.ninja**

Data supplied by manufacturers ($\eta_0$, $k_1$ and $k_2$)

Hourly collector efficiency, $\eta_{STC,i}$

$$\eta_{STC,i} = \eta_0 - k_1 \frac{(T_{supply,water} - T_{air,i})}{I_{GL,i}} - k_2 \frac{(T_{supply,water} - T_{air,i})^2}{I_{GL,i}}$$

Hourly heat output produced by STC (kWh)

<table>
<thead>
<tr>
<th>Collector</th>
<th>$\eta_0$</th>
<th>$k_1$</th>
<th>$k_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPC [4]</td>
<td>0.775</td>
<td>3.73</td>
<td>0.0152</td>
</tr>
<tr>
<td>ETC [4]</td>
<td>0.75</td>
<td>1.18</td>
<td>0.0095</td>
</tr>
</tbody>
</table>


A $c$, assumed 2 m$^2$ per dwelling
<table>
<thead>
<tr>
<th>Name</th>
<th>Technology</th>
<th>Capacity (MW)</th>
<th>Date operational</th>
<th>Totals (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A C Shropshire (Farm AD)</td>
<td>Anaerobic Digestion</td>
<td>2</td>
<td>14/05/2013</td>
<td>6</td>
</tr>
<tr>
<td>Colwick Industrial Estate (Farm and Food waste)</td>
<td>Anaerobic Digestion</td>
<td>2</td>
<td>30/09/2014</td>
<td></td>
</tr>
<tr>
<td>Stoke Bardolph energy crop (Farm AD)</td>
<td>Anaerobic Digestion</td>
<td>2</td>
<td>10/07/2010</td>
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<tr>
<td>Green's Lodge Farm</td>
<td>Biomass (dedicated)</td>
<td>2</td>
<td>14/05/2013</td>
<td>2</td>
</tr>
<tr>
<td>Mountsorrel Landfill Site</td>
<td>Landfill gas</td>
<td>1.6</td>
<td>01/05/1996</td>
<td></td>
</tr>
<tr>
<td>Enderby Warren Phase II</td>
<td>Landfill gas</td>
<td>4.9</td>
<td>01/06/1999</td>
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<tr>
<td>Narborough Landfill</td>
<td>Landfill gas</td>
<td>2.7</td>
<td>11/03/2005</td>
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<tr>
<td>Bradgate Quarry Landfill Gas Scheme</td>
<td>Landfill gas</td>
<td>2.5</td>
<td>01/08/1998</td>
<td>19</td>
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<tr>
<td>Lount/Smoile</td>
<td>Landfill gas</td>
<td>1.1</td>
<td>21/07/2003</td>
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<tr>
<td>Bretby Power</td>
<td>Landfill gas</td>
<td>1.6</td>
<td>01/09/2001</td>
<td></td>
</tr>
<tr>
<td>Dorket Head</td>
<td>Landfill gas</td>
<td>2.8</td>
<td>01/02/2005</td>
<td></td>
</tr>
<tr>
<td>Burnstump Landfill Scheme</td>
<td>Landfill gas</td>
<td>1.8</td>
<td>15/04/1999</td>
<td></td>
</tr>
<tr>
<td>Beeston Weir Hydro Scheme</td>
<td>Small hydro</td>
<td>1.7</td>
<td>01/02/2000</td>
<td>1.7</td>
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<td>East Midlands Distribution Centre</td>
<td>Solar photovoltaics</td>
<td>6.1</td>
<td>02/03/2015</td>
<td></td>
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<tr>
<td>Walnut Yard (Phase 1)</td>
<td>Solar photovoltaics</td>
<td>1.8</td>
<td>31/03/2015</td>
<td></td>
</tr>
<tr>
<td>Radcliffe Solar Farm</td>
<td>Solar photovoltaics</td>
<td>4.2</td>
<td>13/06/2015</td>
<td></td>
</tr>
<tr>
<td>Wymeswold Airfield</td>
<td>Solar photovoltaics</td>
<td>34</td>
<td>28/03/2013</td>
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</tr>
<tr>
<td>Six Hills Solar Farm</td>
<td>Solar photovoltaics</td>
<td>18.7</td>
<td>24/03/2015</td>
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<tr>
<td>Prestop Park Farm</td>
<td>Solar photovoltaics</td>
<td>16</td>
<td>21/03/2015</td>
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<tr>
<td>Packington Solar Farm</td>
<td>Solar photovoltaics</td>
<td>13.9</td>
<td>16/03/2013</td>
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<td>Toyota Solar Farm</td>
<td>Solar photovoltaics</td>
<td>4.6</td>
<td>25/07/2011</td>
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<tr>
<td>Atherstone</td>
<td>Solar photovoltaics</td>
<td>14.7</td>
<td>31/03/2015</td>
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<tr>
<td>The Stables</td>
<td>Solar photovoltaics</td>
<td>1.8</td>
<td>22/08/2014</td>
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<tr>
<td>Gedling Solar Farm</td>
<td>Solar photovoltaics</td>
<td>5.6</td>
<td>15/03/2015</td>
<td>121.4</td>
</tr>
<tr>
<td>East Midlands Airport</td>
<td>Wind Onshore</td>
<td>1</td>
<td>10/05/2011</td>
<td></td>
</tr>
<tr>
<td>Severn Trent STW</td>
<td>Wind Onshore</td>
<td>2.5</td>
<td>26/02/2014</td>
<td></td>
</tr>
<tr>
<td>Newthorpe Wind Turbine</td>
<td>Wind Onshore</td>
<td>2.5</td>
<td>08/04/2014</td>
<td></td>
</tr>
<tr>
<td>Low Spinney Wind Farm</td>
<td>Wind Onshore</td>
<td>8</td>
<td>29/09/2011</td>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOTAL</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NO RENEWABLES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratcliffe</td>
<td>Coal</td>
<td>2000</td>
<td>1968</td>
<td></td>
</tr>
</tbody>
</table>

TOTAL 2000 MW

TOTAL (OVERALL) 2164.1
Simplified framework for the model

**Stage 1**

Heat demand at hour \(i\)

Heat production by renewable sources at hour \(i\) (kWh)

Heat losses in pipes (kWh)

---

**Pipes characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_{\text{in}}) (m)</td>
<td>0.009(^1)</td>
</tr>
<tr>
<td>(D_{\text{out}}) (m)</td>
<td>0.01(^1)</td>
</tr>
<tr>
<td>Insulation material</td>
<td>AluFlex(^2)</td>
</tr>
<tr>
<td>(\lambda) (W/m K)</td>
<td>0.023(^2)</td>
</tr>
<tr>
<td>(T_{\text{supply}}) (°C)</td>
<td>50</td>
</tr>
<tr>
<td>(T_{\text{return}}) (°C)</td>
<td>35</td>
</tr>
<tr>
<td>Length (m)</td>
<td>To be decided</td>
</tr>
</tbody>
</table>

---

\[HL_{p,x \to y,i} = 2 \cdot \pi \cdot \lambda \cdot L_{x \to y} \cdot \frac{(T_{\text{in}} - T_{\text{out},i})}{\ln\left(\frac{r_{\text{out}}}{r_{\text{in}}}\right)}\]

**Note:**
Simplified framework for the model

Stage 1
- Heat demand at hour $i$
- Heat production by renewable sources at hour $i$ (kWh)
- Heat losses in pipes (kWh)

Stage 2
- Scenario 1: Additional heat input needed to meet demands, supplied by TES.
- Scenario 2: Surplus heat produced, to be stored in TES.

Diamond: Heat production > Heat demand + Heat losses?

YES
- Scenario 2: Surplus heat produced, to be stored in TES.

NO
- Scenario 1: Additional heat input needed to meet demands, supplied by TES.
Main properties of TES materials.

<table>
<thead>
<tr>
<th>PCM: Sodium acetate trihydrate(^1)</th>
<th>TCS: MgSO(_4) + zeolite(^2)</th>
<th>Sensible: Water</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density (kg/m(^3))</strong></td>
<td>1450</td>
<td>1453</td>
</tr>
<tr>
<td><strong>Latent heat (h, kJ/kg)</strong></td>
<td>180</td>
<td></td>
</tr>
<tr>
<td><strong>Specific heat of liquid (kJ/kg K)</strong></td>
<td>3.35</td>
<td></td>
</tr>
<tr>
<td><strong>Specific heat of solid (kJ/kg K)</strong></td>
<td>1.97</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature of solid (cold) (°C)</strong></td>
<td>30(^3)</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature of liquid (hot) (°C)</strong></td>
<td>70(^3)</td>
<td></td>
</tr>
<tr>
<td><strong>Melting/freezing point (°C)</strong></td>
<td>58</td>
<td></td>
</tr>
</tbody>
</table>


3 Assumed values.
### THERMAL ENERGY STORAGE

<table>
<thead>
<tr>
<th></th>
<th>Sensible</th>
<th>Latent</th>
<th>Sensible</th>
<th>Thermochemical storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SWT (m³)</td>
<td>PCM (m³)</td>
<td>BWT (m³)</td>
<td>TCS (m³)</td>
</tr>
<tr>
<td>Maximum volume allowed (m³)(^1)</td>
<td>1</td>
<td>1</td>
<td>500000</td>
<td>1</td>
</tr>
<tr>
<td>Temperature charging (°C)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>120</td>
</tr>
<tr>
<td>Temperature discharging (°C)</td>
<td>80</td>
<td>T range available</td>
<td>80</td>
<td>T range available</td>
</tr>
<tr>
<td>Storage capacity (kWh)(^1)</td>
<td>26</td>
<td>55</td>
<td>52250000</td>
<td>143</td>
</tr>
<tr>
<td>Initial energy stored (kWh)</td>
<td>0</td>
<td>0</td>
<td>~</td>
<td>~</td>
</tr>
</tbody>
</table>

\(^1\) The maximum volume allowed when referring to SWT, PCM and TCS is the volume per every 2 dwellings, whereas when referring to BWT the maximum volume is the volume of the whole single unit.
Proposed operating mode for the heating district

Scenario 2: surplus heat to store

Heat sources

Waste heat

Biomass

Solar panels

Heat wasted

Scenario 1: Heat required to meet demands

Other heat sources

Wind

Solar

Power

Power
RESULTS

- Number of dwellings of each type with similar characteristics: 10000;
- Number of persons living in the dwelling: 4;
- Heating hours: 7 am - 9 am, 5 pm - 9 pm;
- Working hours: 8 am to 5 pm;
- No heat demand originated from tap water heating considered here.
- Temperature inside dwelling = 21°C
- Assuming improved U-values for the fabric.

![Diagram showing domestic hourly heat demand for different types of dwellings over the period from 01/01/2018 to 01/12/2018. The graph compares detached, semidetached, terrace, and flat types, with different colors representing each type. The y-axis indicates the domestic hourly heat demand in kWh, ranging from 0 to 30000. The x-axis represents the days from 01/01/2018 to 01/12/2018, with hourly intervals. The graph highlights the peaks and troughs in heat demand throughout the year.]
Number of dwellings of each type with similar characteristics: 10000;
Number of person living in the dwelling: 4;
Heating hours: 7 am - 9 am, 5 pm - 9 pm;
Working hours: 8 am to 5 pm;
No heat demand originated from tap water heating considered here.
Temperature inside dwelling = 21°C
Assuming basic U-valess for the fabric.

RESULTS
RESULTS

Type of dwelling: detached
Number of dwelling with same characteristics: 10000
Number of person living in the dwelling: 4
Heating hours: 7 am - 9 am, 5 pm - 9 pm
Working hours: 8 am to 5 pm
No heat losses in pipes considered for SWT, PCM and TCS
Distance from BWT to dwellings (pipes above the ground): 1000 m
No heat losses in stores considered yet
Temperature inside dwelling = 21°C.
Just ETSTC considered.

High number of heat charges to Big Water Tanks in summer months, due to both lower demand and higher heat production in these months

PCMs start being charged in the spring months, due to SWT reaching maximum capacity

The Big Water Tank help to meet heat demands in winter and autumn months.
RESULTS

Type of dwelling: flat
Number of dwelling with same characteristics: 10000
Number of person living in the dwelling: 4
Heating hours: 7 am - 9 am, 5 pm - 9 pm
Working hours: 8 am to 5 pm
No heat losses in pipes considered for SWT, PCM and TCS
Distance from BWT to dwellings (pipes above the ground): 1000 m
No heat losses in stores considered yet
Temperature inside dwelling = 21°C.
Just ETSTC considered.

The low heat demand in flats leads to maximum capacity reached in SWT, PCM and BWT in summer months and therefore TCS are started to being charged.

The Big Water Tank help to meet heat demands in winter and autumn months.
RESULTS

Type of dwelling: flat
Number of dwelling with same characteristics: 10000
Number of person living in the dwelling: 4
Heating hours: 7 am - 9 am, 5 pm - 9 pm
Working hours: 8 am to 5 pm

No heat losses in pipes considered for SWT, PCM and TCS
Distance from BWT to dwellings (pipes above the ground): 1000 m
No heat losses in stores considered yet
Temperature inside dwelling = 21°C.
Just ETSTC considered.

PCMs start charging when maximum capacity is reached in SWTs and PCMs

TCS devices start charging when maximum capacity is reached in SWTs, PCMs and BWT

BWT starts charging when maximum capacity is reached in SWTs and PCMs
**FUTURE WORK**

i. Identify possible sources of waste heat near Loughborough.

ii. Assume biomass-source heat production capacity (MW).

iii. Introduce heat losses in stores (kWh).

iv. Find a detailed profile for domestic hot water consumption.

v. Calculate friction losses in pipes.

vi. Consider profiles when discharging some TES materials (PCMs).

vii. Find cost of the different materials and technologies in order to carry out a proper study.

viii. Decide lengths of pipes for the different sections of the District Heating. Decide if pipes will be underground or above the ground.

ix. Include different profiles for dwellings.

<table>
<thead>
<tr>
<th>House type</th>
<th>Occupancy level</th>
<th>Number of occupants</th>
<th>Occupant characteristics</th>
<th>Mean appliance gains (W)</th>
<th>Mean active occupancy as % of day</th>
<th>Mean hot water use (litres/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrace</td>
<td>Low</td>
<td>1 adult</td>
<td>Part-time employment</td>
<td>160.4</td>
<td>35.8%</td>
<td>51.4</td>
</tr>
<tr>
<td>Terrace</td>
<td>High</td>
<td>3 adults</td>
<td>2 x full-time employment + 1 x non-working</td>
<td>503.8</td>
<td>54.0%</td>
<td>125.7</td>
</tr>
<tr>
<td>Detached</td>
<td>Low</td>
<td>2 adults/2 children</td>
<td>1 x full-time employment + 1 x non-working</td>
<td>272.0</td>
<td>48.2%</td>
<td>50.0</td>
</tr>
<tr>
<td>Detached</td>
<td>High</td>
<td>2 adults/3 children</td>
<td>1 x full-time + 1 x part-time employment</td>
<td>456.0</td>
<td>55.8%</td>
<td>251.6</td>
</tr>
<tr>
<td>Semidetached</td>
<td>Low</td>
<td>1 adult/1 child</td>
<td>Non-working</td>
<td>199.1</td>
<td>45.0%</td>
<td>85.5</td>
</tr>
<tr>
<td>Semidetached</td>
<td>High</td>
<td>2 adults</td>
<td>Both retired</td>
<td>582.2</td>
<td>54.8%</td>
<td>146.9</td>
</tr>
<tr>
<td>Flat</td>
<td>Low</td>
<td>1 adult</td>
<td>Non-working</td>
<td>115.4</td>
<td>41.2%</td>
<td>42.3</td>
</tr>
<tr>
<td>Flat</td>
<td>High</td>
<td>2 adults/1 child</td>
<td>1 x full-time employment + 1 x non-working</td>
<td>228.2</td>
<td>46.2%</td>
<td>82.7</td>
</tr>
</tbody>
</table>

FUTURE WORK

x. Detailed spatial/temporal model for district heating networks including thermal storage.

xi. Produce results and validate the model.
Simulation of a 4\textsuperscript{th} generation district heating network operating with renewable heat sources and TES technologies

LoT-NET project

Miguel Angel Pans Castillo
Philip Eames

13-12-2019
ANY (EASY) QUESTIONS?